Determination of Barometric Altimeter Errors for the Orion Exploration Flight Test-1 Entry

Denise L. Brown* and Jean-Philippe Munoz*

Odyssey Space Research, LLC, Houston, TX, 77058, USA

Robert Gay†

NASA-Johnson Space Center, Houston, TX, 77058, USA

The Exploration Flight Test 1 (EFT-1) mission is the unmanned flight test for the upcoming Multi-Purpose Crew Vehicle (MPCV). During entry, the EFT-1 vehicle will trigger several Landing and Recovery System (LRS) events, such as parachute deployment, based on on-board altitude information. The primary altitude source is the filtered navigation solution updated with GPS measurement data. The vehicle also has three barometric altimeters that will be used to measure atmospheric pressure during entry. In the event that GPS data is not available during entry, the altitude derived from the barometric altimeter pressure will be used to trigger chute deployment for the drogues and main parachutes. Therefore it is important to understand the impact of error sources on the pressure measured by the barometric altimeters and on the altitude derived from that pressure. The error sources for the barometric altimeters are not independent, and many error sources result in bias in a specific direction. Therefore conventional error budget methods could not be applied. Instead, high fidelity Monte-Carlo simulation was performed and error bounds were determined based on the results of this analysis. Aerodynamic errors were the largest single contributor to the error budget for the barometric altimeters. The large errors drove a change to the altitude trigger setpoint for FBC jettison deploy.

Nomenclature

a	Altitude, ft
p	Pressure, psia
σ_x	Standard deviation of random variable x
μ_x	Mean of random variable x

I. Introduction

The Exploration Flight Test 1 (EFT-1) mission is the unmanned flight test for the Multi-Purpose Crew Vehicle (MPCV). During entry, the EFT-1 vehicle will trigger several Landing and Recovery System (LRS) events, such as parachute deployment, based on on-board altitude information. The primary altitude source is the filtered navigation solution updated with GPS measurement data. The vehicle also has three barometric altimeters that will measure atmospheric pressure during entry. In the event that GPS data is not available during entry, the altitude derived from the barometric altimeter sensed pressure will be used to trigger LRS events. Therefore it is important to understand the impact of error sources on the pressure measured by the barometric altimeters and on the altitude derived from that pressure.

The purpose of characterizing the barometric altimeter altitude error budget was twofold:

*Orion Barometric Altimeter Flight Software Lead, 1120 NASA Parkway Suite 505 Houston, TX 77058, Member.

†Orion Absolute Navigation Lead - NASA, 2101 NASA Parkway, Houston, TX 77058, Member.

1. Determine whether current LRS trigger setpoints will result in LRS events occurring within acceptable ranges given expected barometric altimeter errors; if not, adjust triggers to accommodate expected errors

2. Determine the altitude at which the error in altitude from the barometric altimeters is small enough that it may be used to trigger LRS events

Typically, for error budget calculations it is assumed that all error sources are independent, normally distributed variables. Thus, the initial approach to developing the EFT-1 barometric altimeter altitude error budget was to create an itemized error budget under these assumptions. This budget was to be verified by simulation using high fidelity models of the vehicle hardware and software. However, the simulation results did not match the itemized error budget; the errors at higher altitudes in the simulation were much larger than those predicted by the itemized error budget, while errors at low altitudes in the simulation were smaller than those predicted by the itemized error budget. The discrepancy was caused by the fact that the error sources directly affecting sensed pressure also affected the altitude calculated from that pressure in a non-linear manner, which then compounded errors due to atmospheric modeling.

The final error budget accounted for all known error sources and their interactions. These numbers were used to assess validity of the current LRS trigger altitude settings in the vehicle flight software when using the barometric altimeter altitude to trigger events.

II. MPCV Design

The Multi-Purpose Crew Vehicle (MPCV) is NASA's next-generation space exploration vehicle. A simplified version of the MPCV will be flown for the EFT-1 mission. During the mission, the vehicle will launch, complete two orbits, then perform a high-energy re-entry. This paper will focus on the entry portion of the mission.

II.A. MPCV Flight Hardware Overview

The EFT-1 vehicle has a small navigation sensor suite consisting of two IMUs, a single GPS receiver, and three barometric altimeters. The vehicle will navigate primarily using IMU data aided by GPS measurements. A GPS-aided navigation state and an inertial, IMU-only navigation state will be maintained for each IMU. There is a possibility that GPS measurements will not be available during entry. In this case, the GPS-aided navigation estimates may degrade to the point that altitude calculated from those solutions will not be accurate enough to achieve LRS events within acceptable altitude ranges. The barometric altimeters are intended to act as a back-up source of altitude in the event of loss of GPS data. Possible causes of loss of GPS data include receiver failures as well as failure to quickly regain lock with sufficient satellites following the blackout period during re-entry.

II.B. Barometric Altimeters

The vehicle has three second generation Precision Pressure Transducer (PPT-2) barometric altimeters manufactured by Honeywell International. The sensors are mounted in the midbay compartment near two passive vents. All three sensors are packaged in a single assembly. Figure 1 shows the mounting location of the barometric altimeter assembly and a rendering of the passive vents, which allow pressure equalization of the midbay compartment.

The three barometric altimeters output an analog voltage proportional to the sensed pressure. Nominally the sensors output 0.1 V at vacuum, and 5 V at maximum pressure. The pressure range of the PPT-2 sensors is 0 to 20 psia.

The analog voltage output by the barometric altimeters is sampled and converted to a digital signal by the Analog to Digital Input/Output (ADIO) cards in the Power and Data Units (PDUs). Each PDU has one ADIO card. There are two barometric altimeters routed through PDU C3, and one routed through PDU C4 to provide redundant paths for altitude data.

The digitized voltages from all three barometric altimeters are transmitted to both Vehicle Management Computers (VMCs) over the Onboard Data Network (ODN). The Flight Software (FSW) on the VMCs determines the health of the barometric altimeter digital measurements from the PDUs, filters the voltages, and converts them to pressures based on the nominal ranges of the sensors. Each pressure is then converted

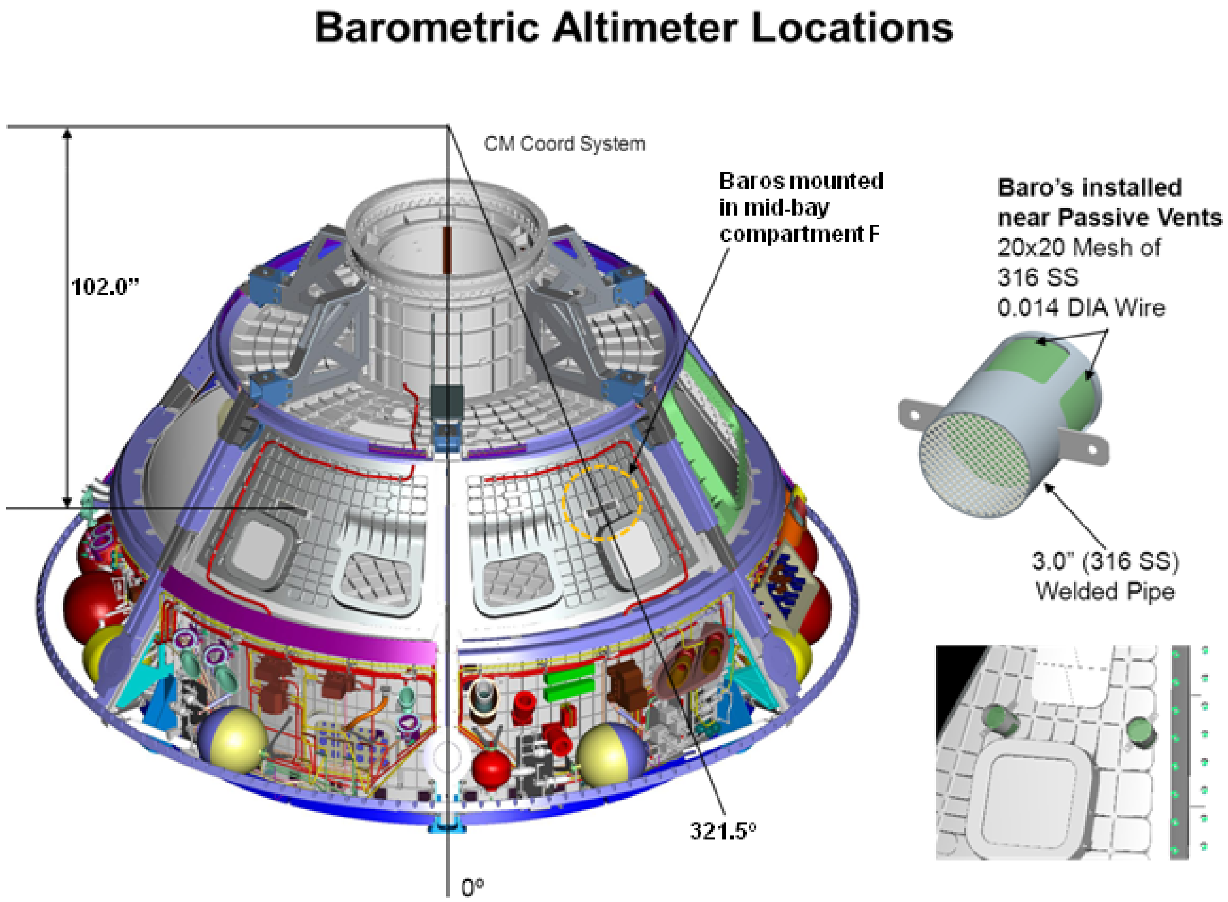

Figure 1: Barometric altimeter assembly location inside the midbay compartment near passive vents

to altitude using a curve fit to the Standard76 Atmosphere model. The barometric altimeter Fault Detection, Isolation, and Recovery (FDIR) software performs a mid-value select among the valid current measurements. The mid-value select algorithm protects against any single undetected failure of a barometric altimeter. The selected barometric altimeter altitude is passed to downstream software that selects among the available altitude sources: barometric altimeter, GPS-aided navigation solutions, and inertial navigation solutions. GPS-aided navigation is the primary source, barometric altimeters are secondary, and inertial solutions are the tertiary source.

The best available altitude is then passed to the Descent and Landing Triggers software, where it can be used to trigger GNC and Landing Recovery System (LRS) events. The best available altitude will be referred to as the Flight Software (FSW) altitude for the remainder of this paper.

II.C. Entry, Descent, and Landing Triggers

Several key events during Entry, Descent, and Landing (EDL) for the EFT-1 mission are triggered based on vehicle altitude knowledge. The EDL events and the nominal altitude for each event are shown in Figure 2.

Each of the key events in Figure 2 has at least two possible triggers in order to ensure the event occurs even in the presence of failures. In many cases, the primary trigger is the best available altitude selected from the altitude sources. As mentioned above, GPS-aided navigation is the primary altitude source, barometric altimeters are secondary, and inertial solutions are the tertiary source.

There are three possible triggers for FBC parachute deployment: flight software altitude, a velocity trigger based on the unaided inertial navigation solutions, and the "Smart" FBC jettison logic. If GPS-aided navigation or barometric altimeter altitude is available, the FBC parachutes will be deployed when either the minimum deployment altitude is reached, or when the FSW altitude is less than the FBC chute deployment altitude ceiling and the RSS of the vehicle sensed pitch and yaw rates exceeds a threshold,

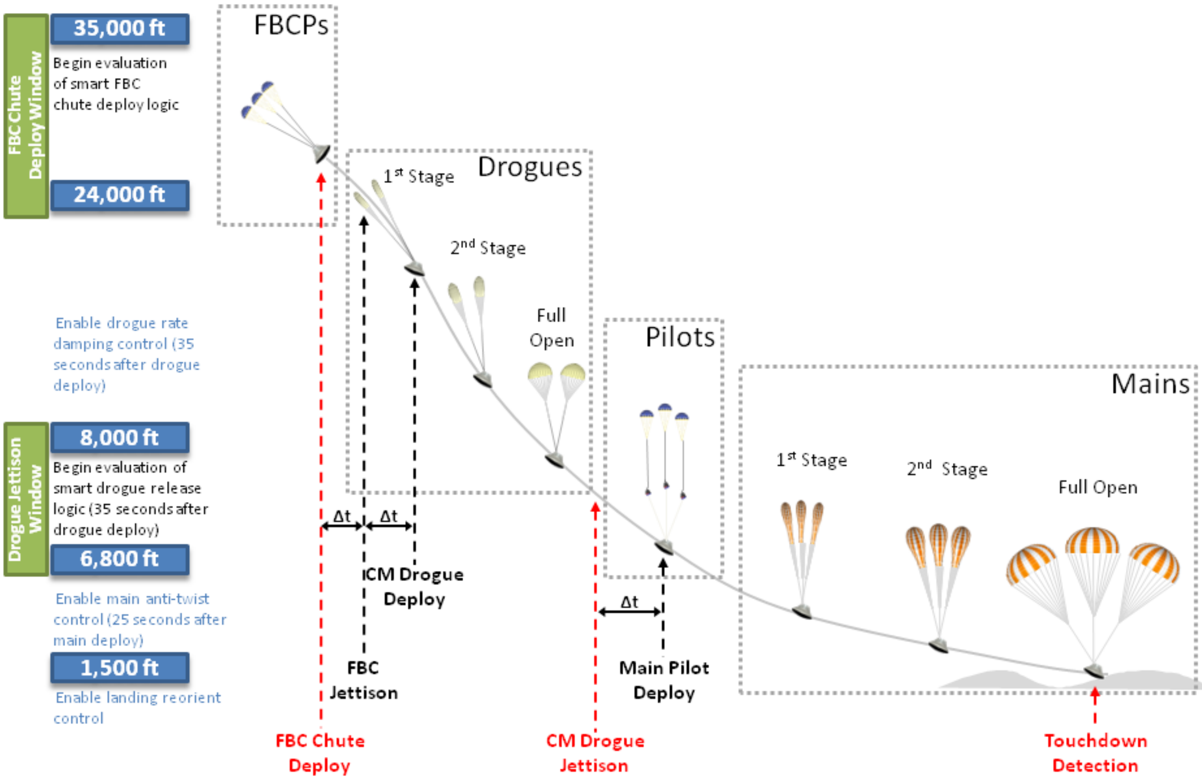

Figure 2: EFT-1 Entry Events

whichever is met first. This latter trigger is referred to as the "Smart" FBC jettison logic. If the FSW altitude source is the unaided navigation solution, the FBC chutes will be deployed when the norm of the estimated inertial velocity descends below the velocity trigger threshold. In general, the velocity trigger results in early FBC parachute deployment.

Following FBC parachute deployment, the FBC mortars are fired, the FBC is jettisoned, and the drogue parachutes are deployed based on timers initiated upon FBC parachute deployment. Once under the drogues, if the source of the FSW altitude is the GPS-aided navigation solution or the barometric altimeters, drogue parachute release is initiated when the FSW altitude is below a ceiling value, the required minimum time under the drogues is achieved, and the "Smart drogue jettison logic allows drogue release. If either of the latter two conditions are not reached before a floor drogue release altitude is reached, the drogues are jettison regardless of the time under them or the "Smart" logic.

If the source of the FSW altitude is the unaided inertial navigation, the drogue parachutes are released after a minimum time under the drogues has been achieved and the "Smart" drogue release logic allows drogue jettison. If drogue release has not been achieved before a maximum allowable time under the drogues has been reached, the drogue parachutes will be released regardless of the dynamic environment. The "Smart" drogue jettison logic uses sensed vehicle body rates to detect the amount of oscillation the vehicle is undergoing. When the oscillation is within a specified deadband, the smart logic will allow drogue chute release.

Following drogue parachute release, the main parachutes are deployed based upon a timer initiated at drogue parachute release. There are two possible modes under the main parachutes: anti-twist control and landing orient. The anti-twist control is designed to prevent the vehicle from twisting up the parachute lines and reducing the ability of the vehicle control system to properly orient the vehicle at landing. The landing orientation logic ensures the vehicle is pointing toward the correct heading at touchdown. Once the drogue parachutes have been jettisoned, a timer is initiated. Once the timer reaches a threshold, if the altitude is above the threshold for start of landing orient mode and the altitude source is GPS-aided navigation or the barometric altimeters, the control mode is set to anti-twist mode. If the landing orient altitude is met, the mode is set to landing orient. If the FSW altitude source is the unaided navigation solution, the transition from anti-twist mode to landing orient mode is based on another timer initiated upon drogue parachute release.

Therefore, there are four EDL events triggered directly from on-board altitude estimates when the source of the FSW altitude is the GPS-aided navigation solution or the barometric altimeters. When neither of these altitude sources is available, other triggers are used. Several GNC and LRS events, such as FBC jettison and main parachute deploy, are always triggered based on timers. If GPS-aided or barometric altimeter altitude are available, these timers are initiated at the start of events triggered from altitude. Therefore, all LRS events are nominally either directly or indirectly triggered based on vehicle altitude. The timers for each timed event are set such that these events should occur within a specific altitude range. The nominal timeline for LRS events is shown in Figure 3.

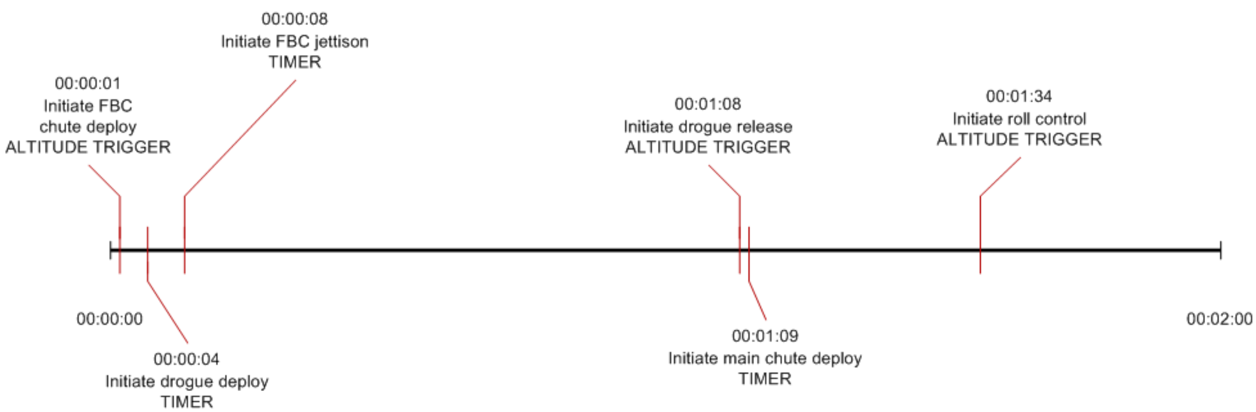

Figure 3: Nominal timeline of LRS events

The rest of this paper will focus on the case of nominal triggers based on barometric altimeter altitude, and how the barometric altimeter altitude budget affects the setting of the trigger altitudes in the flight software.

III. Simulation Tools

The Orion Guidance, Navigation, and Control (GNC) team developed a high fidelity Trick[2]-based simulation tool called Osiris to be used for GNC analysis. The Osiris simulation models the vehicle sensors and effectors as well as environments and vehicle dynamics, and allows for six degree of freedom simulation of the vehicle state. The Osiris simulation models the three barometric altimeters, including possible error sources. Individual error sources can be enabled and disabled independently.

A separate prototype flight software simulation called Ramses was also developed as a testbed for GNC algorithms. The Ramses simulation contains all guidance, navigation, and control algorithms as well as the sensor data processing algorithms and Fault Detection, Isolation, and Recovery algorithms.

The Osiris simulation can be used to drive the Ramses flight software simulation in a closed-loop manner in which Osiris provides the expected sensor data to Ramses, Ramses processes that data and calculates effector commands, and the commands are sent back to Osiris, which propagates the vehicle dynamic state forward to the next time step. In this manner, the entire mission can be simulated.

The Osiris-Ramses simulation can be run in Monte Carlo fashion with input dispersions defined in data files. Mass properties, sensor errors, effector errors, and ranges of environmental conditions as well as initial states can be dispersed. The Monte Carlo capability was utilized in the formation of the barometric altimeter error budget.

The flow of data in the Osiris-Ramses simulation is shown in Figure 4.

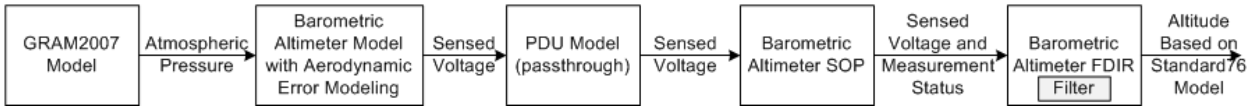

Figure 4: Flow of barometric altimeter data in the Osiris-Ramses simulation environment

IV. Barometric Altimeter Altitude Error Sources

There are four main error sources that cause the barometric altimeter sensed altitude to deviate from truth. These error sources are:

1. Sensor errors
2. A/D conversion errors
3. Aerodynamic effects
4. Atmosphere model errors

There are other error sources that have a smaller impact on the overall error budget, such as waves and tides and data transmission latencies. The following sections discuss the modeling of the major error sources and the quantification of their individual contributions to the total error budget.

V. Itemized Error Budget

Traditional error budgeting assumes all variables are independent, normally distributed variables. The definition of the standard deviation of a random variable x is

$$\sigma_x = \sqrt{Var(x)} \tag{1}$$

where Var(x) is the variance of x and is the second moment of random variable x about the mean of x, μ. The variance is expressed as

$$Var(x) = E[(x-\mu)^2] \tag{2}$$

where $E(x)$ is the expected value of x. The joint variance of two random variables x and y is defined as

$$\begin{aligned} Var(x+y) &= E[(x-\mu_x)^2] + E[(y-\mu_y)^2] + E[(x-\mu_x)^2(y-\mu_y)^2 \\ &= Var(x) + Var(y) + Cov(x,y) \end{aligned} \tag{3}$$

where $Cov(x,y)$ is the covariance of random variables x and y. If x and y are independent, there is no correlation and this term is zero. Therefore the total standard deviation of two random variables x and y is given by

$$\begin{aligned} \sigma_{x+y} &= \sqrt{Var(x+y)} \\ &= \sqrt{Var(x)+Var(y)} \\ &= \sqrt{\sigma_x^2+\sigma_y^2} \end{aligned} \tag{4}$$

Equation (4) can be expanded to any number of random variables, thus the total error based on the assumption of independent error sources is the square root of the sum of the squares of the standard deviations of the individual error sources, i.e. the RSS of the standard deviations of the individual error sources.[1] For error budgets, usually the 3-sigma values and not the 1-sigma values for standard deviation are used.

The itemized error budget for the barometric altimeters originally assumed all error sources were are independent, zero-mean, and normally distributed. However, during the process of characterizing individual error sources, it became apparent that some of the individual error sources biased sensed altitude in a specific direction, and were therefore not zero-mean. Thus it was decided to add the sources with non-zero mean (including the sign of the bias) to the RSS of the zero-mean variables in order to more accurately represent the error in the barometric altimeter altitude. The following sections describe the individual error sources in detail.

V.A. Converting Pressure Errors to Altitude Errors

With the exception of the atmospheric modeling errors, latency errors, and errors due to waves and tides, all of the errors discussed above are expressed in terms of pressure. However, the goal was to define the errors in terms of altitude.

The barometric altimeter FSW converts pressure to altitude using a curve fit to the 1976 US Standard Atmosphere model.[3] In order to determine the altitude error for a given pressure error without double booking errors induced by this conversion to altitude, it is necessary to use partial derivatives of the atmosphere model curve fit to convert the pressure error directly to an altitude error. The method is described below.

An example curve fit of altitude as a function of the natural log of pressure is shown in Figure 5 below, where $x = \ln(pressure)$.

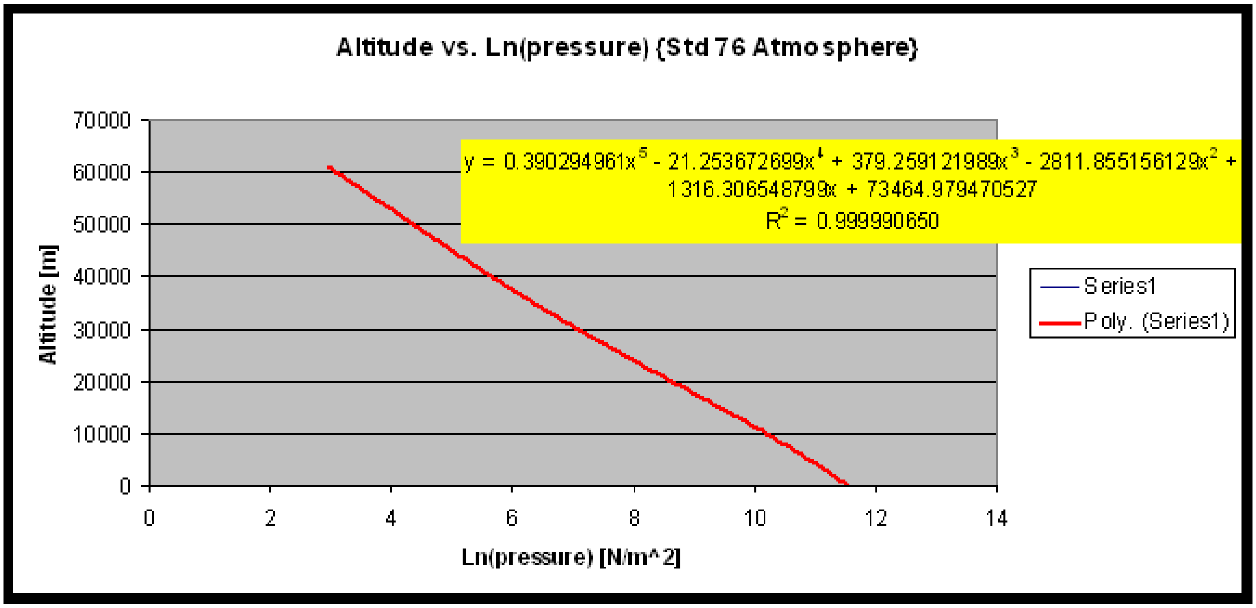

Figure 5: Curve fit of 1976 US Standard Atmosphere model. Altitude is expressed as a function of the natural log of pressure.

This curve fit and a reverse curve fit that gives the natural log of pressure as a function of altitude are both needed for the calculation of altitude errors from pressure errors. The curves shown here are both valid up to approximately 60,000 m, or 197,000 feet.

The derivative of the curve shown in Figure 5 with respect to $\ln(pressure)$ is

$$\frac{d(a)}{d(\ln(p))} = 5 * 0.390294961 * (\ln(p))^4 - 4 * 21.253672699 * (\ln(p))^3 + \\ 3 * 379.25912989 * (\ln(p))^2 - 2 * 2811.855156129 * (\ln(p) + 1316.306548799 \quad (5)$$

Therefore the change in altitude is equal to the change in pressure multiplied by the above equation, where $\ln(p)$ in the above equation is first calculated using a reverse curve fit that defines $\ln(p)$ as a function of altitude. This curve fit is:

$$\ln(p) = 11.5272913 - 0.00011506143a - 2.54388769e^{-9}a^2 \\ +5.88892511e^{-14}a^3 - 3,37942857e^{-19}a^4 - 9.18098698e^{-25}a^5 \quad (6)$$

All of these calculations must be performed for a known altitude and a known pressure error. The process of calculating the altitude error based on pressure error at a given altitude using Standard76 partials is as follows:

1. Calculate $ln(p)$ using the equation for ln(p) above for a known altitude

2. Calculate pressure $p = \exp(\ln(p))$

3. Calculate $\frac{da}{d(\ln(p))}$ using (5)
4. Compute the two $d(\ln(p))$ terms using $\ln(p)$ from (6), the pressure from step 2, and the known pressure error, p_{error}

$$d(\ln(p))_1 = \ln(p + p_{error}) - \ln(p) \tag{7}$$

$$d(\ln(p))_2 = \ln(p - p_{error}) - \ln(p) \tag{8}$$

5. Calculate the altitude error

$$a_{error} = \frac{1}{2}\left(|\frac{da}{d(\ln(p))} * d(\ln(p))_1| + |\frac{da}{d(\ln(p))} * d(\ln(p))_2|\right) \tag{9}$$

This altitude error is independent of the atmosphere modeling errors discussed previously.

V.B. Sensor Errors

The barometric altimeter specification sheet lists the maximum barometric altimeter error as 0.09% full-scale (FS). The barometric altimeters for EFT-1 will output 0.1 V at vacuum, and 5 V at the maximum sensed pressure of 20 psi. The full scale sensed pressure range is 0 to 20 psi. In terms of voltage the full scale error translates into 0.0041 V, and to 0.018 psi in terms of pressure.

The sensor errors at each altitude of interest were calculated using the known sensor error of 0.018 psi and the method above. The altitude error due to sensor errors is shown in Table 1.

Table 1: Altitude error due to sensor errors

LRS Event	Nominal Altitude (ft)	Error (ft)
-	55,000	278
-	50,000	220
-	45,000	176
Start Smart FBC Jettison Logic	35,000	114
FBC Chute Deploy	24,000	74
Start Drogue Rate Damping	20,000	63
Main Chute Deploy	8,000	42
Start Roll Control	1,500	34
Touchdown	0	32

The sensor errors are zero-mean, so biases due to sensor errors can result in sensed pressures higher or lower than truth pressure.

V.C. A/D Conversion Errors

The barometric altimeters output an analog voltage signal. This signal is converted to a digital value by the Power and Data Unit (PDU) Analog/Digital Input/Output (ADIO) cards. The analog to digital conversion in the ADIO card has a spec error of 1% FS. The input voltage range for the A/D conversion is 6 V, which equates to an error of 0.06 V or 0.2 psi. The A/D error is expected to manifest as a bias.

The A/D conversion error was calculated at each altitude of interest. The results are shown in Table 2. The A/D conversion error can bias the sensed pressure to be either higher or lower than truth pressure.

V.D. Aerodynamic Effects

Given the location of the barometric altimeters, the sensed pressure will be affected by the dynamic conditions present during vehicle re-entry. These errors are all lumped together under the category of aerodynamic errors. There are three separate contributions to the total aerodynamic error at the barometric altimeter assembly:

Table 2: Altitude error due to A/D conversion errors

LRS Event	Nominal Altitude (ft)	Error (ft)
-	55,000	3,116
-	50,000	2,446
-	45,000	1,965
Start Smart FBC Jettison Logic	35,000	1,273
FBC Chute Deploy	24,000	818
Start Drogue Rate Damping	20,000	703
Main Chute Deploy	8,000	462
Start Roll Control	1,500	377
Touchdown	0	361

1. Steady wake effects resulting in a pressure differential between midbay compartment F and the free stream
2. Oscillating wake effects
3. Acoustic effects

The GNC team coordinated with the aerosciences team to create models of these effects. The models were based on an analysis and wind tunnel testing performed by Lockheed Martin Space Systems Company (LMSSC) Orion Aerosciences and LMSSC Loads and Dynamics. There are three key limitations of the aerodynamic models:

1. CM RCS jet interaction was neglected pending future assessment by the aerosciences team
2. Supersonic data for the CM oscillating wake pressure model was sparse
3. Aerodynamic effects are not explicitly correlated to vehicle attitude

At the time of this document's writing, the RCS jet interaction models were still being developed. The sparseness of supersonic wake data was not a driving limitation given the low Mach values under the parachutes. From a GNC perspective, the lack of correlation to vehicle attitude was the major limitation. The aerodynamic errors were only defined over specific attitude ranges, some of which were exceeded in certain scenarios. Work is ongoing to create models correlating aerodynamic effects to vehicle attitude.

V.D.1. Steady Wake Effects Model

The steady wake pressure model (also referred to as the CM compartment pressure model) used the standard set of EFT-1 dispersed trajectories, the ¡EXPLAIN ACRONYM¿ CAP aerodynamic loads database, and variable discharge coefficients generated using Computational Fluid Dynamics (CFD) to assess the altitude-dependent pressure inside midbay compartment F, where the barometric altimeters are located. Conservative assumptions were made on model uncertainties.[5] The model is a table look-up of the difference between compartment pressure and the free stream pressure at a given altitude. It is valid down to altitudes of around 24,000 feet. There are minimum and maximum bounding cases for two different crew module masses: 20200 lbm and 23000 lbm.

Below 24000 feet, a table of coefficient of pressure vs. Mach is used to model the pressure differential. This model has a minimum and maximum bounding case, but no mass dependencies. Therefore the same values are used for each bounding case regardless of vehicle mass.

V.D.2. Oscillating Wake Effects Model

The oscillating wake pressure model was derived from results of the 05-CA wind tunnel test. The results were spot-checked by CFD/LES simulation of the CM in free-stream (additional CFD/DES cases pending by AR-135).[5] Those data will be reviewed based on upcoming 89-CA wind tunnel testing. The oscillating wake model provides a Mach-dependent frequency plus an amplitude based on free-stream dynamic pressure. The model is valid below 100,000 feet.

V.D.3. Acoustic Effects Model

The acoustics model was provided by Loads and Dynamics using entry aerodynamic environments adjusted for CM compartment effects.[5] The model simply contains 36 seconds of acoustics data. A frequency spectrum analysis revealed the signal is a 60 Hz sinusoid with pink noise and white noise. The original signal was sampled at a very high rate; the GNC simulation uses 2.5 seconds of this signal sampled at 200 Hz because of array size limitations. The loads and dynamics teams has confirmed looping through the signal is an appropriate way to include acoustic effects. The model is valid below 100,000 feet.

The models discussed above were implemented in the GNC Osiris simulation. Osiris is a Trick-based simulation that models sensors, effectors, environments, and vehicle dynamics. The Osiris simulation drives a separate standalone simulation containing prototype flight software. In conjunction, the two simulations are used to analyzed vehicle state and performance during all mission phases.

The implementation of the aerodynamic error models in the Osiris simulation is described in detail in the Osiris pressure sensor model document.[6] Note that these models are completely decoupled from vehicle attitude. Each of the three aerodynamic error models can be enabled and disabled individually.

Monte Carlo sets were run for all four bounding cases in the Osiris-Ramses simulation to define the worst case aerodynamic errors:

1. Minimum mass, minimum compartment pressure differential model
2. Maximum mass, minimum compartment pressure differential model
3. Minimum mass, maximum compartment pressure differential model
4. Maximum mass, maximum compartment pressure differential model

All other error sources impacting the sensed pressure were disabled during these runs. The mean, maximum, and minimum total error in sensed pressure over all runs in each of the four sets of Monte Carlo runs were calculated. These were then converted to altitude errors using the method discussed above. Figure 6 below shows the altitude error versus truth geodetic altitude in feet for all four bounding cases. The altitude error is defined as the 'truth' altitude from the Osiris simulation minus the altitude output from the barometric altimeter flight software.

From Figure 6, it can be seen that aerodynamic effects generally bias pressure low (truth minus sensed pressure almost always positive), which translates into a higher sensed altitude than truth altitude. These errors are not zero-mean, and the upper and lower bounds on the error are shown in the plot.

When converted to an altitude error, the pressure error at each altitude of interest based on this data results in the bounding altitude errors shown in Table 3.

A negative sign indicates the sensed altitude is higher than the truth altitude. As seen in Figure 6, the aerodynamic errors nearly always bias the altitude high. This will result in LRS events occurring at lower altitudes than nominally planned. The impacts of this are discussed later.

V.E. Atmospheric Modeling Errors

The barometric altimeter FSW converts measured pressure to altitude using an extended 1976 US Standard Atmosphere model. The model is valid up to 232,000 feet. Any measured pressure less than the Standard76 model pressure at this altitude results in the maximum altitude of 232,000 feet. The 1976 US Standard Atmosphere model is an idealized, steady-state representation of the earth's atmosphere; on any given flight day, the actual atmosphere may differ significantly from the model.

For verification purposes, the GRAM2007[4] atmosphere model is considered to represent the truth atmosphere on a given flight day. Therefore, error resulting from the use of the Standard model instead of

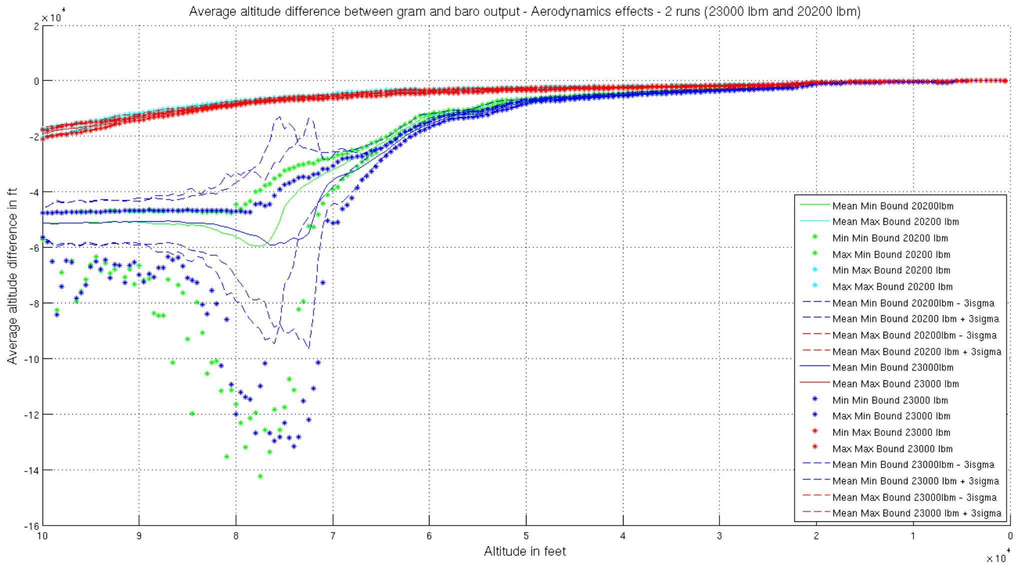

Figure 6: Altitude error due to aerodynamic effects

using GRAM2007 to convert pressure to altitude in the flight software must be included in the altitude error budget.

To estimate the errors due to use of the Standard76 model in flight software as opposed to using a curve fit or other implementation of GRAM, a Monte Carlo set was run using the Osiris-Ramses simulation. The GRAM month was dispersed for these runs, as were all of the standard GRAM parameters, but no other error sources were enabled. Therefore the sensed pressure was perfect. The difference between the altitude calculated from the perfect sensed pressure and the truth altitude from the simulation represents the error induced by use of the Standard 76 Atmosphere model to perform the conversion from pressure to altitude in the barometric altimeter FSW. The mean, minimum, and maximum altitude errors over the full set of Monte Carlo runs is shown in Figure 7.

The minimum and maximum bounding errors at the altitudes of interest are shown in Table 4.

As with the aerodynamic errors, the atmospheric modeling errors almost always bias the sensed pressure in a specific direction. In general, the altitude from GRAM2007 is generally higher than the altitude from the 1976 US Standard Atmosphere model.

Table 3: Altitude error due to aerodynamic effects

LRS Event	Nominal Altitude (ft)	Minimum Error (ft)	Maximum Error (ft)
-	55,000	-12,928	-2,774
-	50,000	-8,222	-2,369
-	45,000	-6,596	-2,186
Start Smart FBC Jettison Logic	35,000	-4,462	-1,702
FBC Chute Deploy	24,000	-2,845	-1,611
Start Drogue Rate Damping	20,000	-1,284	-452
Main Chute Deploy	8,000	-507	-133
Start Roll Control	1,500	-19	7
Touchdown	0	-18	19

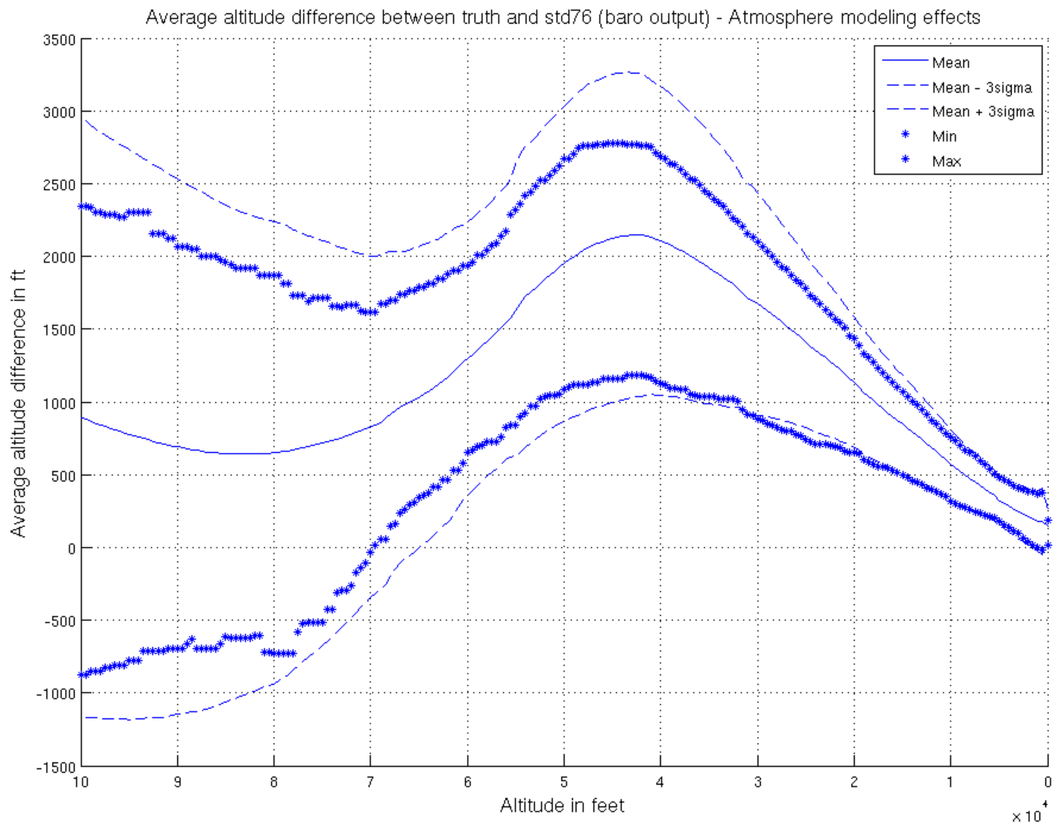

Figure 7: Difference between 'truth' altitude and sensed altitude. No error sources affecting sensed pressure were enabled in these runs, so this error is solely due to the differences between GRAM2007 and the 1976 US Standard Atmosphere model.

It should be noted that, while GRAM2007 is considered the 'truth' atmospheric model throughout this paper, there is no guarantee that GRAM will match the actual conditions on the day of flight any better than the 1976 US Standard Atmosphere model. This is the case even if the GRAM RRA option is enabled to enhance GRAM's predictive capabilities.

V.F. Latency

A total end-to-end latency of 100 ms is budgeted to the barometric altimeters. The altitude errors resulting from the 100 ms latency is shown in Table 5. The altitude rate of change values were estimated from Monte Carlo runs for a nominal re-entry.

The latency will always bias the sensed altitude higher than truth altitude, hence the negative signs in the altitude error column of the table.

V.G. Waves and Tides

Although their impact is slight, waves and tides can also contribute to errors in altitude derived from the barometric altimeters. These errors are estimated to be approximately ±14 feet. This value is independent of altitude. Wave and tide errors are zero-mean, so biases in sensed pressures resulting from waves and tides can be higher or lower than truth pressure.

Table 4: Altitude error due to atmospheric effects

LRS Event	Nominal Altitude (ft)	Minimum Error (ft)	Maximum Error (ft)
-	55,000	525	2,511
-	50,000	864	3,034
-	45,000	997	3,250
Start Smart FBC Jettison Logic	35,000	891	2,759
FBC Chute Deploy	24,000	615	1,830
Start Drogue Rate Damping	20,000	552	1,491
Main Chute Deploy	8,000	165	585
Start Roll Control	1,500	-82	287
Touchdown	0	5	262

Table 5: Altitude error due to latencies

LRS Event	Nominal Altitude (ft)	Altitude Rate of Change (ft)	Altitude Error (ft)
-	55,000	600	-60
-	50,000	600	-60
-	45,000	600	-60
Start Smart FBC Jettison Logic	35,000	600	-60
FBC Chute Deploy	24,000	600	-60
Start Drogue Rate Damping	20,000	200	-20
Main Chute Deploy	8,000	200	-20
Start Roll Control	1,500	38	-4
Touchdown	0	38	-4

V.H. Itemized Error Budget Results

For a traditional itemized error budget, at this point all of the individual error sources would be combined using Equation (4). However, given the directionality inherent to some of the error sources, this method was not appropriate. Therefore, the error sources without inherent directionality were combined using Equation (4), then the remaining three directional error sources with their signs intact were added to that value. The resulting total error budget is shown in Table 6.

Table 6: Itemized barometric altimeter altitude error budget

LRS Event	Nominal Altitude (ft)	Minimum Bounding Error (ft)	Maximum Bounding Error (ft)
-	55,000	-15,607	2,790
-	50,000	-9,909	1.965
-	45,000	-7,647	2,961
Start Smart FBC Jettison Logic	35,000	-4,925	2,260
FBC Chute Deploy	24,000	-3,127	965
Start Drogue Rate Damping	20,000	-1,473	1,709
Main Chute Deploy	8,000	-842	881
Start Roll Control	1,500	-499	653
Touchdown	0	-395	624

VI. Monte Carlo Simulation

A Monte Carlo analysis with all of the error sources discussed in the previous sections enabled was run to provide validation of the itemized error budget. For the Monte Carlo simulation, the sensor error included both noise and bias components. The A/D conversion error was modeled as a random bias. The results of the analysis are shown in Table 7.

Table 7: Barometric altimeter altitude error budget

LRS Event	Nominal Altitude (ft)	Minimum Bounding Error (ft)	Maximum Bounding Error (ft)
-	55,000	-20,295	2,004
-	50,000	-11,340	2,065
-	45,000	-7,908	2,242
Start Smart FBC Jettison Logic	35,000	-4,263	1,752
FBC Chute Deploy	24,000	-2,677	1,146
Start Drogue Rate Damping	20,000	-881	1,557
Main Chute Deploy	8,000	-612	868
Start Roll Control	1,500	-409	670
Touchdown	0	-425	191

It is clear from Tables 6 and 7 that, compared to the full Monte Carlo analysis with all interactions between error sources modeled, the itemized budget underestimates the errors at higher altitudes and overestimates them at lower altitudes. The reason for this discrepancy lies in the violation of one of the underlying assumptions made in the construction of the itemized error budget: error source independence.

It should be obvious from previous sections that the atmospheric modeling errors are not independent of the other error sources. The error incurred from atmospheric modeling directly depends on the sensed pressure, which is in turn affected by all of the other error sources. Therefore an independent quantification of atmospheric modeling errors is not possible. The Monte Carlo analysis modeled this interaction between the error sources, and thus provides the more accurate representation of the overall error budget.

VII. Impacts of the Barometric Altimeter Error Budget on Design of the LRS Event Trigger Altitudes

As stated previously, one of the purposes of quantifying the errors in the altitude derived from the barometric altimeters was to determine whether LRS events triggered from that altitude would occur within acceptable altitude ranges. Therefore it is important to to determine the truth altitude at which each event would occur given worst case barometric altimeter errors. For example, barometric altimeters consistently reading low could estimate the altitude to be 35,000 feet at a truth altitude of 36,615 ft. Table 8 shows how this calculation was performed.

Table 8: Determining Truth Altitude Range Within Which Smart FBC Jettison Logic Will Start

Truth Altitude (ft)	Baro Error Max (ft)	Baro Error Min (ft)	Baro Altitude Low (ft)	Baro Altitude High (ft)
37,000	1,669	-4,748	35,331	41,478
36,500	1,599	-4,693	34,901	41,193
36,000	1,578	-4,583	34,422	40,583
35,500	1,580	-4,342	33,920	39,842
35,000	1,572	-4,263	33,420	39,263
34,500	1,533	-4,185	32,928	38,685
34,000	1,546	-4,003	32,467	38,003
33,500	1,450	-3,983	31,954	37,483
33,000	1,464	-3,983	31,454	36,983
32,500	1,331	-3,885	31,050	36,385
32,000	1,290	-3,762	30,536	35,762
31,500	1,290	-3,762	30,036	35,262
31,000	1,299	-3,563	29,670	34,563

For each truth altitude in the left-most column, the minimum and maximum bounding errors at that altitude (columns 2 and 3) were subtracted from it to calculate the values the barometric altimeters could output at that truth altitude given the expected errors at that altitude. The values the barometric altimeters would output are shown in columns 4 and 5. If the barometric altimeters are reading high (minimum bounding error), the FSW altitude will be the value shown in column 4. If they are reading low (maximum bounding error), the FSW altitude will be the value shown in column 5. Therefore, the Smart FBC jettison logic could be started at truth altitudes between 36,615 feet and 31,312 feet. These values were obtained by performing linear interpolation of the highlighted cells in Table 8 to find the truth altitude at which the barometric altimeters would output the start of Smart FBC jettison logic trigger altitude of 35,000 feet.

Repeating this exercise for all of the EDL events triggered based on FSw altitude yields the true altitude ranges at which each event would occur with the current altitude trigger settings. These values are shown in Table 9.

As seen in the first row of Table 9, smart FBC jettison logic start might occur 115 feet higher than the desired maximum altitude of 36,500 feet with the target trigger altitude set to 35,000 feet, but all other events will occur well within their allowable ranges if the source of the FSW altitude is the barometric altimeters. The 115 foot excess over margin was deemed acceptable for the Smart FBC jettison logic. Also note there is no overlap of the ranges at which the various events could occur, so if for any reason the barometric altimeters were to oscillate between the high and low error bounds, all events would still occur within acceptable ranges.

An alternate approach could have been taken had the bounds for the EDL events been defined, but the

Table 9: Truth Altitude Ranges Within Which Altitude-Triggered EDL Events Will Occur

LRS Event	Targeted Altitude (ft)	Maximum Altitude (ft)	Minimum Altitude (ft)	Maximum Alt Baro (ft)	Minimum Alt Baro (ft)
Smart FBC Jettison Logic Start	35,000	36,500	30,000	36,615	31,312
FBC Parachute Deployment	33,500	36,500	20,500	25,109	22,084
Drogue Chute Release Ceiling	8,000	9,500	5,000	8,933	7,238
Drogue Chute Release Floor	8,000	9,500	5,000	8,933	7,238
Landing Orient Mode Initiation	1,500	2,500	1,000	2,210	1,070

goal was to determine the target altitudes. To define the allowable range of each trigger, the barometric altimeter altitude errors at the known upper and lower bounds for each event could have been added to the bounding altitudes to compute where the triggers should be set. Figure 8 shows how this would be accomplished.

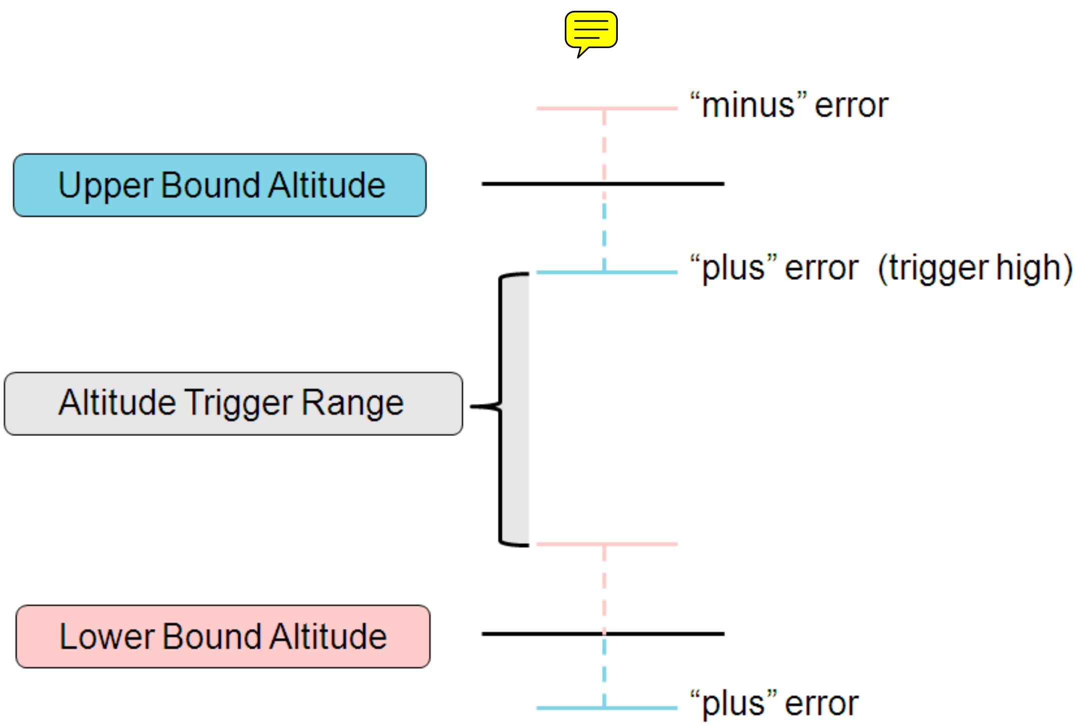

Figure 8: Using the Barometric Altimeter Altitude Budget to Define EDL Trigger Ranges

VIII. Defining Maximum Altitude at which Barometric Altimeters are Valid

The secondary purpose of characterizing the barometric altimeter altitude errors was to determine at which point the errors become small enough to allow use of the sensors. Figures 9 and 10 show the total altitude errors at 500 foot intervals.

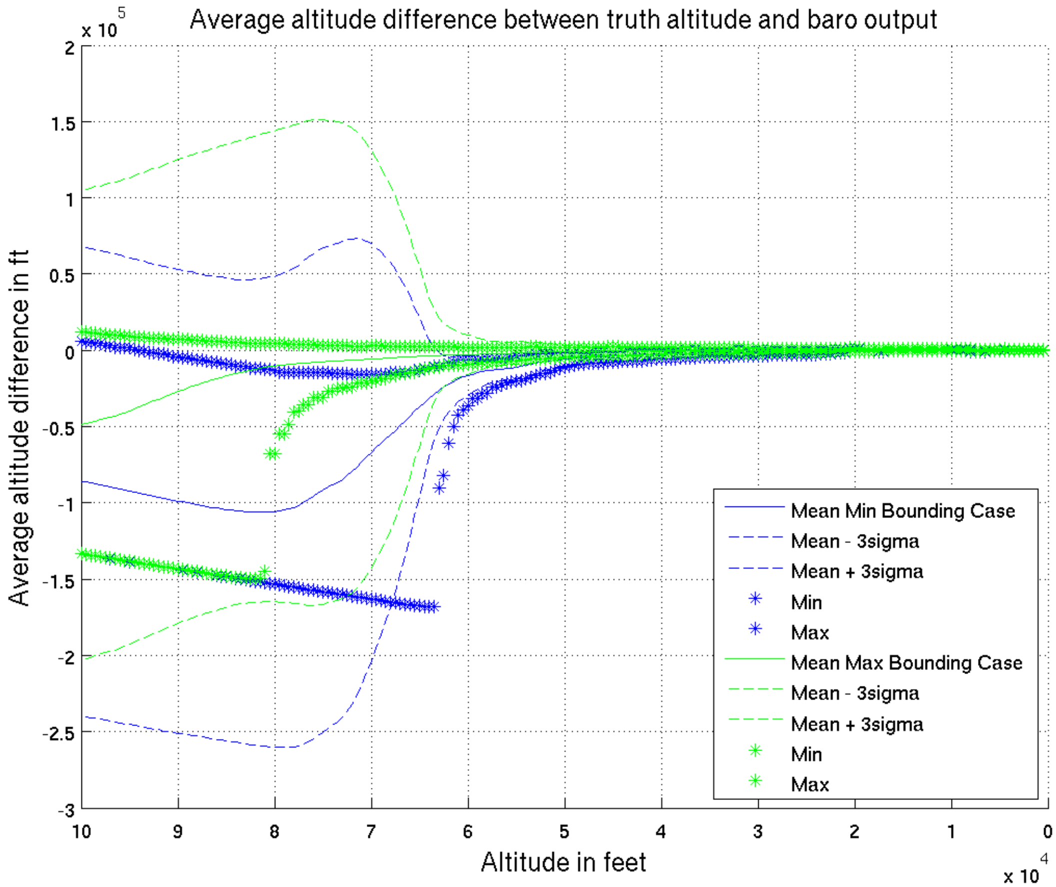

Figure 9: Barometric altimeter altitude errors at 500 foot intervals

The linear large altitude error trend in Figure 9 is an artifact of how negative and very small voltages are handled in the flight software. Due to noise, sensor errors, and A/D conversion errors, the voltage from the barometric altimeters read by the FSW can be less than the spec minimum value of 0.1 V. Any voltage representing a pressure less than the minimum pressure at which the FSW model can convert pressure to altitude results in an altitude output of the maximum model altitude from the flight software. This causes the linear trend seen between 100,000 and 65,000 feet in Figure 9.

All of the LRS events occur in the lower altitude range shown in Figure 10. There is a knee in the altitude error curves at around 50,000 feet in the figure, after which altitude errors decrease rapidly. Therefore, barometric altimeter altitude should not be used at truth altitudes higher than 50,000 feet. Based on the error budget, a truth altitude of 50,000 feet corresponds to a calculated altitude of 61,340 feet. The barometric altimeter flight software contains a gate that only allows use of the barometric altimeter altitude once the barometric altimeter altitude is less than the gate altitude threshold.

However, although the barometric altimeter altitude errors become very large at sensed altitudes of higher than 61,340 feet, there is another factor that drives the setting of the barometric altimeter gate. The tertiary backup to GPS and barometric altitude is a velocity trigger based on the unaided navigation solution. The velocity trigger is discussed above. The setting for this trigger can result in FBC chute deployment at very high altitudes, so if GPS data is unavailable and the barometric altimeter gate is set too low, the velocity trigger can cause the drogue chutes to be deployed at too high an altitude.

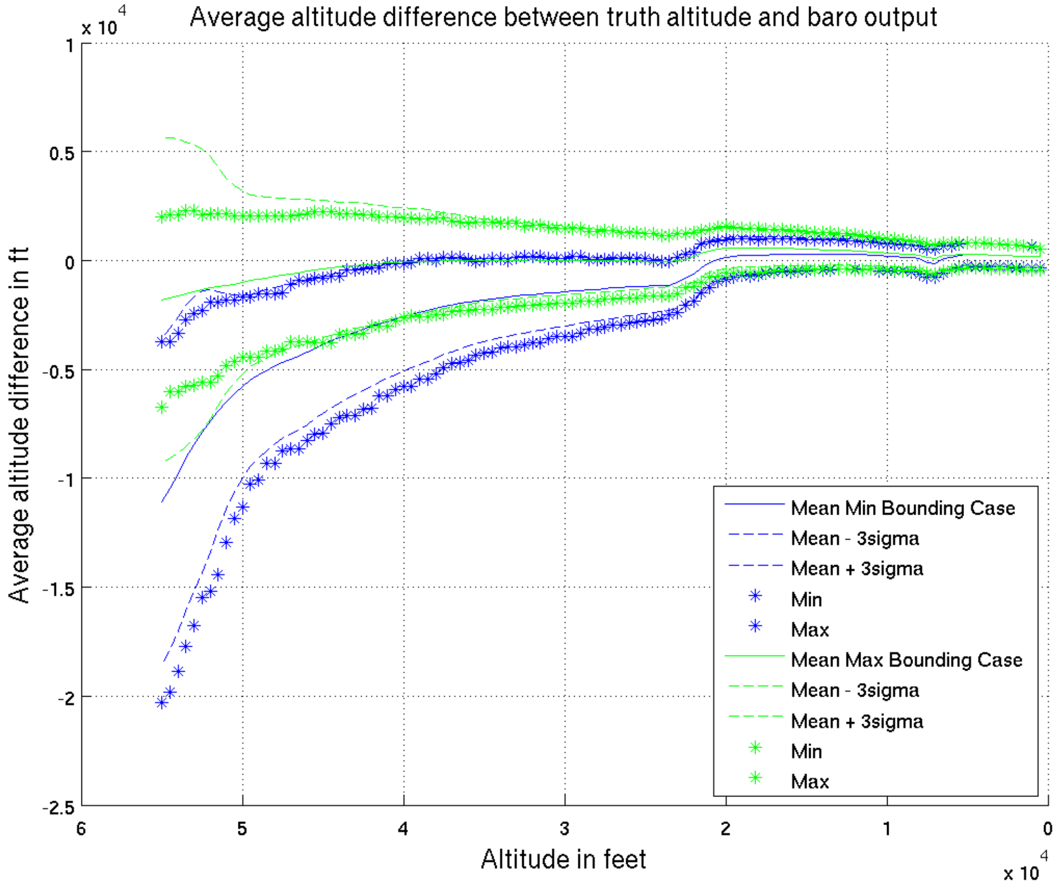

Figure 10: Barometric altimeter altitude errors at 500 foot intervals from sea level up to 55,000 feet

Given that, it was decided to set the barometric altimeter gate to 70,000 feet. The reason for this is that, if the barometric altimeters are reading high, FBC jettison will not be triggered too early even if the barometric altimeter altitude is considered valid while errors are still very large.

IX. Conclusion

The initial attempt to characterize the altitude error budget for the EFT-1 barometric altimeters using the typical itemized error budget approach was stymied by lack of independence between error sources. Therefore a full Monte Carlo simulation with all error sources and their interactions enabled was performed to define the altitude error budget. The resulting errors drove the decision to move the trigger altitude for FBC parachute deployment to a higher altitude in order to ensure drogue parachute deployment occurred above the minimum allowable altitude. The barometric altimeter errors are very large above an altitude of 50,000 feet; therefore the barometric altimeter flight software employs a gate to prevent use of altitude from the barometric altimeters above a certain altitude.

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