CHANGO: A SOFTWARE TOOL FOR BOOST STAGE GUIDANCE OF THE SPACE LAUNCH SYSTEM EXPLORATION MISSION 1

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The Space Launch System (SLS) Exploration Mission 1 (EM-1) test flight will use open-loop guidance for Boost Stage (BS) flight. A table of attitude commands as a function of altitude, called the chi table, will be loaded onto the flight computers. The chi table will be generated using the measured winds on launch day by the Chi Angle Optimizer (CHANGO) software tool. Details of CHANGO's design are given, including a Three Degrees-of-Freedom (3-DOF) simulation and a numerical minimization routine. CHANGO's use in launch day operations is also described.

INTRODUCTION

The Day of Launch I-Load Update (DOLILU) System is the means by which the Space Launch System (SLS) Vehicle trajectory is designed, verified, and uploaded on the Day of Launch (DOL) in order to ensure a safe flight. Launch vehicles are designed to fly down a narrow angle of attack (alpha or α) and angle of sideslip (beta or β) corridor in order to keep them within structural load limits.[1] The alpha and beta response of the launch vehicle can vary significantly based upon the winds experienced on the DOL. SLS Boost Stage (BS) flight employs an open-loop guidance scheme through Solid Rocket Booster (SRB) separation.[2]

In the SLS open-loop scheme, the vehicle will fly a prescribed set of attitudes as a function of the change in altitude since launch. This set of reference attitude values and corresponding altitude reference independent values, called Initialization Loads (I-Loads), are designed with ground software using winds measured on the DOL with the goal of minimizing alpha and beta and, therefore, related ascent integrated vehicle structural loads.

To verify the design, a Six Degrees-of-Freedom (6-DOF) launch simulation is used to evaluate loads in the presence of a measured atmosphere (wind and thermodynamics). All integrated vehicle structural loads must be within limits for a safe launch. If they are not, the vehicle cannot launch and must delay. When all integrated vehicle structural loads are

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verified to be within limits, the I-Loads are then uploaded to the Core Stage (CS) Flight Software (FSW). The effects on integrated vehicle structural loads due to wind changes during the period between measurement of wind data and launch are protected statistically. DOL winds continue to be assessed to verify the safe flight design before flight. The final "Go" or "No Go" for flight is given at a predefined time before lift-off.

Chi Angle Optimizer (CHANGO) designs the BS trajectory I-Loads which are uploaded to the vehicle's flight computer and used during ascent by the flight software. The wind and atmosphere conditions are measured prior to launch and pre-processed to become input to the CHANGO software along with the DOL estimated Propellant Mean Bulk Temperature (PMBT) and other fixed-value inputs determined from pre-DOL evaluations. Execution of the CHANGO software determines the subset of I-Loads that prescribe the vehicle attitude and throttle from liftoff to SRB jettison. The data is formatted as a table with an independent variable of delta-altitude from liftoff and is referred to as the Chi Table.

Vehicle structural loads due to aerodynamic forces and moments can be minimized by maintaining zero total angle of attack during the high dynamic pressure phase of flight. For a specific measured wind, the vehicle attitude angles that result in zero total angle of attack can be computed. Since the measured wind is not identical to the actual wind experienced during ascent, there will be some expected divergence from zero total angle of attack using the attitude angles determined from the measured wind. As was the case with the Space Shuttle, SLS launch availability has been determined to be unacceptable if mean monthly winds are used as the "measured" wind due to the large variation in wind causing corresponding large divergence from zero total angle of attack and, consequently, unacceptable structural loads. The SLS launch availability requirement demands the use of launch-day wind measurements taken shortly before launch to design the Chi Table, which is uploaded via the DOLILU process.

This paper will describe CHANGO's modeling and numeric optimization. The Chi Table itself is discussed, as well as the use and modification of the Chi Table for actual flight scenarios. Finally, results of simulations during the development and use of CHANGO are given.

DESIGN METHODOLOGY

On launch day, CHANGO incorporates the measured and filtered wind and computes the attitude angles required to orient to and then follow zero total angle of attack during the high dynamic pressure phase of ascent. The computed attitude angles are roll, pitch, and yaw, formed using the Yaw-Pitch-Roll Euler angle sequence to go from a North-East-Down (fixed at launch) frame to the vehicle body frame.

CHANGO consists of an inner Three Degrees-of-Freedom (3-DOF) simulation that is called multiple times by an outer optimization routine. The 3-DOF simulation follows the textbook launch profile for atmospheric flight.[3] The numeric optimization routine is an implementation of an off-the-shelf minimization routine.

Figure 1 shows the high level CHANGO simulation details. Detailed descriptions of the items in Figure 1 are given in the following sections.

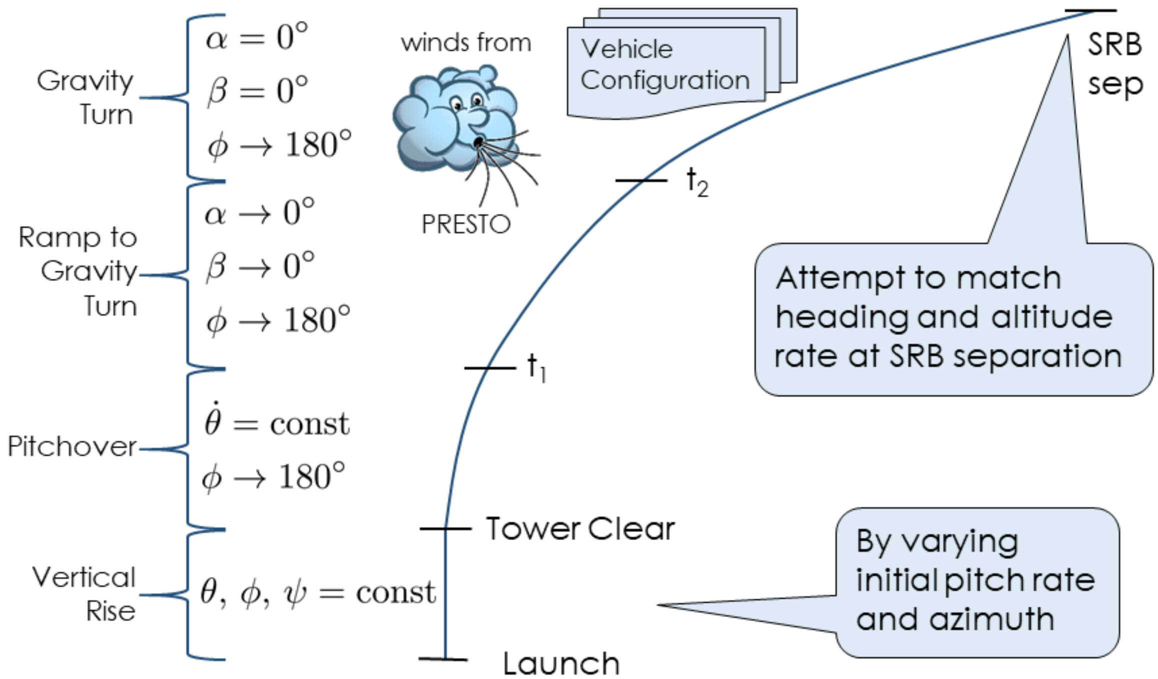

Figure 1: High Level CHANGO Simulation Details

Simulation

CHANGO follows the standard sequence for a crewed launch vehicle.[3] First, a vertical rise holds attitude constant until the launch tower is cleared. Next a constant pitchover is initiated. Following the pitchover, the aerodynamic angles (α and β) follow a linear ramp to zero. During the gravity turn, the aerodynamic angles are held at zero. Additionally, an exponential roll to a heads-down orientation is initiated at the start of the pitchover, and continues until SRB separation. The maneuver to a heads-down position has heritage from the Shuttle program where crew members desire a view of the horizon.

CHANGO's trajectory simulation is phase-based, with flight events separating the phases. Each flight phase has different attitude alignment logic. CHANGO's 3-DOF simulation starts when the vehicle's thrust-to-weight ratio equals one, and ends at the calculated SRB separation time. The times to start and end the ramp to the gravity turn are inputs that may change with vehicle configuration or launch month. A time constant controls the aggressiveness of the roll, and this value is not expeted to change. The rate of the pitchover is one of two design variables that CHANGO iterates on. The sequence of flight events and phases is described in Table 1.

CHANGO is designed to be lean, to reduce run-time and increase reliability. The input models to CHANGO are provided by the relevant disciplines. Atmospheric ascent design is performed using a 3-DOF trajectory simulation with simplified models for propulsion, mass, and aerodynamics characteristics of the BS SLS vehicle. Gravity is modelled as an oblate earth using the J2 zonal coefficient only. Atmosphere and wind models are updated to include DOL measured data from Profile Envision and Splicing Tool (PRESTO). PRESTO is a tool developed in-house at Marshall Space Flight Center (MSFC) to create a vertically complete wind profile from wind measurements. The SRB propulsion model is adjusted to account for the DOL estimated PMBT. Most data is provided as a lookup table, with linear interpolation between entries. The aerodynamic force tables are reduced from a set of tables for different Mach numbers to simple constant derivatives. Table 2 summarizes the models used in the 3-DOF trajectory simulation.

Table 1: 3-DOF Attitude Alignment

EVENT: Liftoff	Vehicle Thrust-to-Weight Ratio (T/W) equals one
PHASE: Vertical Rise	Hold liftoff attitude until tower is cleared
EVENT: Start Pitchover	Altitude exceeds tower height
PHASE: Pitchover	Begin roll to commanded value Constant pitchover rate until time t_1 Yaw to launch azimuth plane
EVENT: Start Ramp	Time t_1 reached
PHASE: Ramp to Gravity Turn	Continue roll command Pitch and yaw to linearly drive angle of attack and sideslip angles to zero by time t_2
EVENT: Start Gravity Turn	Time t_2 reached
PHASE: Gravity Turn	Continue roll command Pitch and yaw to maintain zero angle of attack and zero sideslip angle from t_2 until SRB separation
EVENT: SRB Separation	SRB separation thrust level reached

Table 2: Simplified Models for 3-DOF Trajectory Simulation

Model:	Description:
Atmosphere	Table from PRESTO
Wind	Table from PRESTO with adjustments toward mean monthly wind and ramp from zero velocity at zero altitude
Propulsion	Table lookups for SRBs and Core, plus correction for atmospheric pressure effects • SRBs: Table of thrust as a function of time, with adjustments for PMBT • Core: Table of thrust as a function of throttle level*
Mass	Vehicle total mass based on wet mass at liftoff minus propellant consumption • SRBs: Table of mass flow rate as a function of time • Core: Table of mass flow rate as a function of throttle level*
Aerodynamics	Tables for axial force; computation for lateral forces • Axial direction: Tables of axial thrust force as a function of Mach number and base force as a function of altitude • Lateral directions: Aerodynamic force computed as a function of angle of attack (α) and sideslip angle (β), using constant force derivatives
Gravity	Oblate Earth model using J2 zonal coefficient only
	*throttle is input as a function of time

Optimization

Numerical Scheme CHANGO's target set consists of a heading and altitude rate at SRB separation. The target values are determined well in advance of the DOL via trajectory optimization with mean monthly winds. Through an iterative process, CHANGO finds the initial pitchover rate and launch azimuth (the independent parameters) which minimize the error in the two targeted parameters (the dependent parameters) at the time of SRB separation.

In general, the launch azimuth is strongly correlated with the heading at SRB separation, and the initial pitchover rate is strongly correlated with the altitude rate at SRB separation. CHANGO uses an adaptation of Powell's method to solve this 2-dimensional minimization problem.

As depicted in Figure 2, through an adaption of Powell's method,[4] CHANGO's `powell` uses a line minimization algorithm, `linmin`, that chooses each successive direction without explicit computation of the function's gradient. Within `linmin`, `mnbrak` conducts cost function evaluations to bracket the minimization routine, `brent`. This adaptation of Powell's method avoids a buildup of linear dependence by discarding the prior direction that resulted in the largest decrease in the cost function.

In CHANGO's case, the cost function is an optimization statement as a function of the heading and altitude rate at SRB separation. Those parameters are found by running the aforementioned 3-DOF trajectory simulation. Once the change in cost function is small enough in `powell`, the Chi Table is written out using trajectory data from the last 3-DOF run.

Optimization Statement The cost function is simply the sum of the weighted squared error of the dependent parameters from their target values. The weightings are inputs to CHANGO. As Powell's method is not specifically set up to handle boundaries, upper and lower bounds on the independent parameters are set as inputs to CHANGO. If a guess value lies outside of these bounds the cost function is set to 1×10^{30}, ensuring that the invalid guess does not return the minimum. The equation for the cost function and variable definitions are given below.

$$J = f\left(\psi_{launch},\, \dot{\theta}_{init}\right) = w_{\dot{h}} \frac{\left(-v_{z,\mathrm{NED},sep} - \dot{h}_d\right)^2}{\dot{h}_d^2} + w_{\psi} \frac{\left(\psi_{sep} - \psi_d\right)^2}{\psi_d^2}$$

Design Space As previously noted, the optimization statement makes use of weightings to apply to the altitude rate and heading terms. Initially, the terms were weighted equally. However, after sweeping a range of pitch rates and then a range of azimuths for a particular mean monthly wind, the altitude rate term of the cost function was observed to change much faster than the heading term in both cases. The heading term weight was then changed to 0.75, while the altitude rate term weight was changed to 0.25. Testing a few runs with both sets of weightings showed a reduction in Powell's method iterations needed to find a

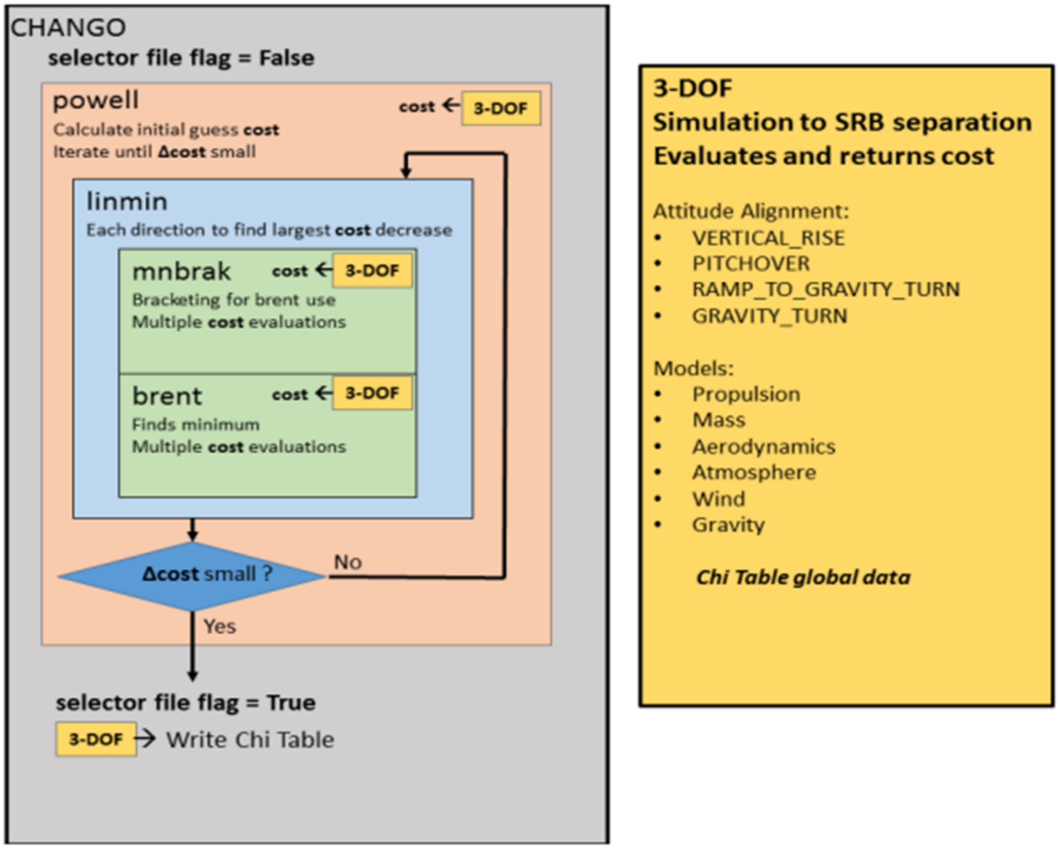

Figure 2: Numerical Scheme Overview

J	Cost Function
ψ_{launch}	Launch Azimuth
$\dot{\theta}_{init}$	Initial Pitchover Rate
$w_{\dot{h}}$	Altitude Rate Cost Weighting
$v_{z,\mathrm{NED},sep}$	Downwards Velocity at SRB Separation
$\dot{h}_d$	Desired Altitude Rate
w_ψ	Heading Cost Weighting
ψ_{sep}	Heading at SRB Separation
ψ_d	Desired Heading

solution. Thus, the latter set of weightings were adopted into the baseline CHANGO inputs. Though the evaluation of proper weightings was not exhaustive, the weightings have proven robust for thousands of different wind and atmosphere combinations, providing trajectories that fly very close to the desired SRB separation targets.

With the chosen weightings, the shape of the cost function as a function of launch azimuth and initial pitchover rate can vary wildly depending on the design wind. Figure 3 shows a couple of examples of these design spaces. CHANGO's implementaiton of Powell's method has proven to be very robust to these varying design spaces through hundreds of thousands of runs.

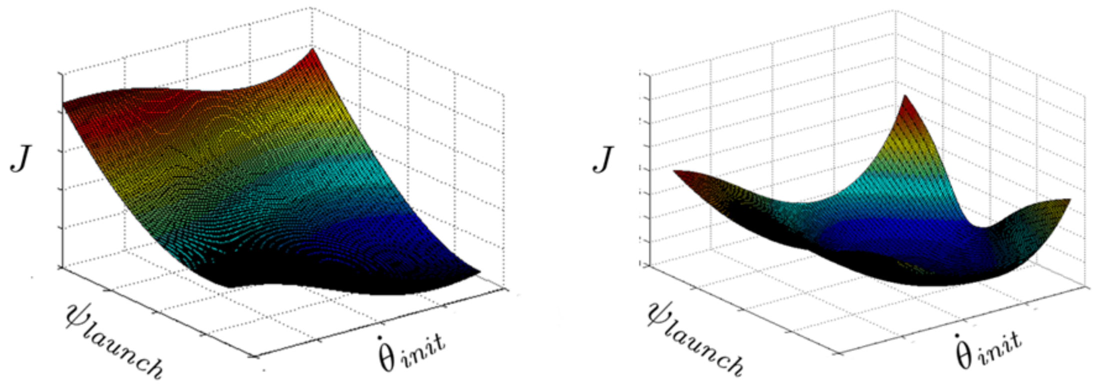

Figure 3: Representative Design Spaces

The Chi Table

Upon success of the trajectory design process, the 3-DOF simulation runs one final time, and Chi Table parameters are stored. Table 3 provides a description of each Chi Table parameter: delta altitude, attitude angles, and throttle. As provided in the table, the attitude angles are defined using North-East-Down (NED) and SLS Body coordinate systems.[1] Figure 4 defines the NED Coordinate Frame, with the X-axis (X_G) in the local horizontal frame and pointing north, the Y-axis (Y_G) in the local horizontal plane and pointing east, and the Z-axis (Z_G) completing the right-handed system (pointing down). As shown in Figure 5, the SLS Body Coordinate Frame's X-axis rests on the geometric centerline of the CS of SLS and points in the forward direction. The SLS Body's Coordinate Frame's Y-axis points to the centerline of the right-hand booster, with the Z-axis completing the right-hand rule.

The delta altitude, attitude angles, and throttle are saved from the 3-DOF trajectory simulation at 1-second intervals and at the transition events (see Table 1) to capture appropriate trajectory granularity in the Chi Table. Logic exists to ensure that the altitude of each new row is a minimum of 1 foot above the previous row. This ensures that the independent variable is monotonically increasing, and prevents writing multiple rows if a transition event occurs near a 1-second interval.

Table 3: Chi Table Parameter Description

	Delta Altitude	**Attitude Angles**	**Throttle**
Description	Altitude gained since launch.	Roll, Pitch, and Yaw angles using a 3-2-1 Euler angle to go from NED (fixed at launch) coordinate system to SLS Body coordinate system.	Commanded throttle level of SLS's RS-25 engines.
Units	feet	degrees	

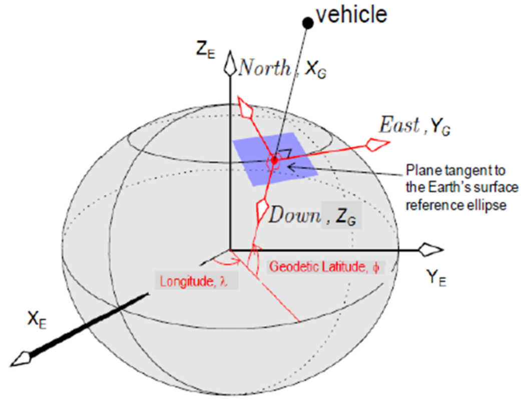

Figure 4: NED Frame

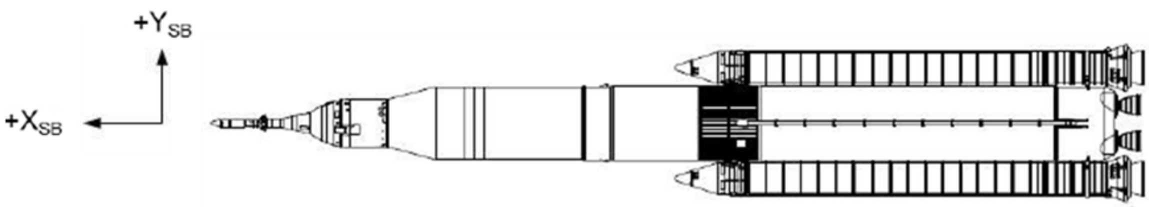

Figure 5: SLS Body Frame

Launch Window Adjustments CHANGO is used to define the reference launch azimuth for 6-DOF simulation. SLS's launch window algorithms affect how CHANGO is used on the vehicle. CHANGO designs the Chi Table using a reference launch azimuth, which is then used in the guidance targets. In the event of a launch slip, defined as a launch either before or after the reference launch time, the Chi Table will be modified. Specifically, the yaw commands changed by a constant bias term as a function of the launch slip.

Off Nominal Usage The Chi Table is designed for use by the nominal vehicle. The loss of a single main engine, called an engine-out, is an important off-nominal condition that SLS must protect for. In the event of an engine-out, SLS's flight software may make two modifications to the Chi Table.

The first modification is to the throttle level. If there is a planned throttle-down to handle maximum dynamic pressure (max-q), the throttle value in the Chi Table will be too low, and the vehicle will needlessly lose performance. In this case, the flight software will override CHANGO's throttle, setting it to a higher level to restore performance while still accounting for the max-q event. Typically the vehicle will simply throttle up to the maximum power level. If the planned throttle-down was particularly low, the new value will be limited to ensure that the thrust does not exceed the desired value.

The second modification is to the pitch. 3-DOF trajectory design work shows that in an engine-out, the ideal Chi Table has a different pitch profile, but is otherwise similar. During the initial 3-DOF studies, the vehicle follows the original Chi Table until the engine-out event, then is allowed to re-optimize the trajectory. After simulating a variety of engine-out times, it was found that a pitch augmentation in the form of a second-order curve, as a function of altitude gained since the engine-out, can capture the general shape of the optimized trajectory for engine-outs at any time during BS flight. A single set of coefficients is stored as an I-Load for engine-out protection, striking a balance between optimizing for all possible engine-out times and minimizing resource use and testing for an unlikely failure mode.

RESULTS

CHANGO was developed in-house at National Aeronautics and Space Administration (NASA) MSFC by the SLS guidance team. It is the official software that will be exercised by the DOLILU team on the DOL to generate the Chi Table for SLS's first stage guidance. In order to deliver this software, a rigorous software verification and validation process was completed prior to officially delivering the tool to Flight Operations Directorate (FOD) at Johnson Space Center (JSC).

Performance

CHANGO has been used for verification of official SLS Monte Carlo analysis. In the typical SLS Monte Carlo setting, CHANGO is run 2000 times with randomized winds and atmospheres, as well as variations in thrust behavior. For every case, CHANGO has shown consistent convergence. Figure 6 shows the number of iterations taken by CHANGO to find a solution under wind and thrust variations for a typical SLS configuration.

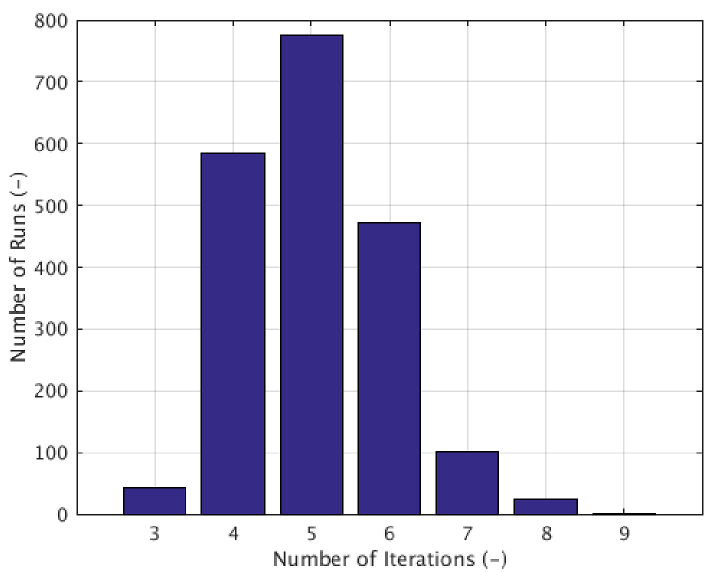

Figure 6: CHANGO iteration count for a typical 2000 seed Monte Carlo simulation.

Verification

An independent verification and validation analysis was performed in which Program to Optimize Simulated Trajectories (POST), a 3-DOF trajectory optimization tool for ascent flight, was run alongside CHANGO for time history comparison. A nominal flight was simulated for both programs using the same Ground Rules and Assumptions (GR&A), including the time to start the gravity turn, the roll program to achieve a heads-down orientation, reference frames, rotation sequences, etc. Both tools generated Chi Tables that contained an attitude described by an NED-to-SLS-Body roll, pitch and yaw angle sequence as function of delta-altitude. Both tools showed an excellent comparison. Figures 7 through 9 show Euler angles (roll, pitch, and yaw) for both CHANGO and POST, along with the difference between the two simulations.

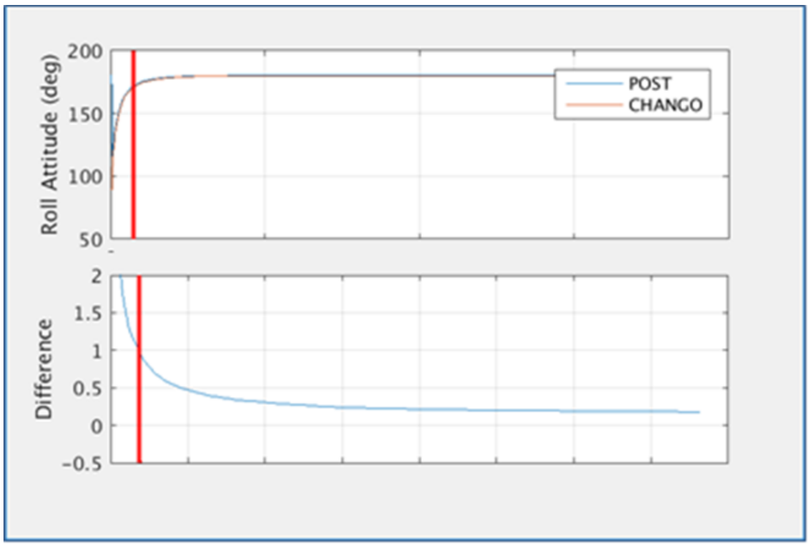

Figure 7: Roll angle and comparison for CHANGO and POST.

Initially, differences between the two simulations are large because the initial attitude has a pitch of 90 degrees. As both CHANGO and POST use a yaw-pitch-roll sequence, this results in undefined roll and yaw angles at a pitch of 90 degrees. Once the pitch angle goes below 90 degrees, the differences in the roll and yaw channels are less than 1 degree, finally converging to 0.25 degrees between the two simulations. The vertical red bar on each plot shows the minimum time before any comparison was made.

Chi Tables from both POST and CHANGO were run in two separate 6-DOF simulations, and an excellent comparison was observed. Figure 10 shows the total angle of attack during BS flight when run in Marshall's Aerospace Vehicle Representation in C (MAVERIC) a 6-DOF simulation tool. Figure 11 shows a similar comparison of Chi Tables from POST and CHANGO when run in a different 6-DOF simulation, Stability Aerospace Vehicle Analysis Tool (SAVANT). This provides independent verification of the MAVERIC results, where both results showed an excellent agreement between the two Chi Tables. The difference plots in this section show that CHANGO is a simple, reliable, and robust tool.

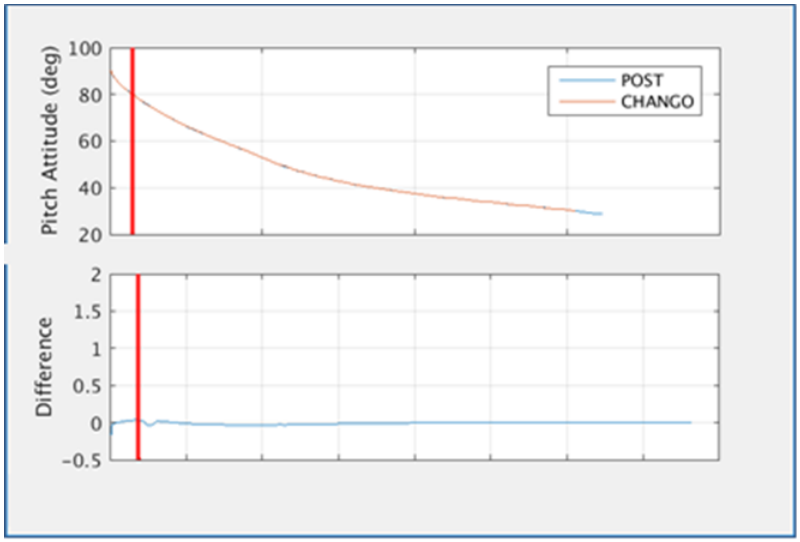

Figure 8: Pitch angle and comparison for CHANGO and POST.

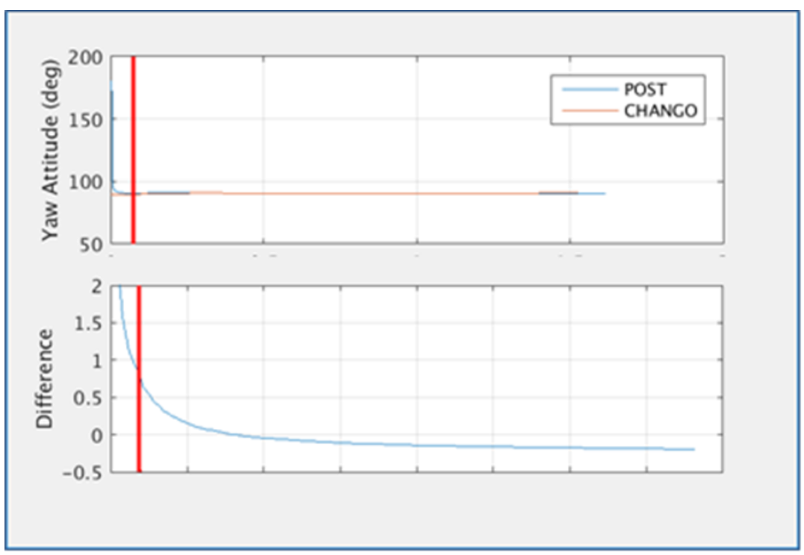

Figure 9: Yaw angle and comparison for CHANGO and POST.

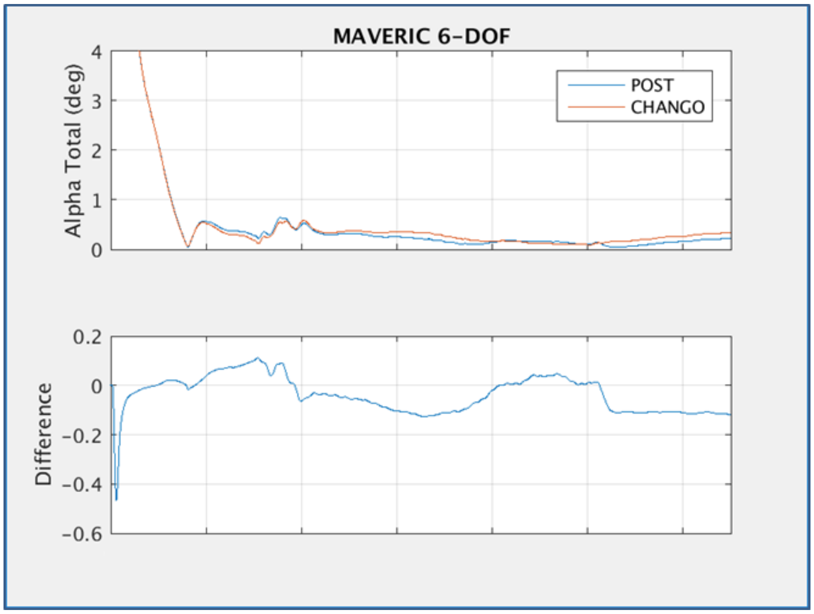

Figure 10: Alpha-total comparison for CHANGO and POST in MAVERIC.

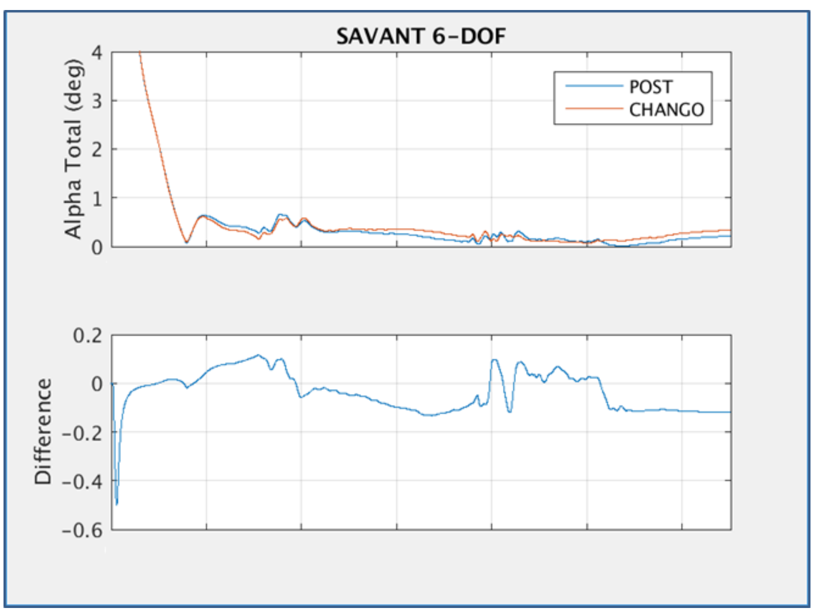

Figure 11: Alpha-total comparison for CHANGO and POST in SAVANT.

CONCLUSION

The SLS Exploration Mission 1 (EM-1) test flight will use open-loop guidance for BS flight. A table of attitude commands as a function of altitude, called the Chi Table, will be loaded onto the flight computers. The Chi Table will be generated by the CHANGO software tool using the measured winds on launch day. CHANGO has been simulated more than 100,000 times in MAVERIC's 6-DOF environment and has demonstrated its reliability and simplicity of usage. CHANGO targets two parameters and uses a parameter optimization technique to find solution which is well documented in published literature. It inherits the wind model, thrust model, mass properties, aerodynamics and gravity models from external sources, which are used as inputs to CHANGO. The GR&A and resulting attitude profile are similar to SLS and its predecessor, the Space Shuttle.

CHANGO has been shown to be robust and reliable. Its output is nearly identical to other industry standard trajectory optimization tools. It has been shown to work in multiple 6-DOF simulations. CHANGO will be used to support future NASA missions beyond EM-1.

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