# Orion GN&C Mitigation Efforts for Van Allen Radiation

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**The Orion Crew Module (CM) is NASA's next generation manned space vehicle, scheduled to return humans to lunar orbit in the coming decade. The Orion avionics and GN&C architectures have progressed through a number of project phases and are nearing completion of a major milestone. The first unmanned test mission, dubbed "Exploration Flight Test One" (EFT-1) is scheduled to launch from NASA Kennedy Space Center late next year and provides the first integrated test of all the vehicle systems, avionics and software.**

## Nomenclature

*ARINC* = *Aeronautical Radio, Incorporated*
*CCR* = *Cross Channel Restart*
*CM* = *Crew Module*
*EFT-1* = *Exploration Flight Test One*
*EI* = *Entry Interface*
*EKF* = *Extended Kalman Filter*
*ELV* = *Expendable Launch Vehicle*
*FCM* = *Flight Control Module*
*FDIR* = *Fault Detection, Isolation and Recovery*
*FILTNAV* = *Filtered Navigator*
*GCI* = *GN&C Command Interface*
*GN&C* = *Guidance Navigation and Control*
*GPS* = *Global Positioning System*
*HWIL* = *Hardware in the Loop*
*ICRF* = *International Celestial Reference Frame*
*ITRF* = *International Terrestrial Reference Frame*
*LEO* = *Low Earth Orbit*
*PDU* = *Power and Data Unit*
*OIMU* = *Orion Inertial Measurement Unit*
*ODN* = *Orion Data Network*
*RPM* = *Reset Protected Memory*
*SECO* = *Secondary Engine Cuttoff*
*SCR* = *Self Checking Pair*
*SDR* = *Stored Data Restart*
*SEU* = *Single Event Upset*
*SLDB* = *Separately Loadable Database*
*SM* = *Service Module*
*TM* = *Timeline Manager*
*VPU* = *Video Processing Unit*
*UPP* = *User Parameter Processor*
*VL* = *Virtual Link*

## I. Introduction

THE Orion Crew Module (CM) is NASA's next generation manned space vehicle, scheduled to return humans to lunar orbit in the coming decade. The Orion avionics and Guidance Navigation and Control (GN&C) architectures have progressed through a number of project phases and are nearing completion of a major milestone. The first unmanned test mission, dubbed "Exploration Flight Test One" (EFT-1) is scheduled to launch from NASA Kennedy Space Center late next year and provides the first integrated test of all the vehicle systems, avionics and software.

The EFT-1 mission will be an unmanned test flight that includes a high speed re-entry from an elliptical orbit, which will be launched on an expendable launch vehicle (ELV). Figure 1 shows the ground track and altitude profile of the 4 hour and 10 minute mission. The ELV will place CM and the ELV upper stage into a low Earth orbit (LEO) for one revolution. After the first LEO, the ELV upper stage will re-ignite and place the combined upper stage/CM into an elliptical orbit whose perigee results in a high energy entry to test CM response in a

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relatively high velocity, high heating environment. The trajectory was chosen to provide higher stresses on the thermal protection and guided entry systems, as compared against a lower energy LEO entry. However the required entry geometry together with constraints on inclination and landing location result in a trajectory that lingers for many hours in the Van Allen radiation belts (Figure 2). This exposes the vehicle and avionics to much higher levels of high energy proton radiation for far longer than a typical low Earth Orbit or lunar transit trajectory would encounter. As a result, Van Allen radiation exceeds the design environment for the Orion avionics system, and poses a significant risk to the Flight Control Module (FCM) computers that house the GN&C flight software.

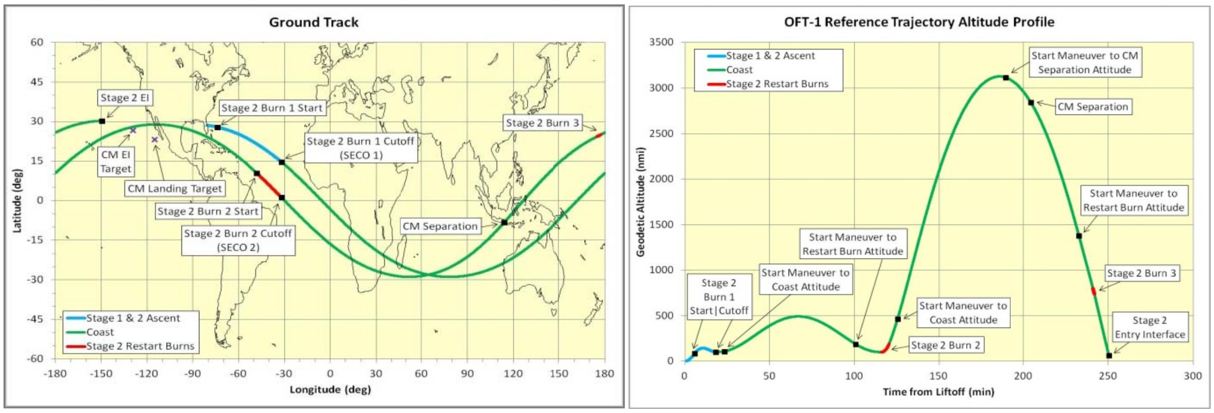

Figure 1. EFT-1 Groundtack and Altitude Profiles.

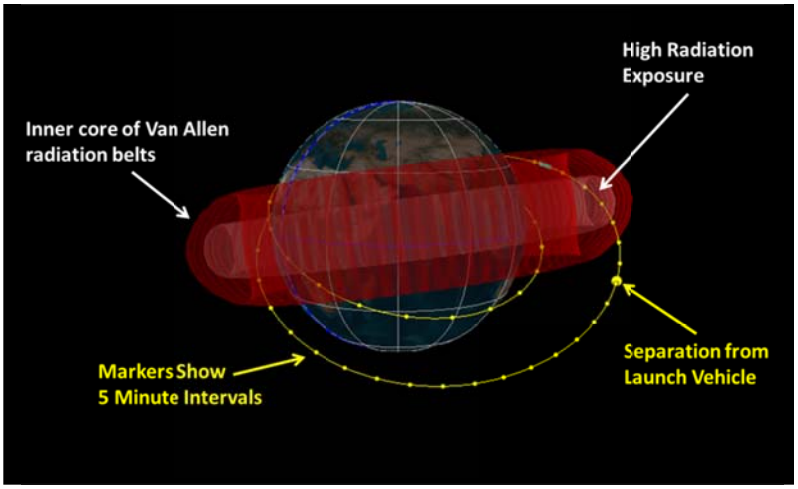

Figure 2. EFT-1 Trajectory and Van Allen Radiation Exposure

The measures taken by the Orion GN&C, Flight Software and Avionics teams to mitigate the risks associated with the Van Allen radiation on EFT-1 are covered in the paper. Background is provided on the radiation environment and the Orion avionics, as well as an overview of the GN&C software architecture. The measures taken to handle radiation induced failure of the one or both of the FCM's are presented, and finally simulation and actual hardware-in-the-loop (HWIL) results are shown confirming the validity of the implementation.

## A. Radiation Environment

Figure 3 shows the EFT-1altitude profile with the proton flux encountered during the flight. While there are two periods of exposure to Van Allen proton radiation, most of the robustness requirements are driven by the second, descending passage through the belts during which high levels of flux persist for more than 20 minutes. During this period, a single event upset (SEU) of one or both of the FCM's has high enough probability to justify the mitigation steps described below.

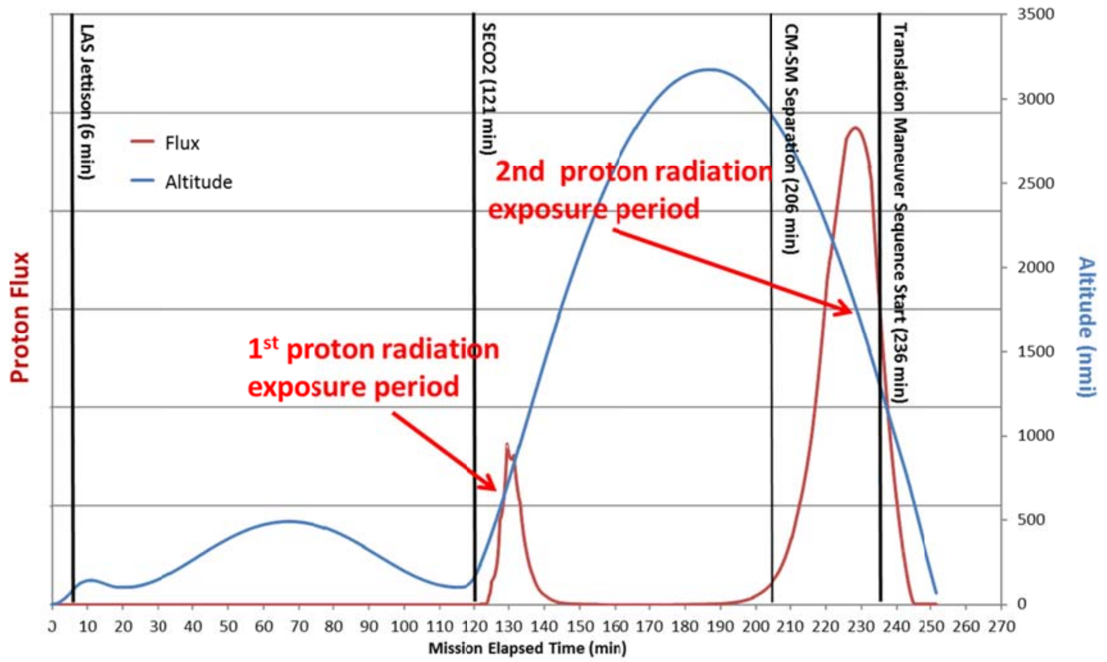

Figure 3. Radiation Flux and Orion Altitude Profile

## II. Avionics and Flight Software Overview

### A. Avionics

Figure 4 is a simplified diagram of the Orion avionics. GN&C sensors include two Orion Inertial Measurement Units (OIMU's), a Vision Processing Unit (VPU) to process camera images, three barometric altimeters housed together and a single Global Positioning (GPS) receiver. All of the sensors communicate to one of two Power and Data Units (PDU's). The PDU's multiplex analog and serial data from the sensors and write the data to the Orion Data Network (ODN). The OIMU's write their data directly as messages to the ODN, but they are routed through PDU network switches as shown.

Sensor data are passed via the ODN to the GN&C software application within one of two Flight Control Modules (FCM's). Each FCM contains a self-checking pair (SCP) of processors mounted on a single card, each with its own memory. The SCPs run identical applications and provide protection against incorrect outputs caused by radiation-induced upsets or other processor problems. When an FCM detects a mis-compare between the two SCP processors, the FCM ceases outputting commands to the ODN. The OIMUs and PDUs have a priority logic which accepts commands from FCM1 unless FCM1 commands are unavailable, in which case, commands from FCM2 are processed. This process allows for automated redundancy for an FCM failure. Table 1 summarizes the Orion avionics components of interest.

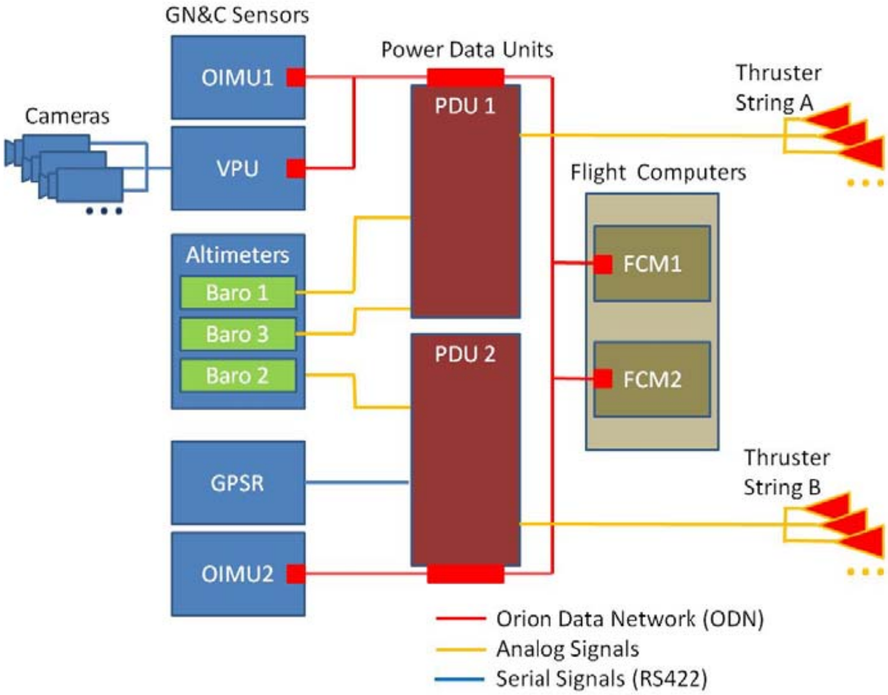

Figure 4. Orion Avionics Diagram

Table 1. Orion Avionics Components

| Component | Description |
|---|---|
| Orion Inertial Measurement Unit (OIMU) | •Senses vehicle body rates<br>•Senses vehicle acceleration |
| Global Positioning System Receiver (GPSR) | •Receives GPS satellite RF signals<br>•Generates pseudorange and deltarange measurements for each satellite<br>•Performs Receiver Autonomous Integrity Monitoring (RAIM) algorithms |
| Barometric Altimeter (BALT) | •Senses static pressure at the capsule outer shell |
| Video Processing Unit (VPU) | •Performs onboard video processing and telemetry downlink<br>•Performs backup attitude propagation<br>•Houses backup cross channel restart software |
| Power and Data Unit (PDU) | •Supplies onboard network schedule for ODN<br>•Supplies power for avionics units<br>•Supplies commands to RCS thruster units<br>•RS422 serial data communication from GPSR onto the ODN |
| Flight Control Module (FCM) | •Primary Time management software<br>•Primary Vehicle Timeline management software<br>•Primary Command and Data Handling software<br>•Primary Guidance, Navigation and Control software |

Should a single FCM failure occur, it is often desirable to restart the failed FCM and restore redundancy, so the ODN and FCM software provide a ***cross-channel data*** stream to initialize critical states in the failed FCM from the running FCM. This means that the GN&C applications resident in the FCMs must have the capability to provide and accept initialization data from its counterpart FCM. The process of starting one FCM from the other is referred to as a “Cross Channel Restart” (CCR) and will be detailed in subsequent sections.

Since the EFT-1 mission’s second pass through the Van Allen belts has significant duration, Orion is also required to protect for dual FCM failures occurring simultaneously, or nearly simultaneously. Automated protection for dual FCM failures is provided by storing attitude and translation navigation data and using the stored data to re-initialize the GN&C applications. The translation state data are time-tagged and kept static in non-volatile memory during the restart process. However, because Orion has no external attitude sensor for EFT-1, attitude data must be propagated with IMU gyro inputs during the time that the FCMs are inoperative to maintain attitude knowledge. For this reason, attitude propagation software is embedded on a processor in the VPU. The attitude state is continuously updated by the FCMs until a dual FCM failure event. At that point, the VPU continues to propagate attitude until the FCM’s are restarted from stored data. This process of re-starting the both FCM’s from stored data is called a “Stored Data Restart” (SDR) and will also be described in subsequent sections.

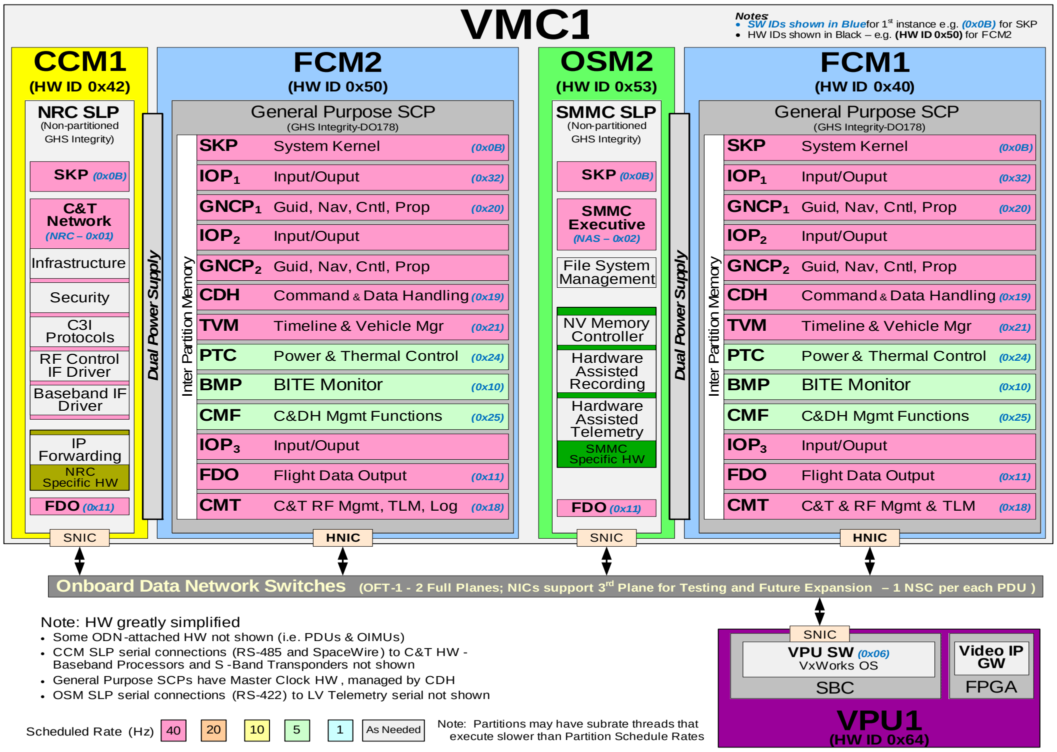

Figure 5. Orion Dual Flight Control Module (FCM) Partition Architecture

## III. GN&C Software Architecture

The Orion GN&C software is implemented in the FCMs as an Aeronautical Radio, Incorporated (ARINC) 653 Time-space Partition [reference for ARINC OS]. The GN&C partition consists of and executive framework that houses algorithms which are autocoded from MATLAB/Simulink.

The navigation portion of the software (Figure 4) includes two channels, each of which is associated with one of the OIMUs. Each channel has an extended Kalman Filter (EKF) that executes at 1 Hz, and provides GPS measurement updates to the filtered navigation (FILTNAV) module, which propagates the state based on OIMU data between measurements. Each channel also houses a pure inertial propagator (Inertial Nav) that provides an inertial-only backup solution to protect for corruption of the state by a faulty GPS. Note that each channel has an independent IMU, but both channels receive measurements from the single GPS on the EFT-1 vehicle.

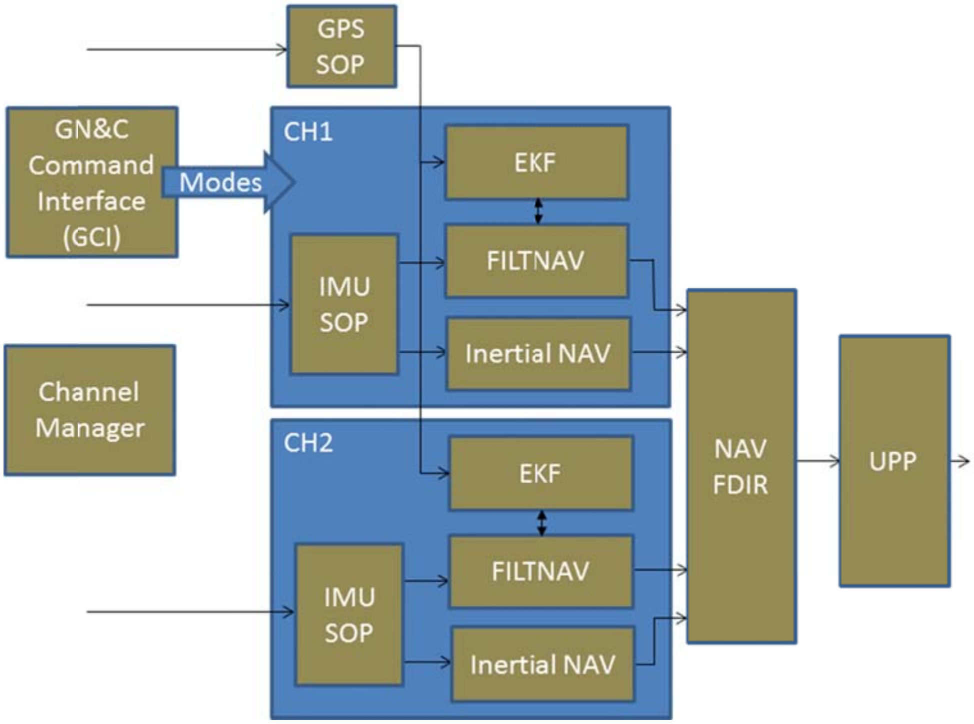

Figure 6. Diagram of GN&C Navigation Dual Channel Software Architecture

Downstream of the dual channels, navigation fault detection, isolation and recovery (Nav FDIR) software selects the state for use by guidance and control from the filtered (GPS aided FILTNAV state) or the inertial state from channel one or channel 2. The selected inertially referenced state is sent to the user parameter processor (UPP) for processing to generate required navigation data for downstream customers. UPP outputs include Earth fixed states, flight data parameters such as angle of attack, bank and sideslip as well as filtered angular rates and accelerations.

### B. Inflight Restarts: Overview of Cross Channel Restart (CCR) & Stored Data Restart (SDR)

When radiation upset event conditions are detected by the self-checking pair FCM hardware (or if one is intentionally commanded by ground operators), this triggers a restart of the affected FCM hardware while the rest of the avionics continue to operate. In the event that the non-restarting FCM is operating and uninhibited it continues to fly the vehicle closed loop without interruption. However for EFT-1 there is also a real, although low probability chance that the secondary FCM may not be operational at the time of the restart. This constitutes what is referred to as a dual FCM restart and was deemed to be significant enough of a risk to the program to develop a solution in software. In the dual restart case a combination of data stored in non-volatile FCM memory and auxiliary VPU hardware is used to provide enough critical data to restart the FCM(s) without an active counterpart. In either restart case, all of the critical GN&C flight software states and data must be transferred to the restarting FCM and utilized in the application software to initialize all the algorithms at the appropriate point in the mission event sequence. The paper presents a high level overview of the embedded restart logic on each FCM for determining upon restart or power up whether one of the restart cases is encountered or if the vehicle is proceeding through a nominal power up on the launch pad.

### C. GN&C Software

The GN&C software executes on one of the many software partitions allocated on each FCM. This paper presents an overview of the EFT-1 GN&C software architecture with a heavy focus on navigation, as most of the complexity in performing inflight restarts deals with restarting the navigation software. The timing and rate monotonic scheduling scheme is summarized to provide background for the sections that discuss how the multi-rate navigation system is re-anchored to the current Orion time during the restart process.

The Orion GN&C software architecture includes a GN&C command interface (GCI) that provides moding commands and configuration data to navigation, guidance and control domain modules. Automated sequences are enacted within GCI by sequencing through data configurable activities loaded onto the vehicle via Separately Loadable Databases (SLDBs). Each activity consists of the appropriate mode commands and configuration data needed to accomplish the activity objective. GCI also contains software to perform automated transitions between activities based on data configurable transition criteria. The vehicle "Timeline Manager (TM)" is responsible for coordinating event transitions across all vehicle subsystems including GN&C, and the interface for communicating changes across all subsystems is through "mission segments". Within the GN&C subsystem, GCI responds to a new mission segment by kicking off a new sequence of activities. Transitions between mission segments within the TM software are often based on state data and flags provided by GN&C. While all of the GN&C state data cannot be synchronized between the FCMs, transitions between the high level segments are synchronized to ensure that segment boundaries could never occur at slightly different times within each FCM. This critical event synchronization is accomplished by including the transition status of the counterpart FCM in the segment transition criteria. The paper describes the critical state data exchanged between TM and GCI counterpart instances in order to ensure that vehicle configuration parameters, sequencing information as well as command data are preserved during a restart.

The navigation software is divided in to two "channels" associated with each of the redundant Orion IMUs. Each channel includes both filtered and inertial solutions. The filtered solutions incorporate GPS measurements within a 1 Hz Extended Kalman Filter (EKF) that interacts with a 40 Hz inertial propagator. In addition a separate, inertial solution is maintained on the vehicle for each navigation channel to provide a backup for the filtered navigation solution taking measurements from the Orion GPS receiver which has never been flown in an exo-atmospheric environment. The paper discusses the mechanisms for initializing both the filtered and inertial states during a restart as well as the navigation trades used to identify and prioritize the subset of navigation filter states that passed between FCMs. Additionally other non-navigation algorithms also require cross channel initialization, including fault detection, isolation and recovery (FDIR) and entry guidance algorithms. Finally, after describing the software architecture and necessary navigation features required to support single and dual FCM restarts, the effect on the navigation system performance is quantified.

## IV. Restart Solutions GN&C Flight Software

*AUTHOR'S NOTE (TO BE REMOVED): In the previous sections we establish the Avionics architecture and FCM partition architecture, as well as the GN&C FSW Architecture and the concept of Inflight CCR and SDR restarts. We also want to establish enough background in the Navigation architecture to discuss multiple Navigation channels, filtered vs. Inertial solutions, etc. Here we elaborate into the specific implementation for the GN&C partition and show performance plots for the navigation filters.*

The EFT-1 Orion mission is largely meant to be a test flight that will prove out many avionics and software designs such that much of the vehicle design can be considered validated for subsequent lunar missions and beyond. However, certain aspects of the EFT-1 design will not be carried forward into later missions due to the nature of the design. It is important to recognize the restart architecture for EFT-1 is one of the areas that will very likely evolve into a very different scheme for later missions. The trajectories and time spent lingering in high radiation environments will be drastically different for subsequent missions as most all trajectories departing from LEO punch through the Van Allen radiation belts comparatively quickly. In addition, the planned addition of a third redundant FCM will add to the overall robustness of the avionics. The Navigation system will be upgraded to include star trackers, sun sensors and optical navigation technologies that will aid in the acquisition of and maintenance of critical states during flight. As such the design of the inflight CCR and SDR approaches will likely only be necessary for EFT-1, although certain components and methodologies may apply in the future. However, it is nonetheless critical to the program that the vehicle is protected for radiation induced upset events as it was deemed to be a significant risk to the success of the mission.

Figure 7 depicts the region of the EFT-1 trajectory over which the vehicle software is required to support *automated* inflight restarts. Most notably, this region encompasses the entire period over which the heaviest Van Allen radiation will be experienced, including the period in which the CM separates from the Service Module (SM) and translation maneuver sequences are initiated. This event is referred to as CM/SM separation (the SM is inert for this mission and remains attached to the launch vehicle). After Orion descends to an altitude of 500 nmi (five minutes prior to entry interface), inflight restarts are not supported and an FCM failure after that point would result in the vehicle returning on the secondary redundant FCM. Ground operations also has a contingency command available to restart an FCM if needed outside these regions.

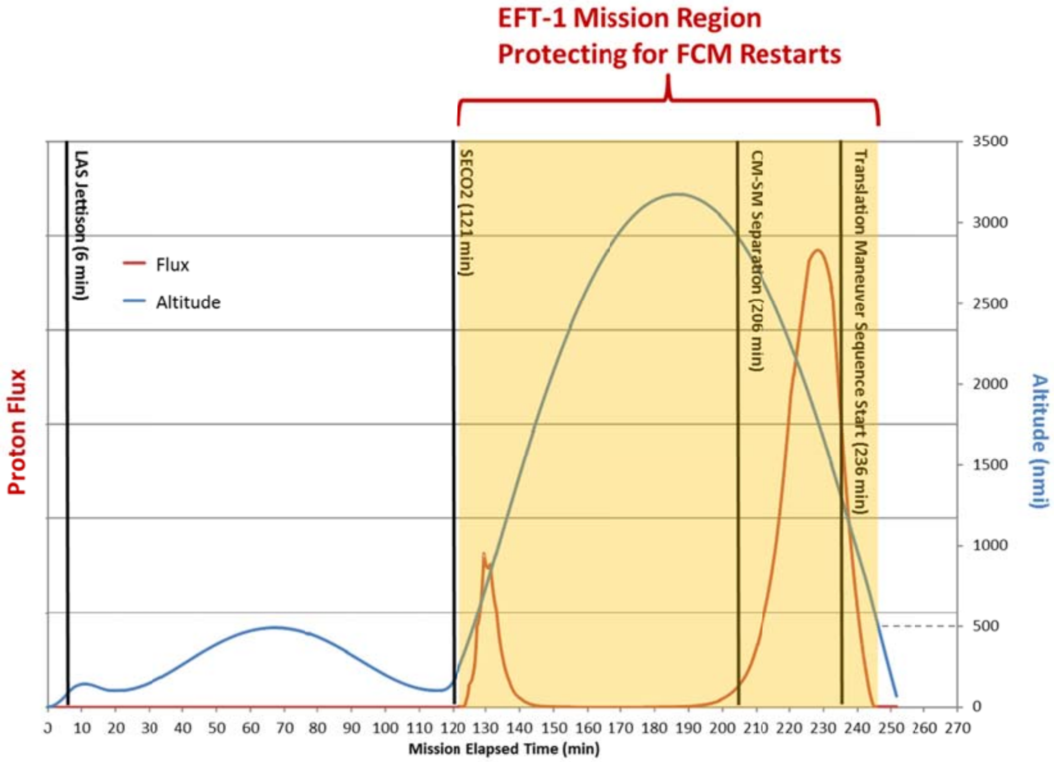

Figure 7. Exploration Flight Test-1 Inflight Restart Protection Region

The following sections detail the most important aspects of the inflight restart design as it pertains to the GN&C partition, followed by results that demonstrate the expected performance for the EFT-1 mission through analysis and Monte Carlo results.

## A. FCM Partition Cross Channel Data

The overall design philosophy for restart of the GN&C partition follows from the partition restart guidelines[1]. Each FCM partition, as detailed in Figure 5, establishes one or more virtual link (VL) cross channel data messages with the required data needed to reinitialize the partitions at a restart epoch. Bandwidth considerations were a factor in this design, as there are limitations in the quantity of data that could be exchanged over the ODN network on a given execution cycle. Fortunately for the EFT-1 design thus far there has been enough bandwidth available to fit all inter-partition cross channel data within these constraints. Just prior to the beginning of each 1Hz cycle, each partition issues their cross channel data messages over the ODN such that their counterpart could make use of this data during a restart event. Once an FCM restart is initiated, it is expected to be completed in 9-15 seconds allowing time for the core kernel software and data loads to be instantiated and loaded into memory. Then upon restarting each partition first checks to determine if counterpart cross channel data messages are available prior to falling into the default case that initializes the software sitting on the ground at the launch site.[*]

An important aspect of the FCM design is that the partition cross channel data messages are stored in inter partition reset protected memory (RPM), which is depicted in Figure 5 as a shared memory area on each FCM. The RPM data area is used to support the Stored Data Reset (SDR) case when a counterpart FCM is unavailable to provide restart data because data written to RPM persists across reset events, provided that the FCM continues to remain powered over the commanded reset. This is a critical aspect of the SDR case, as RPM can be used in lieu of

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[*] Considerable effort was also expended to ensure that a simulation environment could populate cross channel data using the same methods to restart one or more FCMs at various points along the mission profile in order to facilitate testing requirements.

any other cross channel data message to restart an FCM. More details on this restart method will be provided on SDR in subsection D.

For the GN&C partition especially, some specialized considerations were also required for restart to function properly. GN&C algorithms require additional inputs that are not captured in the GN&C cross channel data messages. These data include 1) the Timeline Management phase, segment and mission sequencing information as well as 2) the Command and Data Handling Orion Time broadcast. These items allow the GN&C partition to know what in part of the mission sequence a restart is taking place as well as the current Orion Time required to process IMU messages off of the ODN. Both of these items are obtained by allowing the GN&C partition to subscribe to the TVM and partition cross channel data (AKA "cross strapped" partitions), at some expense to the complexity of the restart process. Some consideration was given to the option of including these data items within GN&C partition cross channel data, however this was ruled out for the EFT-1 design.

### B. GN&C Cross Channel Data

The GN&C partition requires several areas of data exchange to support the inflight restart capabilities discussed in the subsequent sections. This cross channel data represents all of the critical GN&C states that are required to initialize GN&C partition while in orbit in the EFT-1 mission in the regions depicted in Figure 7. The state areas and examples of each are discussed in turn are broadly characterized into four areas as follows:

1) Sequencing and command data
2) Fault Detection, Isolation and Recovery (FDIR)
3) Guidance and Control
4) Navigation

***Sequencing cross channel data*** is comprised of all states that tell the GN&C partition where the vehicle is within the mission sequence such as the current GN&C Activity[2] and the Activity elapsed time. This critical state data informs the GN&C partition what parameter configurations to load for each operating CSU at that point in the mission. All GN&C command data is exchanged as part of the cross channel data message to inform the restarting partition about any changes that may have been issued by the ground to override default states that exist in memory. For example, the ground could potentially issue a contingency command to override the default landing site target (latitude, longitude) and without passing this knowledge between FCMs this command would need to be reissued to the FCM after each restart event. The EFT-1 mission has only a handful of commands that may be issued by the ground in a contingency scenario, as such this list of cross channel parameters is relatively small. For subsequent missions with many more potential commands and crew interactions this approach will likely not be feasible, however there will also likely be a fail-safe and writable file system onboard which will mitigate much of the need for this capability.

***FDIR cross channel data*** includes all parameters that are necessary to those algorithms such as hardware failure states, persistence counters and other key parameters necessary to determine the health of GN&C related sensors during the mission. This set of state data does not comprise a lot of bandwidth in bytes, but without this key knowledge the restarting application would not have critical knowledge about which sensors are failed or suspect. Exchanging this type of state information mitigates for the highly undesirable case that a navigation channel is selected differently on a restarting FCM than its counterpart.

***Guidance and Control*** algorithms actually do not require any cross channel data exchange for the EFT-1 mission. Control and pointing algorithms are mostly dependent on the Navigation states and inputs directly from the IMU and as a result do not require much in terms of restart states. Initially there was some concern that a control algorithm could require knowledge of the thruster firing states in order to meet minimum jet on-time requirements, however this concern was abated through analysis[3]. For EFT-1 all of the Guidance algorithms are not active during the period of restart susceptibility shown in Figure 7, although things such as the guided landing target are included for reasons described above.

***The Navigation state data*** comprises the bulk of the GN&C cross channel data required for EFT-1, as such this data will be described more comprehensively. Applicable reference frames for navigation state information include the International Celestial Reference Frame (ICRF) – an Earth centered inertial frame, and the International Terrestrial Reference Frame (ITRF), an Earth centered, Earth fixed frame. As described earlier in Section II and depicted in Figure 6, the Navigation system maintains four independent solutions for position, velocity and attitude quaternions all of which must be transferred to the restarting FCM to maintain the integrity of the system. In addition, the two instantiations of the EKF maintain 2 x 26 = 52 filter states corresponding to the GPS clock bias (bc) and drift (dc) states, accelerometer and gyro biases, scale factors, misalignments, etc. for each navigation channel. The filter states, $\boldsymbol{X}$, may be expressed as[4]

$$\boldsymbol{X} = \left[\boldsymbol{r}^{\boldsymbol{ICRF}^{\boldsymbol{T}}} \quad \boldsymbol{v}^{\boldsymbol{ICRF}^{\boldsymbol{T}}} \quad \boldsymbol{\phi}^{\boldsymbol{T}} \quad b_c \quad d_c \quad p_1 \quad p_2 \quad \cdots \quad p_{24}\right]^{\boldsymbol{T}}$$

where the components of $\boldsymbol{X}$ represent the inertial position ($\boldsymbol{r}^{\boldsymbol{ICRF}}$), inertial velocity ($\boldsymbol{v}^{\boldsymbol{ICRF}}$), attitude Euler axis rotation vector ($\boldsymbol{\phi}$), clock bias ($b_c$) and clock drift ($d_c$). The remaining state parameters ($p_{1\text{-}24}$) represent Markov states that corresponding to the estimated IMU error states which are optimized in the filter implementation to take advantage of matrix sparseness using an efficient UDU formulation[5].

Finally and very importantly, the EKF also requires knowledge of the uncertainty for each of the filter states, commonly expressed in the form of a state covariance matrix, ($P_{35x35}$). The elements of the covariance may be expressed as a function of Gaussian standard deviation values ($\sigma_i$) and correlation coefficients ($\rho_{ij}$) as

$$P_{i,j} = E\left\{\left(X_i - \bar{X}_j\right)^2\right\} = \begin{cases} \sigma_{ii}^2 & \forall\, i = j \\ \rho_{ij}\sigma_i\sigma_j & \forall\, i \neq j, \qquad \left|\rho_{ij}\right| \leq 1 \end{cases}$$

Besides exceeding the cross channel bandwidth limitations, it is inefficient and unnecessary to transfer the entire $P$ covariance matrix to the restarting FCM because $P$ is symmetric. To limit the amount of data required to restart the navigation filters, the covariance matrix data is down selected to include the entire diagonal of 35 state variance values ($\sigma_{ii}^2$), as well as the 36 correlation coefficients ($\rho_{ij}^*$) corresponding to the upper 9x9 position, velocity and attitude state correlations, for each navigation channel. All of the correlations between the clock bias, clock drift and IMU error states ($\rho_{ij}^p$) are dropped for the purposes of inflight restarts as this information is assumed to be negligible for the purposes of restarting the filters for the EFT-1 mission. Of primary concern in this exchange are the cross correlation terms relating the attitude to position and velocity states, as there is no external source for attitude information for EFT-1 and those state correlations allow the coupled attitude-translation EKF to make corrections to the attitude state in a GPS measurement rich environment.[6] It is worth noting that although the clock bias ($b_c$) and drift ($b_d$) states are available in cross channel data, these initial values are derived from the GPSR estimates as the GPSR hardware is not affected by a restarting FCM. Bias and drift variances ($\sigma_{b_c}^2$, $\sigma_{b_d}^2$) are obtained from either the GPSR hardware or parameter (SLDB) loads as opposed to cross channel data.

Considerable effort was expended in determining how to represent and make use of the cross channel covariance data in the restarting EKF. In addition, the Navigation team debated the merits and pitfalls of inflating the values of $P$ in the restarting filter to account for unmodeled disturbance forces to prevent a situation where the filter became too 'smug', thereby rejecting otherwise valid measurements and allowing position and velocity. The counterpoint concern that was raised in inflating the values was related to difficulties in the case that multiple FCM restarts were encountered on the mission. In fact, it is somewhat likely that multiple FCM resets will be encountered on EFT-1. Ultimately it was decided that the best compromise was to leave the EKF covariance values unscaled during a restart event, but instead represent the cross channel covariance terms in the UVW coordinate frame where they would be less likely to change substantially over any reasonable restart interval. These concerns are mostly related to the performance during a stored data reset where there will be some period of time in which neither FCM is computing a navigation solution. These are assumptions which must be validated through analysis and test over the next year leading up to the EFT-1 mission.

The navigation solutions for any recursive filter are naturally sensitive to initial conditions during an inflight restart. Although all the critical navigation states are passed between FCMs, there are enough parameters missing and differences with respect to measurement processing to guarantee that a restarting FCM and its counterpart will produce slightly different solutions after a cross channel or stored data restart occurs. If no other failures are present, neither FCM will be any more correct than the other, however this feature of the design does lead to more complexity in the analysis of the system stability and failure modes, particularly during the entry phase of flight. In scenarios where FCMs are not completely in sync numerically, the overall closed loop system response is chaotic in nature, much like the well-known 'butterfly effect'. Slightly different navigation solutions between FCMs can easily lead to slightly different control thruster firing patterns, which in turn raises questions about how to deal with a flight control module that is attempting to control the vehicle, but in reality whose outputs are never reaching the effectors. This is particularly true for onboard fault detection algorithms and pyro sequencing algorithms that may rely on the past thruster firing history to perform their functions. These topics will not be addressed in much greater detail for this paper in lieu of more details and results on the nuances of and approach for ensuring navigation robustness for EFT-1.

One of the key takeaways from the development of the EFT-1 cross channel restart and inflight restart capability is that GN&C algorithms must be designed at the onset with inflight restarts in mind. Whenever persistent states are used in an algorithm developers must be trained to ask themselves whether those individual states are critical to the overall success of the mission and if so, how those states should be initialized in the event of an inflight restart. It can be very costly and invasive to develop initialization and synching routines into the system as an afterthought to the GN&C algorithm design process. Secondly, it is very helpful for developers to have design and implementation standards (AKA "design patterns") in place to provide examples and to assist in the design of restart functionality, such that all GN&C algorithms cohere into an overall picture when restarts are taking place. Otherwise many similar approaches for the same functionality are invented and communication of the design may become more complicated and error prone.

### C. Restart Capabilities and Testing

Inflight restart performance for the GN&C subsystem is assessed with the aid of closed loop Monte Carlo simulations of the overall system performance with variations in all of the key system driving parameters such as GPS constellation and firmware errors, IMU error sources, RCS thruster performance and latencies, mass properties and atmospheric effects. With current limitations of the simulation environment available only a single FCM may be simulated at a given time, however this limitation can be overcome to effectively analyze and bound restart performance through the following restart procedure:

1) Identify key simulation restart epochs of interest where CCR and SDR are to be analyzed. These points should initially be selected to bound some of the possible worst case scenarios in which restarts may occur.
2) Run end-to-end Monte Carlo simulations of the entire mission profile, recording key restart data and error statistics at the key restart epochs.
3) Restart the simulation and FSW using the CCR/SDR restart functionality at the epochs of interest, accounting for the appropriate navigation and truth state dispersions at that particular restart point.

While not as elegant as fully simulating restarts with dual FCMs running, the above procedure does permit the overall restart performance and functionality to be assessed. Future development of the simulation architecture may enable restarts to be fully dispersed as would be performed for any other Monte Carlo input parameter. The goal for this type of analysis is to stress the system beyond what might be reasonably expected in even the worst case scenarios to see what type of system robustness can be achieved. However it is acknowledged that this type of analysis would not capture the effects seen from multiple (repeated) resets in different configurations. This type of analysis will be the subject of later technical studies. For the EFT-1 trajectory several restart epochs were analyzed for CCR and SDR performance as depicted in red text in Figure 8:

- **The SECO2 Restart Epoch** is setup to initialize the FSW just following the second large burn and shutdown of the main engines in LEO, roughly 121 minutes after launch. At this point in the trajectory many GPS measurements are available allowing for rapid convergence of the Navigation solution, however inertial velocities and true anomaly rates are also at a maximum for the mission. Restart conditions after the SECO2 epoch were simulated to demonstrate resilience during the first spike in radiation susceptibility as well because it will be a driver for some of the worst case stored data restart cases. The duration for these runs are 10 minutes (600 seconds) to ensure adequate convergence of the GPS solution after a restart event.
- **The CM/SM Separation Restart Epoch** initializes the FSW just after the CM/SM separation event roughly 206 minutes after launch, which is a bounding case from a number of perspectives. First, the number of GPS measurements at this altitude tends to be very sparse at this point in the trajectory and a number of constellation geometries produce less than the minimum number of 5 SVs required to produce a valid and RAIM evaluated solution. Secondly, while the inertial velocities and true anomaly rates are relatively low at this point in the trajectory, the CM/SM separation maneuver does impart delta-V and body rates onto the CM which can add to the restart effects. The cases starting at CM/SM separation are run for roughly 42 minutes (2500 seconds) well past the 500 nautical mile threshold to ensure that GPS has reconverged prior to entry interface.
- **The Entry Interface Restart Epoch** initializes the FSW just prior to the designated entry interface altitude of ~68 nautical mile (400,000 ft) threshold to examine the effect of performing inflight restarts at the latest possible seconds prior to losing GPS in measurement blackout. Notice that this restart epoch is roughly 5 minutes after the last Van Allen radiation effects are expected, and entry velocities are very high at this point. Indeed, this would be one of the worst possible moments to experience single or dual FCM resets. So if some

level of robustness can be achieved even at this point this should provide some measure of confidence that the system will hold together at earlier points in the trajectory. All entry cases are

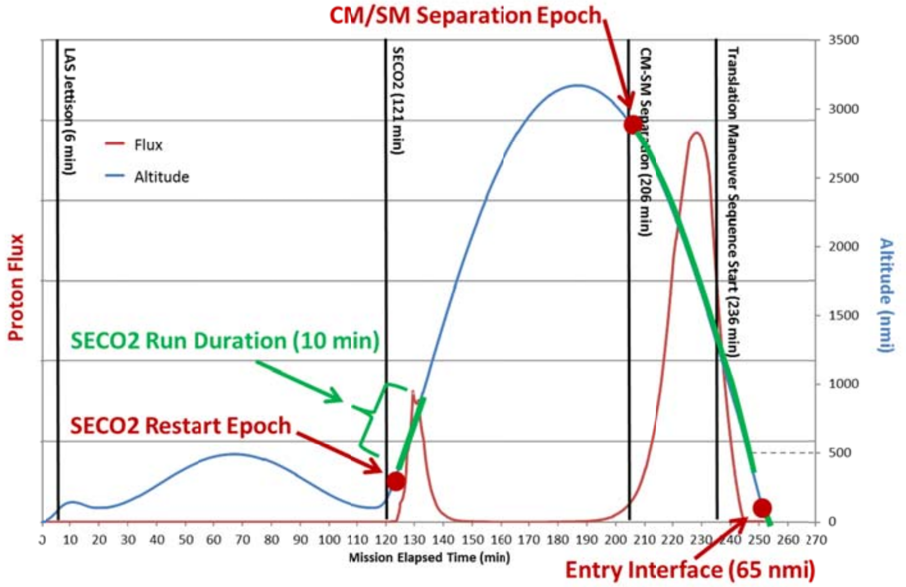

Figure 8. Exploration Flight Test-1 Inflight Restart Epochs of Interest

All of the subsequent analysis test cases shown make use of these three restart epochs as they bound some of the worst possible points in the trajectory for which inflight restarts may take place. While it is certainly possible that additional anomalies could crop up by performing restarts at other epochs in the mission or by repeating multiple resets at various points throughout the trajectory, these bounding cases provide reasonable confidence that the system will hold together as intended and the flight software will operate as intended. Figure 8a shows the total number of GPS measurements expected as a function of time for a representative EFT-1 trajectory. Note the correlation in the number of measurements with altitude and the relative sparseness of available measurements around CM/SM separation.

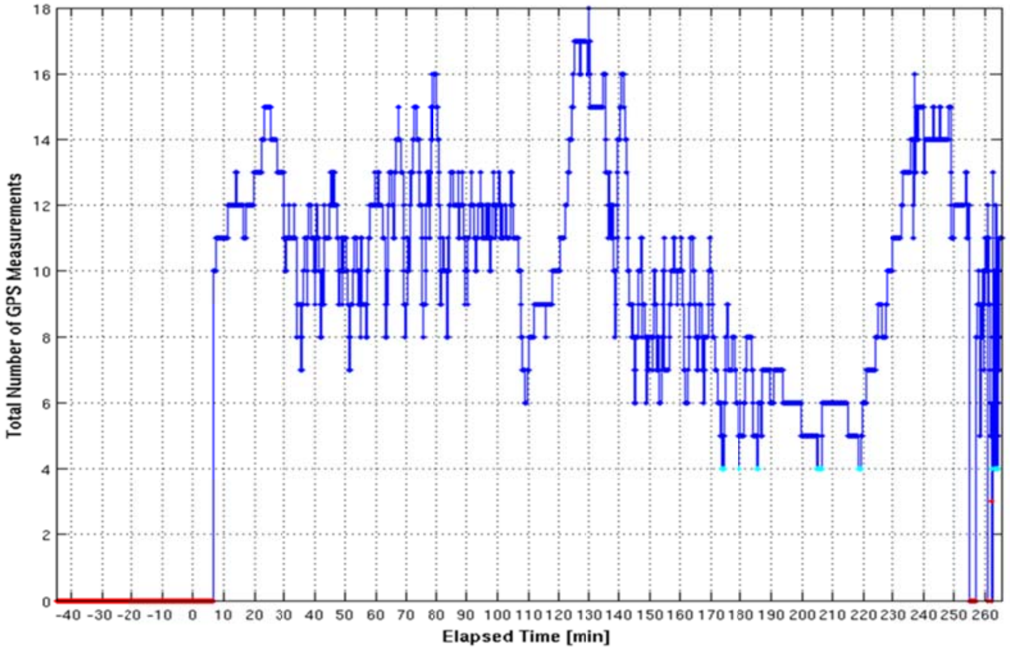

**Figure 8a.** Total Number of GPS Measurements for the EFT-1 Trajectory

### D. Cross Channel Restart Performance

In this section the CCR restart performance for the navigation system is quantified through a number of Monte Carlo simulations beginning at the restart epochs depicted in Figure 8. Each restart epoch is accompanied by sets of 500 run Monte Carlos with dispersed GPS constellation and firmware errors, IMU error sources and initial condition states, which represent the Navigation EKF filter performance at that point in the trajectory. In the following performance plots Figures 9 and following, state errors are computed relative to the corresponding truth states for the ensemble of cases shown. Each ensemble of errors also includes a mean error, taken at each time step along the trajectory. Finally and very importantly, the ±3σ EKF filter covariance values are represented for each component as a minimum (best performing) and maximum (worst performing) over the ensemble of Monte Carlo cases. The covariance bounds provide an indication of how well the filter's confidence in its solution aligned with the actual errors. If all measurements were completely Gaussian in nature and all error sources complete captured correctly, then the filter should produce errors that remain within the ±3σ bounds ~99.975 % of the time.

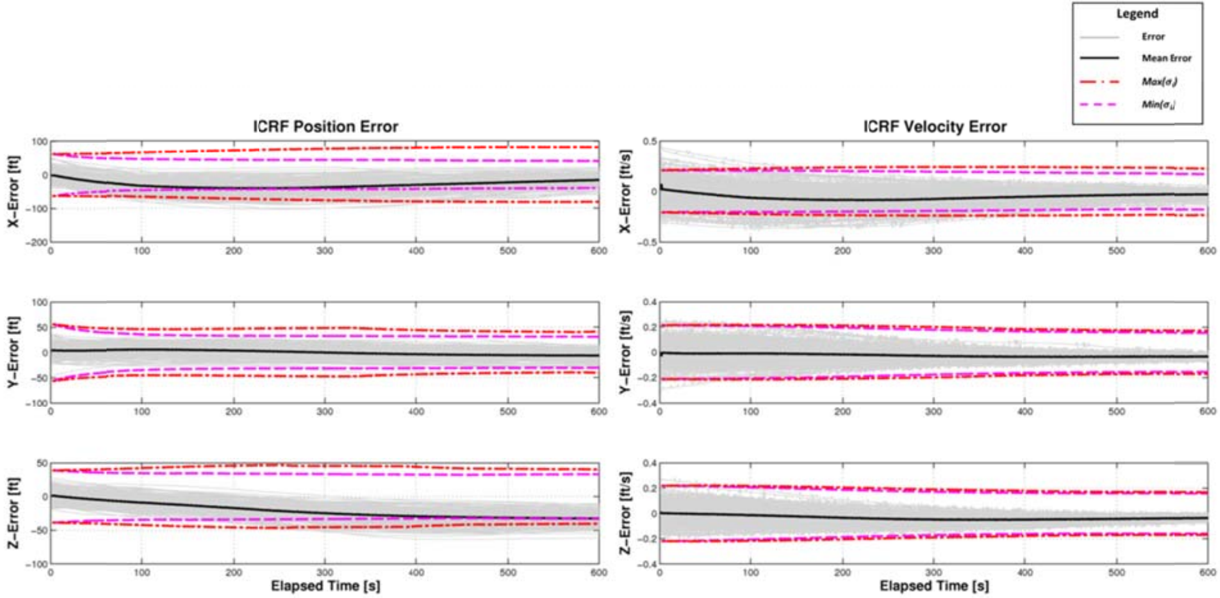

Figure 9. SECO2 CCR Inflight Restart Navigation (Position, Velocity) Performance

The SECO2 CCR restart case is depicted in Figure 9, showing good performance. From the restart position and velocity plots in Figure 9, it should be noted that the filter $3\sigma$ covariance bounds remain more or less constant over the course of this run, bounding the errors. This indicates an overall healthy filter and that the initial covariance restart bounds are consistent for this restart epoch as the filter continues to process GPS PR and DR measurements. Points in the trajectory in which the ensemble of errors (as characterized by the mean error) tend to walk outside of the 3 covariance bounds (e.g., Position component Z) are indicative of the EKF performance when attempting to process time-correlated PR and DR measurements as zero mean Gaussian random variables. In reality these measurement are not Gaussian but contain errors due to Ionosphere and Troposphere effects. These are issues that are not due to restarts specifically but endemic of how the measurements are modeled and these must be addressed as part of filter tuning.[7]

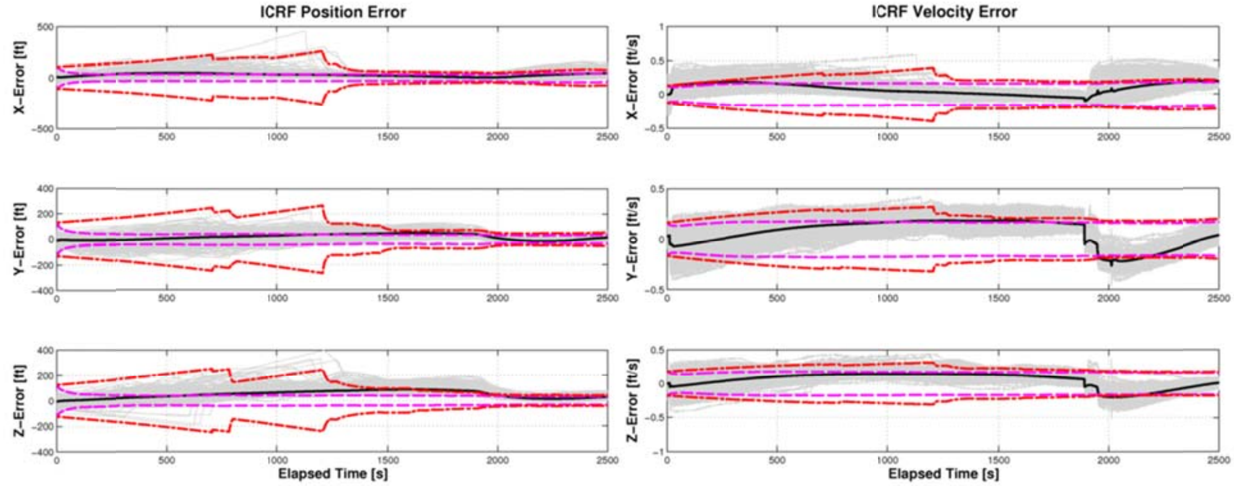

Figure 10. CM/SM Separation CCR Inflight Restart Navigation (Position, Velocity) Performance

Figures 10 and 11 capture the CCR restart performance after the CM/SM separation event through the 500 nautical mile altitude threshold shown in Figure 9. The CM/SM separation restart epoch takes place near apogee at much higher altitude and as a result many fewer GPS satellites are in view. Of those measurements available, it is very likely that a large percentage of them will be low elevation SVs which can introduce noticeable errors due to Ionospheric and Tropospheric effects. The covariance bounds for the position, velocity and the clock states indicate that a subset of the runs are indeed encountering poor satellite geometries as the start of the run, however all runs are converged by the end of the run as more satellites become available. Initial tip off rates and delta-v's injected by the CM/SM separation maneuver are sensed and appropriately incorporated into the filter position, velocity and attitude states. The attitude profiles for this phase of flight are very well behaved.

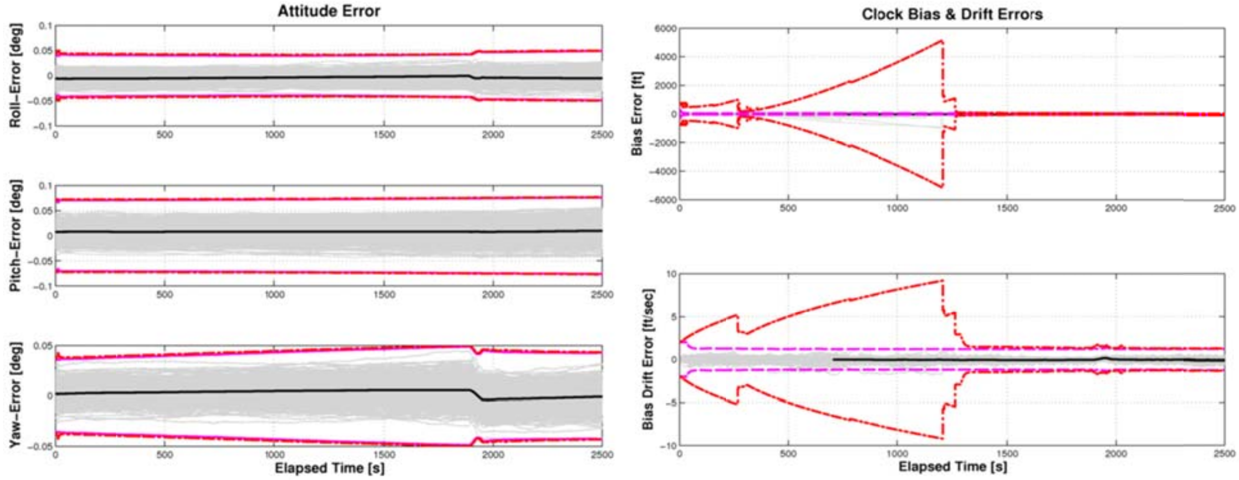

Figure 11. CM/SM Separation CCR Inflight Restart Navigation (Attitude, Clock Bias and Drift) Performance

Finally, Figure 12 describes the performance at the Entry Interface restart epoch. Roughly 10-20 seconds of GPSR measurement processing are encountered prior to the start of GPS blackout. Measurement blackout lasts roughly 150 seconds before GPS is reacquired for the final descent and landing phase. Overall the performance is well behaved for an entry case as the position and velocity errors remain well bounded by the covariance values and within touchdown requirement bounds.

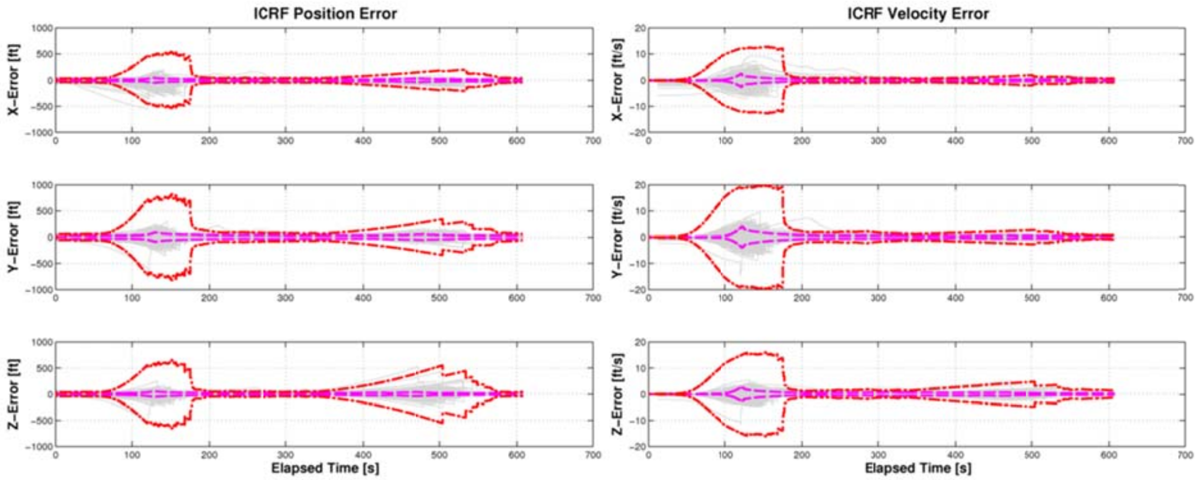

Figure 12. EI Entry CCR Inflight Restart Navigation (Position, Velocity) Performance

### E. Stored Data Restart Performance

Stored Data Restart is conceptually very similar to a Cross Channel Reset with some noticeable differences. First and most foremost, since neither FCM will be running for many seconds while the FCMs reboot there will inevitably be a gap in IMU and GPS measurement processing over the stored data restart. Position and velocity states are less susceptible to being issues for the EFT-1 mission because GPS measurements can be reacquired after the restart event. However for EFT-1 Orion has no external source for attitude knowledge and every cycle IMU data is not processed attitude errors will grow, potentially leading to a loss of vehicle scenario. As a consequence of this for EFT-1 it was determined that a third redundant source for attitude knowledge was required that would be capable of bridging the gap over the stored data restart interval. The VPU was selected as the best location to perform this function and serve as a pseudo backup computer, due to its relative radiation tolerance and throughput loading for the EFT-1 mission. Figure 13 depicts the concept of Stored Data Restart with multiple FCM and VPU interactions. At some point in the mission over the time of radiation exposure described in Figure 7, one of the FCMs is triggered to reset. It naturally takes the computer some time to reboot, $\Delta t_{FCM}$, during which the secondary FCM also resets. When the first FCM completes its reboot cycle it first looks for a counterpart cross channel message. Not seeing one available, it instead looks to the VPU for the same data and can perform a reset based on the data from this source instead. The VPU backup software is designed to take attitude and state information from *either* FCM, provided that at least one valid message is received on a given execution cycle. If no valid messages are received, the VPU software applies a basic attitude propagation function from the latest samples of 200Hz OIMU data. This is accomplished for all four of the Filtered/Inertial, Channel1/2 attitude states being maintained for EFT-1. In addition, the VPU would capture any changes in mission sequencing data if those transitions happened to occur after the first FCM went down but prior to the second resetting. Thus, when the FCM completes a SDR it is able to receive an up-to-date attitude state as well as the current Orion time tag from the VPU. The second FCM that undergoes a reset (FCM 2 in Figure 13) will restart from the active FCM using the CCR method described earlier. In the extremely unlikely event that both FCMs undergo resets on exactly the same minor cycle then they would both perform a Stored Data Reset from the VPU.

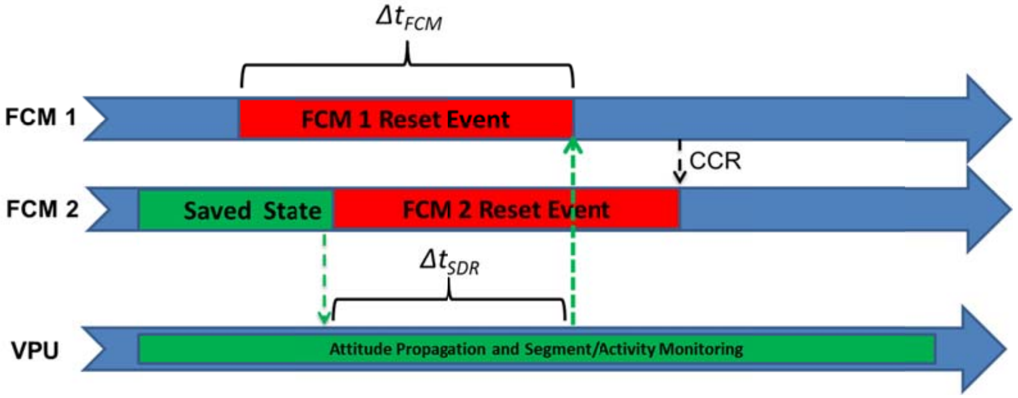

Figure 13. Diagram of expected Stored Data Restart (SDR) Timing

Once the propagated attitude and sequencing states are obtained from the VPU software the primary FCM GN&C partition has enough information to restart from Reset Protected Memory as it would in a CCR case with the exception of one additional step. The position and velocity translational states must be propagated forward over the SDR outage time, $\Delta t_{SDR}$, otherwise very large errors will be introduced when restarting the filters at orbital velocities. Some consideration was given to propagating position and velocity from IMU delta-V measurements in the VPU as well as attitude. However this was decided to be more complexity than is required for the VPU software, at the expense of being unable to account for non-conservative accelerations over the interval $\Delta t_{SDR}$. Therefore a simple low order gravitational propagation scheme was built into the GN&C SDR restart logic. This scheme propagates all four sets of Filtered/Inertial, Channel 1/2 translational states forward to the appropriate epoch after a SDR event. This propagation scheme accounts for J2 effects, but any higher order effects or non-conservative accelerations are neglected for EFT-1. This simple propagation scheme will introduce errors into the navigation states after SDR events, but fortunately these errors can be explicitly quantified in advance. Expected position and velocity performance for this simple low order propagation scheme is shown in Figure 14 for the period of radiation susceptibility in the EFT-1 trajectory. These plots depict the errors introduced solely by the SDR propagation scheme over various restart outage times $\Delta t_{SDR}$. From this performance it should be clear that more error will inevitably be introduced when the orbital velocities are the highest simply because for the same propagation time, $\Delta t_{SDR}$, the vehicle will travel a further distance. In the period of radiation susceptibility this corresponds to times just after SECO2 and just prior to entry interface. Comparatively low errors will be introduced when the vehicle is near apogee. For the subsequent SDR analysis cases, a SDR outage time of 30 seconds is used as a bounding case for robustness testing, as this exceeds the worst case in all scenarios. These errors will show up in the Monte Carlo results by biasing the initial conditions with the magnitudes shown in Figure 14.

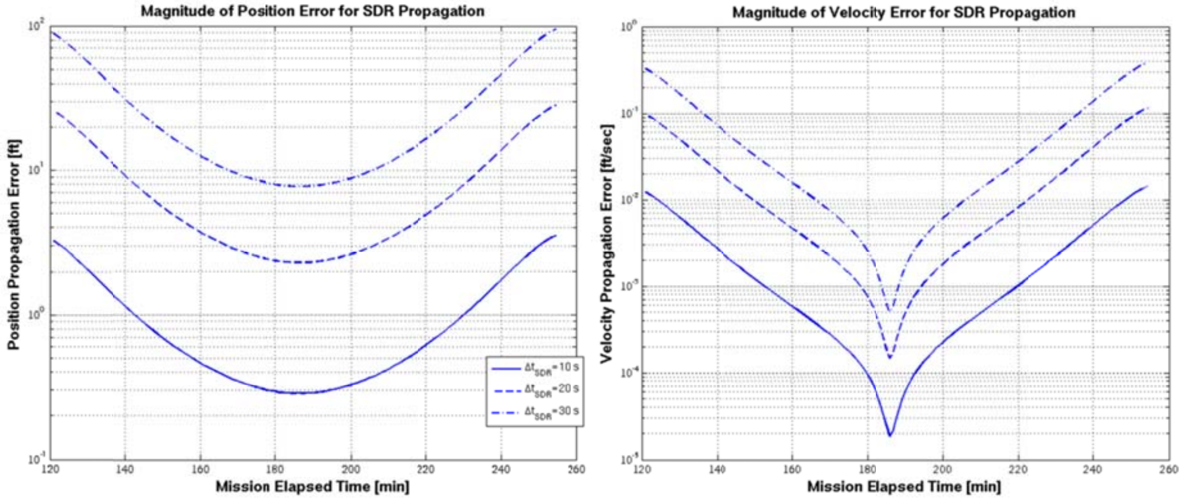

Figure 14. Expected SDR Propagation Performance over the EFT-1 Trajectory Profile

Ideally the position and velocity errors ($\Delta \boldsymbol{r}_{\boldsymbol{SDR}}, \Delta \boldsymbol{v}_{\boldsymbol{SDR}}$ ) introduced after SDR would be far less than the expected uncertainty in the corresponding EKF filter states:

$$\|\Delta \boldsymbol{r}_{\boldsymbol{SDR}}\| \ll 3\sigma_{r_{I,J,K}}$$
$$\|\Delta \boldsymbol{v}_{\boldsymbol{SDR}}\| \ll 3\sigma_{v_{I,J,K}}$$

where the terms $\sigma_{r_{I,J,K}}, \sigma_{v_{I,J,K}}$ represent the cross channel EKF ICRF state uncertainties for position and velocity, respectively. Exceeding these conditions is risky because it can lead to smugness and instability in the restarting filter, however it will be shown that in the worst cases even substantially exceeding these bounds performance is not significantly affected.

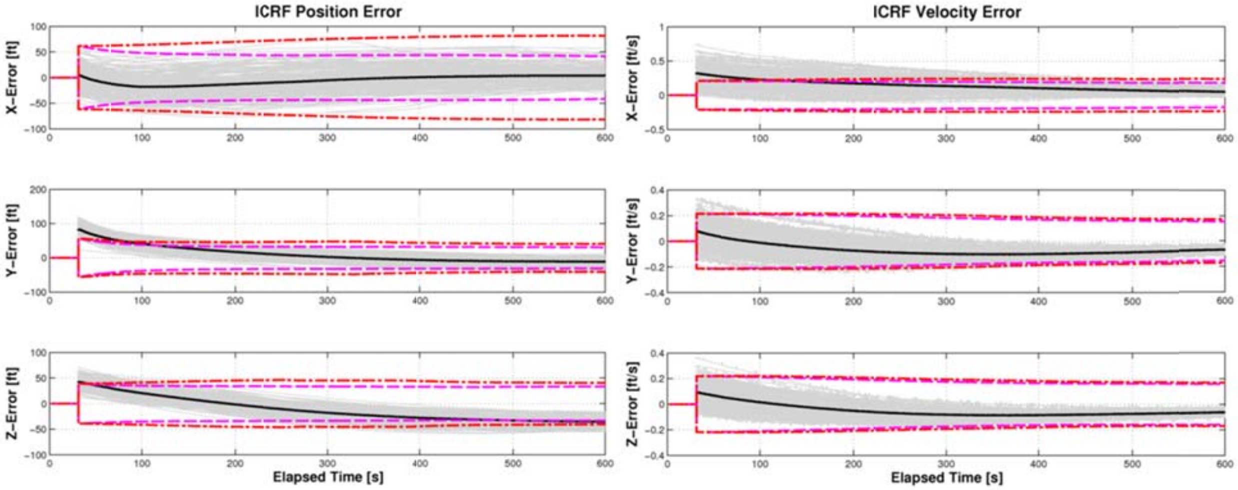

Figure 15. SECO2 30 Second SDR Inflight Restart Navigation (Position, Velocity) Performance

The SECO2 SDR 30 second restart case is shown in Figure 15 with the expected initial condition errors in both position and velocity. Although the SDR propagation errors are large relative to the initial position and velocity uncertainty bounds $\sigma_{r_{I,J,K}}, \sigma_{v_{I,J,K}}$ errors quickly converge within the covariance bounds and performance at the end of the interval largely resembles the corresponding CCR restart case shown in Figure 9.

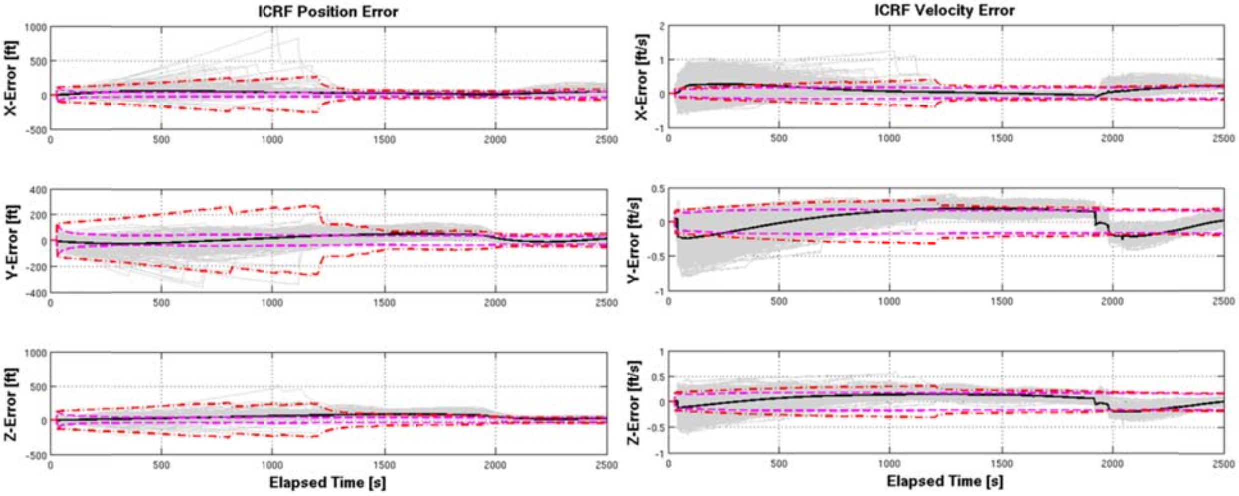

Figure 16. CM/SM Separation 30 Second SDR Inflight Restart Navigation (Position, Velocity) Performance

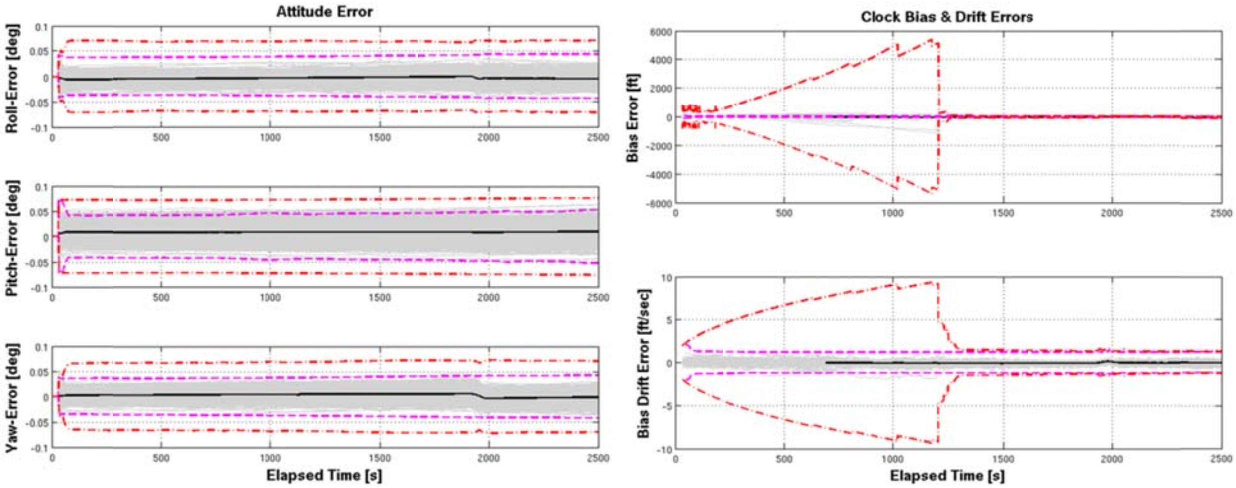

Figure 17. CM/SM Separation 30 Second SDR Inflight Restart Navigation (Attitude, Clock Bias/Drift) Performance

Similarly, a 30 second SDR cases is shown for at CM/SM separation in Figures 16 and 17. Although SDR propagation errors are relatively small at this point in the trajectory, combining this initial error with comparatively large delta-v and body rates due to the CM/SM separation itself at the same time are shown to introduce very large initial velocity errors after the restart event. Notice that despite the unhealthy filter initial conditions after several thousand seconds and greater numbers of GPS measurements these errors are cleaned up to reach performance levels comparable to the CCR restart cases shown in Figures 10 and 11. It is also important to note that the attitude errors in Figure 17 are largely unaffected by SDR as the VPU continues to propagate these states even through the CM/SM separation maneuver. Had the VPU not performed this functionality attitude errors would be shown to grow orders of magnitude higher in this case.

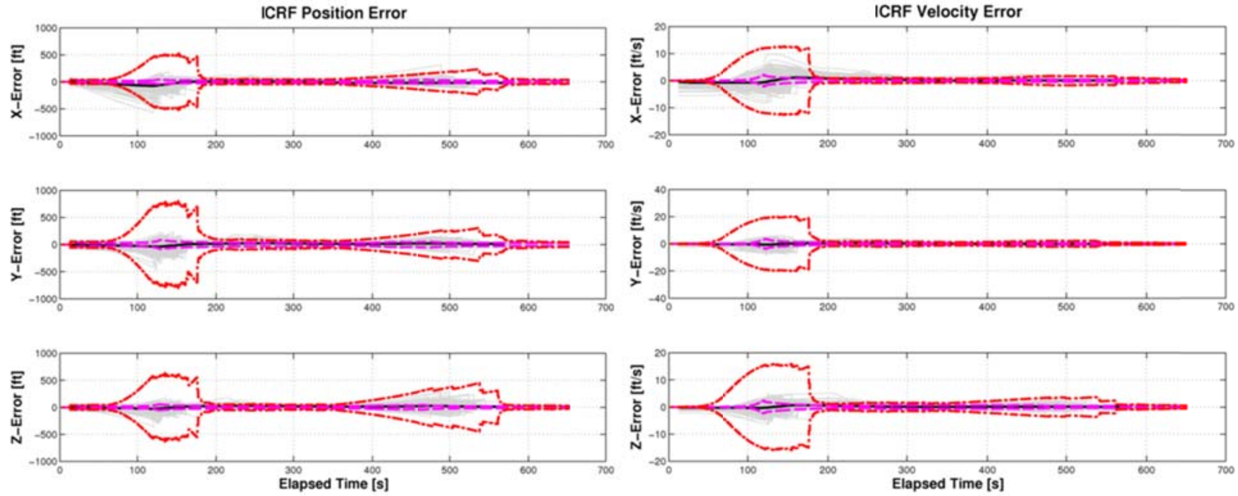

Figure 18. Entry Interface (EI) 12 second SDR Inflight Restart Navigation (Attitude, Clock Bias/Drift) Performance

Finally, a 12 second SDR restart performance at entry interface (EI) is shown in Figure 18. In this case only a few seconds of GPS measurement processing were made available to the restarting FCM prior to hitting GPS blackout. SDR propagation errors are shown to influence the initial position and velocity states as expected, yet these errors are swamped by the errors that accumulate during the blackout period with no GPS and no cases are fail reacquisition of GPS measurements after blackout.

### F. Forward Work

In the previous sections the expected Navigation performance was quantified for a variety of conditions and restart types during the EFT-1 trajectory. While this analysis is far from complete and comprehensive it provides a starting point for future work to demonstrate Orion's robustness to radiation induced upset events along the EFT-1 trajectory. The first item that will further increase confidence in these results will include simulating multiple consecutive inflight restarts of various types and durations along the EFT-1 trajectory. In addition the cases shown need to be proven out with greater numbers of Monte Carlo runs to become more confident in their statistical significance. 500 run Monte Carlos are a good starting point but larger numbers of runs are likely needed to prove out the results. This type of analysis will show more robustness for the effects of cascaded filter initializations in a variety of conditions. In addition, these tests are already being performed in full hardware in the loop simulations with multiple FCMs, engineering equivalent avionics hardware. Some level of inflight restart testing will be performed with actual flight hardware prior to launch.

Secondly, if there are any cases in which SDR propagation errors tend to cause filter divergence it is possible to increase the fidelity of the propagation scheme used for EFT-1. This propagation scheme was meant to be simple and lightweight so as not to needlessly overburden an initializing FCM, however if additional testing shows these assumptions to be in error additional steps to increase the fidelity of the propagator can be taken to mitigate this. It should be noted that for the cases shown in this paper 30 seconds of propagation is larger than the maximum bounds expected

Additional EKF filter tuning may be required to better characterize the measurement and process noise levels in a time-correlated and sparse measurement environment such as that which will be experienced on EFT1. The EKF performance is predicated on the fact that measurement residuals will be well characterized by Gaussian random variables. As shown in earlier performance plots, this assumption is not always valid and additional steps may be required to mitigate these effects. A number of options including dynamic SV measurement masking as a function of elevation angle are being investigated.

Finally, operational flight rules and procedures must be written for the EFT-1 mission that take into account contingency scenarios for inflight restart events. The ground will be monitoring for all such restart events as well as the quality of the onboard navigation solution. Ground rules will be written that allow for contingency operations to command updates to the onboard navigation state in the event the inflight restarts ultimately fail. These scenarios although not desirable will be the last resort to save the vehicle in catastrophic loss of vehicle scenarios.

## V. Conclusion

The Orion inflight restart architecture has been designed to accommodate multiple restarts of the primary flight computers to increase the probability of EFT-1 mission success. The GN&C design for inflight restarts has been shown to be robust to a number of worst case bounding scenarios that can be envisioned for the EFT-1 mission. The concept of Cross Channel and Stored Data restarts are proved out through analysis and Monte Carlo dispersed simulation runs. Although these types of robustness runs are preliminary in nature, they provide initial confidence that inflight restarts will be successful if one or more are encountered on EFT-1.

## Appendix

An appendix, if needed, should appear before the acknowledgements.

## Acknowledgments

Lockheed Martin
NASA
Honeywell

## References

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[1] Vatistas, G. H., Lin, S., and Kwok, C. K., "Reverse Flow Radius in Vortex Chambers," *AIAA Journal*, Vol. 24, No. 11, 1986, pp. 1872, 1873.

[2] Dornheim, M. A., "Planetary Flight Surge Faces Budget Realities," *Aviation Week and Space Technology*, Vol. 145, No. 24, 9 Dec. 1996, pp. 44-46.

[3] Terster, W., "NASA Considers Switch to Delta 2," *Space News*, Vol. 8, No. 2, 13-19 Jan. 1997, pp., 1, 18.

All of the preceding information is required. The journal issue number ("No. 11" in Ref. 1) is preferred, but the month (Nov.) can be substituted if the issue number is not available. Use the complete date for daily and weekly publications. Transactions follow the same style as other journals; if punctuation is necessary, use a colon to separate the transactions title from the journal title.

*Books*

[4] Peyret, R., and Taylor, T. D., *Computational Methods in Fluid Flow*, 2nd ed., Springer-Verlag, New York, 1983, Chaps. 7, 14.

[5] Oates, G. C. (ed.), *Aerothermodynamics of Gas Turbine and Rocket Propulsion*, AIAA Education Series, AIAA, New York, 1984, pp. 19, 136.

[6] Volpe, R., "Techniques for Collision Prevention, Impact Stability, and Force Control by Space Manipulators," *Teleoperation and Robotics in Space*, edited by S. B. Skaar and C. F. Ruoff, Progress in Astronautics and Aeronautics, AIAA, Washington, DC, 1994, pp. 175-212.

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[7] Thompson, C. M., "Spacecraft Thermal Control, Design, and Operation," *AIAA Guidance, Navigation, and Control Conference*, CP849, Vol. 1, AIAA, Washington, DC, 1989, pp. 103-115

[8] Chi, Y., (ed.), *Fluid Mechanics Proceedings*, SP-255, NASA, 1993.

[9] Morris, J. D. "Convective Heat Transfer in Radially Rotating Ducts," *Proceedings of the Annual Heat Transfer Conference*, edited by B. Corbell, Vol. 1, Inst. Of Mechanical Engineering, New York, 1992, pp. 227-234.

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*Reports, Theses, and Individual Papers*

[10] Chapman, G. T., and Tobak, M., "Nonlinear Problems in Flight Dynamics," NASA TM-85940, 1984.

[11] Steger, J. L., Jr., Nietubicz, C. J., and Heavey, J. E., "A General Curvilinear Grid Generation Program for Projectile Configurations," U.S. Army Ballistic Research Lab., Rept. ARBRL-MR03142, Aberdeen Proving Ground, MD, Oct. 1981.

[12] Tseng, K., "Nonlinear Green's Function Method for Transonic Potential Flow," Ph.D. Dissertation, Aeronautics and Astronautics Dept., Boston Univ., Cambridge, MA, 1983.

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[13]Richard, J. C., and Fralick, G. C., "Use of Drag Probe in Supersonic Flow," *AIAA Meeting Papers on Disc* [CD-ROM], Vol. 1, No. 2, AIAA, Reston, VA, 1996.

[14]Atkins, C. P., and Scantelbury, J. D., "The Activity Coefficient of Sodium Chloride in a Simulated Pore Solution Environment," *Journal of Corrosion Science and Engineering* [online journal], Vol. 1, No. 1, Paper 2, URL: http://www.cp/umist.ac.uk/JCSE/vol1/vol1.html [cited 13 April 1998].

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*Computer Software*

[16]TAPP, Thermochemical and Physical Properties, Software Package, Ver. 1.0, E. S. Microware, Hamilton, OH, 1992.

Include a version number and the company name and location of software packages.

*Patents*

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[17]Scherrer, R., Overholster, D., and Watson, K., Lockheed Corp., Burbank, CA, U.S. Patent Application for a "Vehicle," Docket No. P-01-1532, filed 11 Feb. 1979.

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[1] Inflight restart tech memo
[2] King, Odegard, Sequencing Paper AIAA
[3] TBD. Reference for CNC Thruster logic design memo
[4] TBD. EKF tech memos
[5] TBD. UDU formulation
[6] TBD. Reference to coupled attitude filter
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