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
DOLILU Overview

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

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

Time to Launch (H:MM)

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

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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

Measured Wind

“Shaper” Filtered Wind

IN-PLANE WIND SPEED (FPS)
FLIGHT AZIMUTH - 43 DEG

OUT-OF-PLANE WIND SPEED (FPS)
FLIGHT AZIMUTH - 43 DEG

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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

0 Altitude 60,000 ft

0 Altitude 60,000 ft

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Now with a wind 3 ½ hours later

**In-Plane Wind**
Resultant Alpha

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

- Design wind
- Get this wind
- Non-optimized Alpha
- Non-optimized Beta
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

![Alpha-Beta Slice or Plane]

![Alpha-Beta varies with Mach]
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

![Graph showing wind persistence with yellow and red lines.](image-url)
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](image1)

![Wind Change Redline Assessment](image2)

From D. Pupel, 8/29/08 Presentation
Ascent Performance Margin (APM)

- APM is remaining propellant in excess of that required to reach orbit
- DOL performance uncertainties influence pre-launch payload manifesting
- DOLILU designs tend 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