Space Shuttle Day-of-Launch Trajectory Design and Verification

Operational Concepts

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Objective

- Review Space Shuttle day-of-launch trajectory optimization operational concepts
- Demonstrate how the Day-of-Launch Initialization-Load Update process, or DOLILU, can improve launch probability three-fold
- Offer Shuttle DOLILU methodology for future launch vehicles to build on
Background

- Space Shuttle is not certified to lift-off in all weather conditions
- Vehicle’s trajectory is optimized to that day’s wind and environmental conditions
- Designed trajectory must be rigorously assessed to ensure crew and vehicle safety, while accomplishing mission objectives
- DOLILU process results in a trajectory that protects vehicle structural margins and maximizes performance given other factors
- Similarity will transition to future launch vehicles
Since the environment (wind) changes, the DOLILU design and assessment process is repeated every hour from about launch minus 6 hours to lift-off.
Balloon Systems

- Shuttle makes use of weather balloon data on Day-of-Launch (DOL)
  - Wind speed and direction from 0 to ~58,000 ft.
  - Thermodynamic atmosphere data (temperature, humidity, density) from 0 to 100,000 ft
- Weather Balloons are released about 10 miles from the launch pads by Air Force contractors

High-Res
- GPS tracked, attached to clear Jimsphere
- Measures Wind Speed and Direction

Low-Res
- GPS tracked
- Measures Wind Speed and Direction
- Measures Thermodynamic data

Jimsphere
- Radar tracked, no package
- Measures Wind Speed and Direction
Balloon Timeline

Time to Launch (H:MM)

Balloon Rise
Design, High-Q & Roll Assessments
High-Q & Roll Assessments
Roll Assessment

6:00  5:30  5:00  4:30  4:00  3:30  3:00  2:30  2:00  1:30  1:00  0:30  0:00

L-6:15
L-4:50
L-3:45 Contingency
L-3:35
L-2:20
L-1:25 Contingency
L-1:08
L-0:50 Contingency
DOLILU Design

• Shuttle first-stage is “Open-loop”; “Closed-loop” second-stage will fly itself to a target

• DOLILU software optimizes the first-stage trajectory in order to minimize vehicle structural loads and maximize abort capability
  – Targets angle of attack (Alpha), angle of sideslip (Beta), and dynamic pressure (Qbar)
  – Targets staging conditions: altitude rate and optimum azimuth

• Design consists of two elements
  – “Shaper” software uses a low pass filtered wind to obtain
    • Initial pitch and yaw steering commands
    • Throttle up and down table
    • On-board wind table
  – “Biaser” software uses the actual wind to fine-tune the pitch and yaw command by centering the wind-induced Alpha and Beta spikes
Example Wind

In-Plane Wind

Out-of-Plane Wind

Measured Wind

“Shaper” Filtered Wind

“Weather” Filtered Wind

Measured Wind
Resultant Alpha, Beta, Qbar

In-Plane Wind & Resultant Alpha

Out-of-Plane Wind & Resultant Beta

Measured Wind (Different Axis)

Alpha Miss

Alpha & Alpha Target

Beta

Altitude

0
60,000 ft

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Now with a wind 3½ hours later

**In-Plane Wind**
Resultant Alpha

**Out-of-Plane Wind**
Resultant Beta

Non-optimized Alpha

Non-optimized Beta

Design wind

Get this wind

United Space Alliance
Constraints: Alpha/Beta/Qbar

• “Q-planes” constrain the flight envelope to alleviate structural concerns

• Each trajectory point is dispersed by the Root Sum Square of wind persistence, flight derived system dispersions, and atmosphere persistence (Qbar only)

• Limits are reduced for engine out and gust effects
Constraints: Structural Loads and Trajectory

- **Structural Load Indicators (SLI)** protect critical load points on the vehicle
  - Each SLI is dispersed for the Root Sum Square of wind persistence, system dispersions, and gust

- **Trajectory System Rules** protect staging limits, pitch/yaw/roll rates, Range Safety limits, and throttle limits

- **Trajectory Experience Rules** assess attitude errors, angular accelerations, SSME and SRB commanded positions, and on-board wind table
Wind Persistence

- Wind will continue to change after the final assessment
- Wind Persistence statistically accounts for the change on a constraint caused by the wind
- Shuttle uses a statistical distribution using a minimum margin method
MSFC Wind-Only Assessments

- Wind Shear Limits protect the Orbiter Tail
- Measurement Reasonableness Assessment ensures the balloon represents the current environment
- Wind Change Redline Assessment ensures that no late-in-the-count large shift in the wind might invalidate the design:

In-Plane Wind Example

Wind Change Redline Assessment
Ascent Performance Margin (APM)

- APM is remaining propellant in excess of that required to reach orbit
- DOL performance uncertainties influence pre-launch payload manifesting
- DOLILIU designs tends to normalize APM which reduces in-flight dispersion protection
Launch Probability

- With the DOLILU process, the probability of launch increases over an average monthly wind design.
- For example, what if Shuttle did not redesign on launch day, but used the monthly average wind/atmos design?
  - In February, the launch probability would be reduced from 90% to ~30%.
Summary

• Day-of-launch design and assessment is important because it increases the probability of launch

• Winds always change and the Space Shuttle must have some means to account for those changes
  – Space Shuttle trajectory is redesigned on day-of-launch to minimize loads while maximizing performance
  – Many safety improvements and assessment refinements have been made

• The Shuttle concepts of operation can serve as a good basis for future NASA vehicles