

CHANGO: A Software Tool for Boost Stage Guidance of the Space Launch System Exploration Mission 1

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The Day of Launch Initiation 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 and sideslip angle corridor in order to keep them within structural load limits. The angle of attack and sideslip angle response to the launch vehicle experiences can vary significantly based upon the winds experienced on the DOL.

SLS Boost Stage flight employs an open-loop guidance scheme through Solid Rocket Booster (SRB) separation. 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 are designed with ground software using winds measured on the DOL with the goal of minimizing angle of attack and sideslip angle, thereby minimizing related ascent integrated vehicle structural loads. The table of Boost Stage attitude commands as a function of altitude gained since launch is called the chi table.

A software tool called CHANGO (Chi Angle Optimizer) designs the Boost Stage chi table which is uploaded to the vehicle's flight computer and used during ascent by the flight software (FSW). The wind and atmospheric conditions are measured prior to launch and pre-processed to become input to the CHANGO software along with a set of parameters developed in advance of the DOL. CHANGO's target set consists of the heading and altitude rate at SRB separation determined well before launch by the Program to Optimize Simulated Trajectories (POST).

CHANGO consists of a simplified three degree-of-freedom (3-DOF) simulation representing the SLS launch configuration. 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 vary the initial pitchover rate and launch azimuth to solve a 2-dimensional minimization problem.

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 a pre-calculated SRB separation time. The sequence of flight events and phases is given in Table 1.

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

CHANGO varies the launch azimuth and initial pitchover rate to minimize the error to the target state. The equation for the cost function and variable definitions are given below.

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

J	Cost Function
ψ_{launch}	Launch Azimuth
$\dot{\theta}_{init}$	Initial Pitchover Rate
$w_{\dot{h}}$	Altitude Rate Cost Weighting
$v_{z,NED,sep}$	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

It is expected that the core engines will be throttled down during certain parts of flight, for example during the time of maximum dynamic pressure (max-q), or shortly before SRB separation. Planned throttle-down events are referred to as throttle buckets. A table of throttle versus time is an input to CHANGO, and used in the 3-DOF simulation.

The SLS FSW only uses the throttle value from the chi table for max-q throttling. Other throttling events are handled by separate algorithms. To accommodate this design, there is an input indicating the end of the max-q throttle bucket. This input is specified as a time, matching the format of the throttle table. CHANGO converts this time to the corresponding altitude when writing the chi table.

To ensure that CHANGO can quickly and reliably generate a chi table on launch day, cost weightings and limits on initial pitchover rate and launch azimuth must be carefully chosen. Figure 1 shows representative solution spaces varying only the relative weights, demonstrating that poor choice of weights can make a given problem difficult for a numerical minimization scheme.

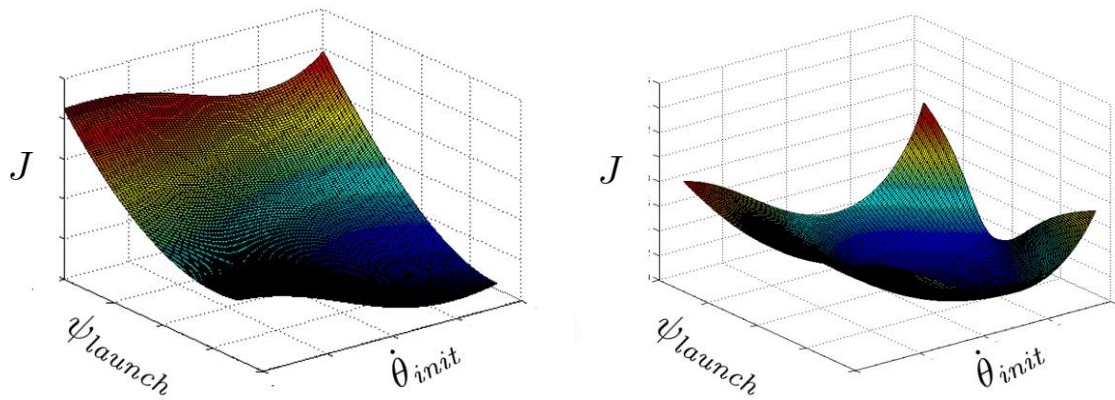


Figure 1. Design space for poorly chosen (Left) and well chosen (Right) weightings

To verify the design, a six degree-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 verified to be within limits, the chi table is then uploaded to the SLS flight computer. The effects on integrated vehicle structural loads due to wind changes during the period between measurement of wind data and launch are accounted for statistically, based on Monte Carlo analysis. 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.

References

Press, William H. *Numerical Recipes in C++: the Art of Scientific Computing*. 2nd ed., Cambridge University Press, 2002.