



Jet Propulsion Laboratory
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Atmosphere Modeling and Performance Sensitivity for the Mars Sample Return Earth Entry System

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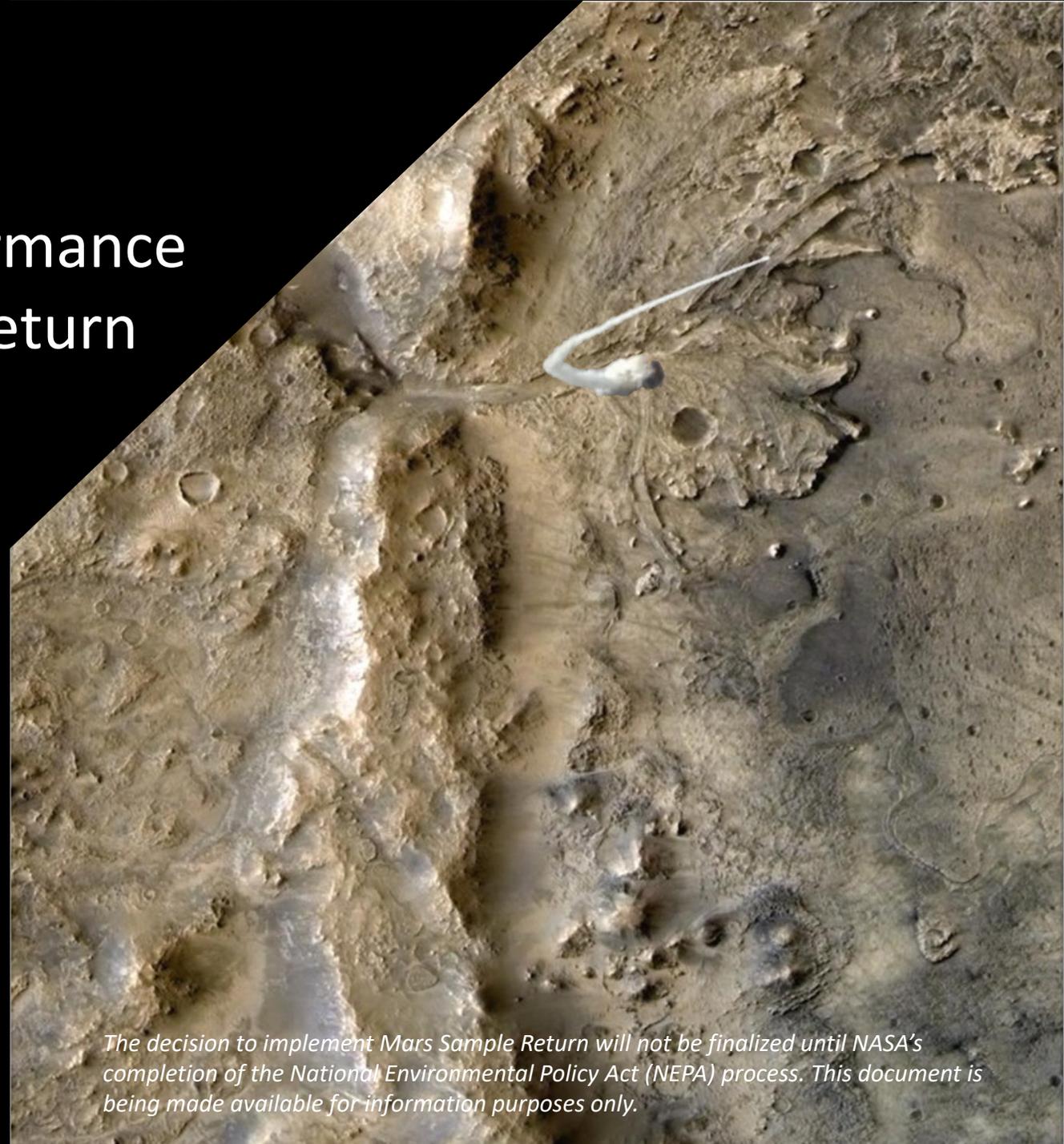
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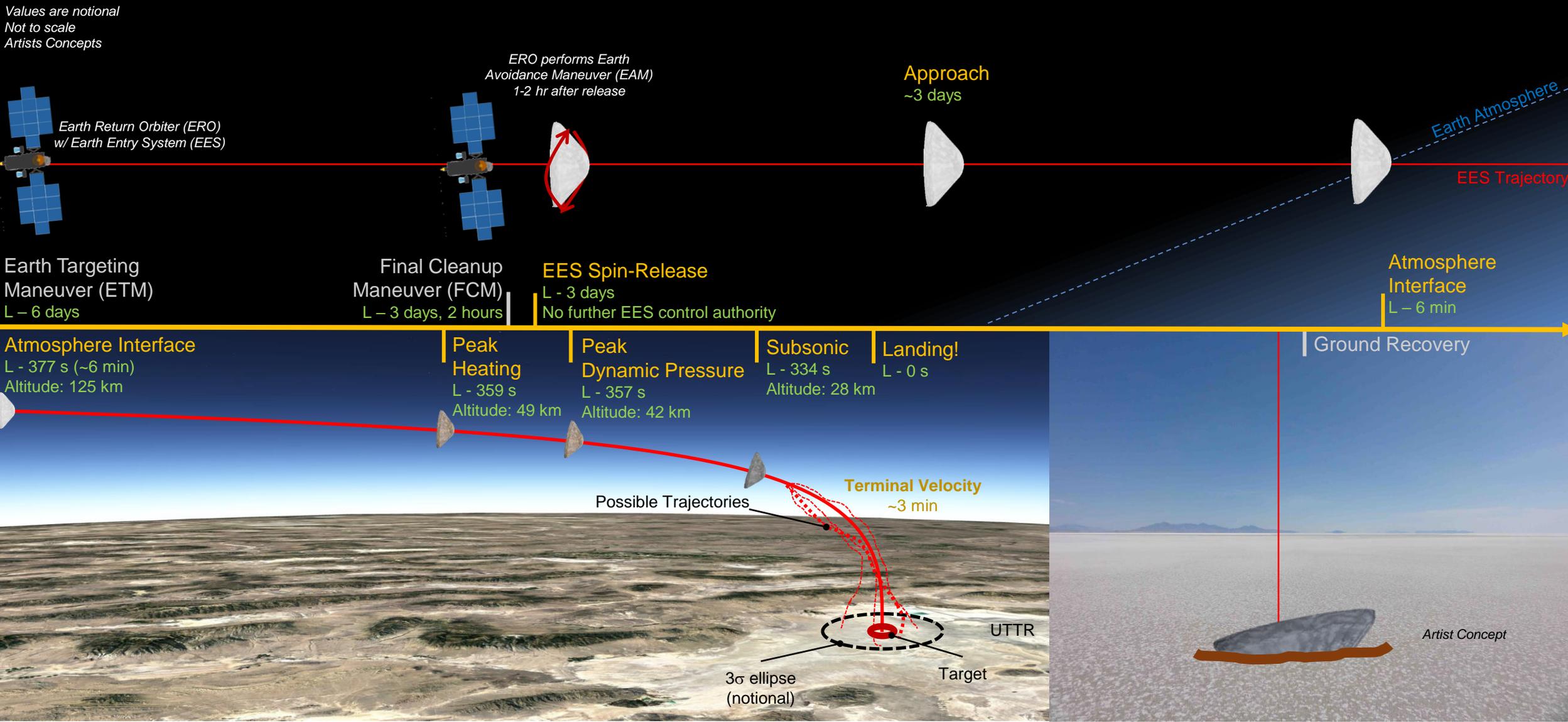


The decision to implement Mars Sample Return will not be finalized until NASA's completion of the National Environmental Policy Act (NEPA) process. This document is being made available for information purposes only.

Approach, Entry, Descent, and Landing (AEDL) Phase Timeline



MARS SAMPLE RETURN



Pre-Decisional Information – For Planning and Discussion Purposes Only



AEDL Earth Atmosphere Modeling Background

- **The Earth Entry System (EES) is designed for maximum reliability in order to minimize the probability of loss of sample containment.**
 - No mechanisms once released from ERO/CCRS, no avionics or active guidance, no parachute
 - Planned landing in soft playa of Utah Test and Training Range (UTTR)
- **The EES would be separated from the ERO/CCRS much earlier than past Earth sample return missions, reducing opportunities to re-target prior to separation based on a weather forecast.**
 - EES separation is on the order of **3 days** prior to Earth entry.
 - Stardust, Genesis, and OSIRIS-REx separation is on the order of **4 hours** prior to Earth entry.

Earth’s atmosphere characteristics, wind in particular, drive key AEDL performance metrics:

- Aerodynamic stability from low supersonic speeds through terminal velocity
- Landing velocity and attitude, which drives landing loads
- Landing “footprint”, which drives the number of surface hazards at UTTR that would be removed

} **Wind Structure**



Wind Distribution

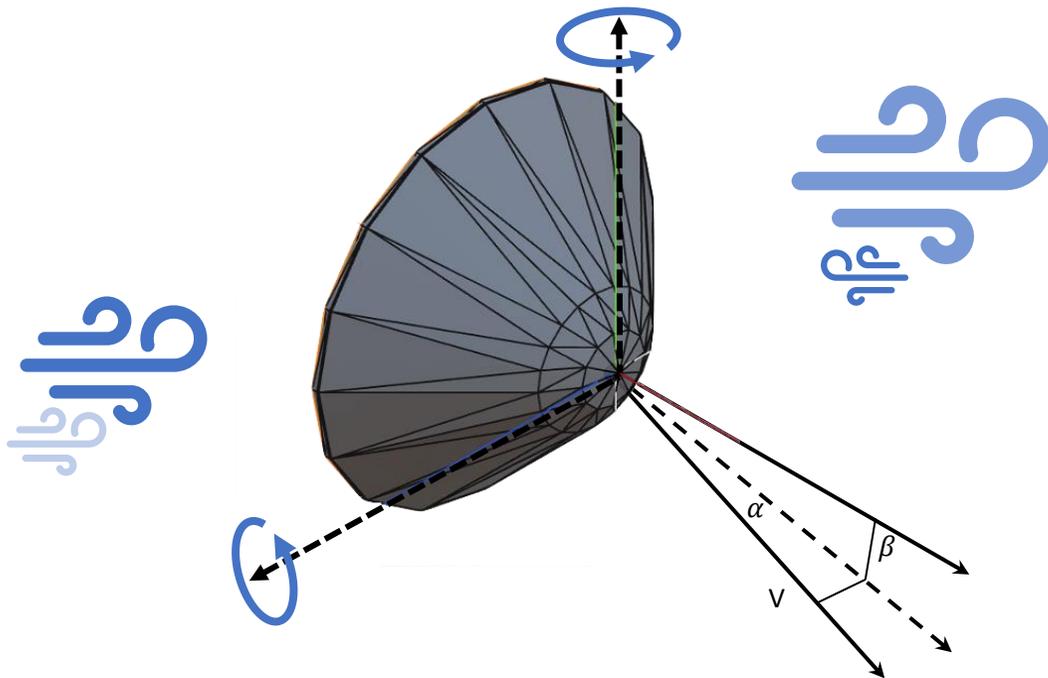
Atmosphere Modeling and Key Metrics Overview



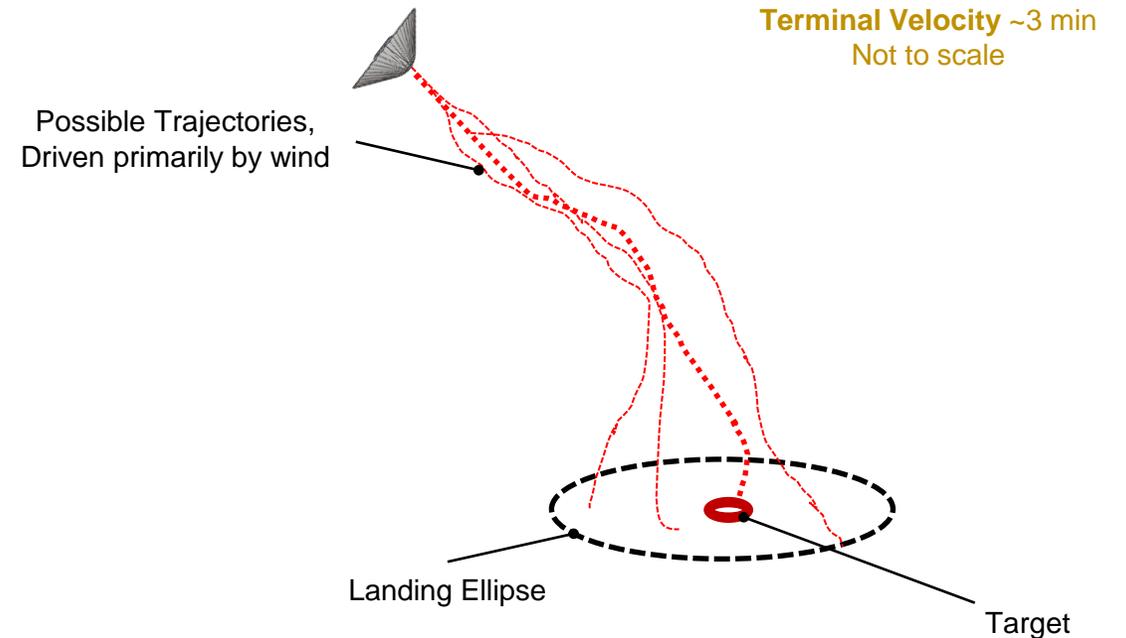
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Initially, atmosphere modeling was conducted solely using EarthGRAM. After collaborating with the National Center for Atmospheric Research, the team improved characterization of winds, understanding of key AEDL performance metrics, and developed new techniques for atmosphere modeling.

Wind Structure → Dynamic Stability



Wind Distribution → Landing Footprint





Wind Structure: Characterization for Dynamic Stability

To quantify small- and large-scale winds, the team developed and iterated metrics of Turbulent Kinetic Energy (TKE) and Vertical Wind Shear. Applied to wind profiles, these analyses methods enabled the team to assess the structure and distribution of small-scale perturbations independent of flight mechanics simulations.

Wind structure metrics improved AEDL comprehension of how wind structure and shear influences EES dynamics.

Turbulent Kinetic Energy

$$KE = \frac{1}{2}(u'^2 + v'^2) \quad \left. \vphantom{KE} \right\} \text{Horizontal components only}$$

$$KE_{small} : \left. \begin{aligned} v' &= \int_0^H (v(z) - \bar{v}) dz \text{ and} \\ u' &= \int_0^H (u(z) - \bar{u}) dz \end{aligned} \right\} \text{Small-scale perturbation}$$

$$KE_{large} : v' = \int_0^H (v(z)) dz \text{ and } u' = \int_0^H (u(z)) dz$$

Vertical Wind Shear

$$W_s = \sqrt{\left(\frac{\partial u}{\partial z}\right)^2 + \left(\frac{\partial v}{\partial z}\right)^2}$$

The altitude window, denoted as H in TKE, can be adjusted based on the scale at which the entry vehicle responds to small-scale turbulence. In the following equations, u = north-south winds, v = east-west winds, w = vertical winds, and z = altitude.

Wind Structure: Dynamic Stability Performance

Utilizing the defined KE_{small} or small-scale perturbation calculations from TKE equations, example flight mechanics (using 6-DOF POST2 and DSENGS simulations) results were produced. High KE_{small} corresponds to a value representative of EarthGRAM profiles, while Low KE_{small} were smoothed profiles similar to those of raw balloon radiosondes (with no added turbulence).

AEDL Metrics @ Impact	Type	Percent Change, Low KE_{small} to High KE_{small}
Stable Off-Vertical Angle @ Impact, High-End	99.87%-tile	+34.27%
AEDL Metrics @ Mach Intervals	Type	
Peak Total Angle of Attack, Mach 1.3 to 1	99.87%-tile	+66.65%
Peak Total Angle of Attack, Mach 1 to 0.85	99.87%-tile	+73.103%
Peak Total Angle of Attack, Mach 0.85 to 0.6	99.87%-tile	+71.40%
Peak Total Angle of Attack, Mach 0.6 to 0.35	99.87%-tile	+63.94%

- As expected, increasing small-scale perturbations (Low to High KE_{small}) influences dynamic stability by increasing angle of attack rates.
- The KE_{small} metric enables the team to run sensitivities and better understand coupling effects (with aerodynamic, mass properties, release states, etc.) as it relates to dynamic stability performance during AEDL.

Table 1. Landing states and Dynamic stability metrics sensitivity to KE_{small}

Wind Distribution: Characterization for Landing Footprint

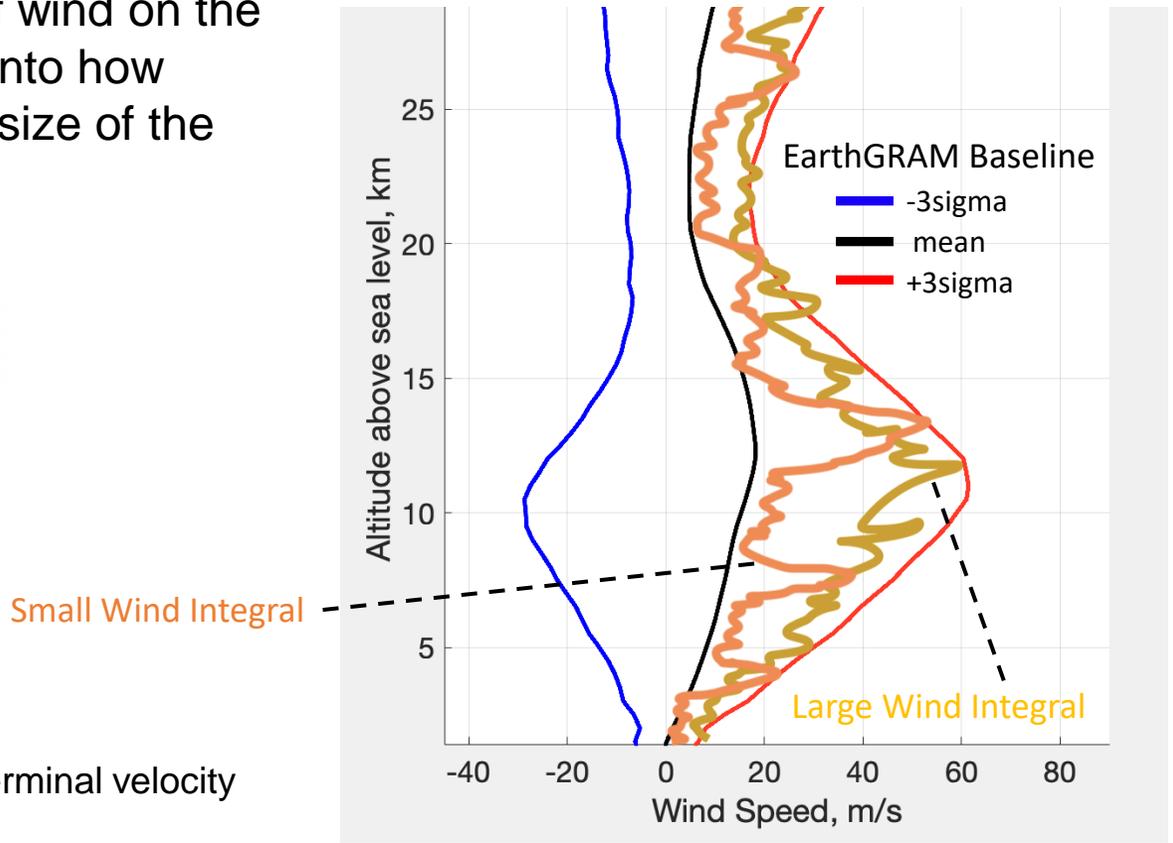
The AEDL team desired a methodology to quantify wind distribution or drift independent of flight mechanics simulation results. Investigation into a metric was influenced by lessons learned of high-wind scenario during 2006 Stardust EDL.

The wind integral metric captures the cumulative impact of wind on the EES's displacement distance, providing valuable insights into how wind factors (or the nature of different datasets) affect the size of the landing footprint ellipse in flight mechanics results.

$$\text{Wind Integral (by component)} = \frac{1}{V_z} \int_{H_1}^{H_2} u dz, \quad \frac{1}{V_z} \int_{H_1}^{H_2} v dz$$

u = north-south winds, v = east-west winds, V_z = vehicle vertical velocity (terminal velocity estimation), z = altitude, and $H_{1,2}$ = altitude range to calculate the integral.

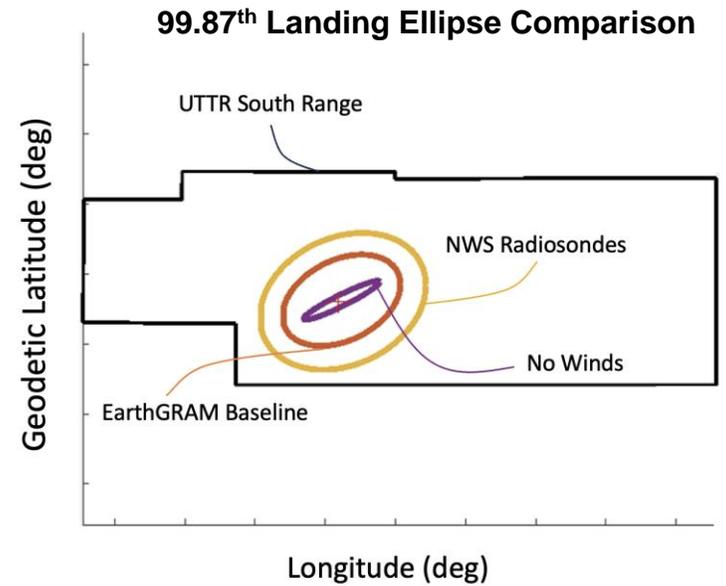
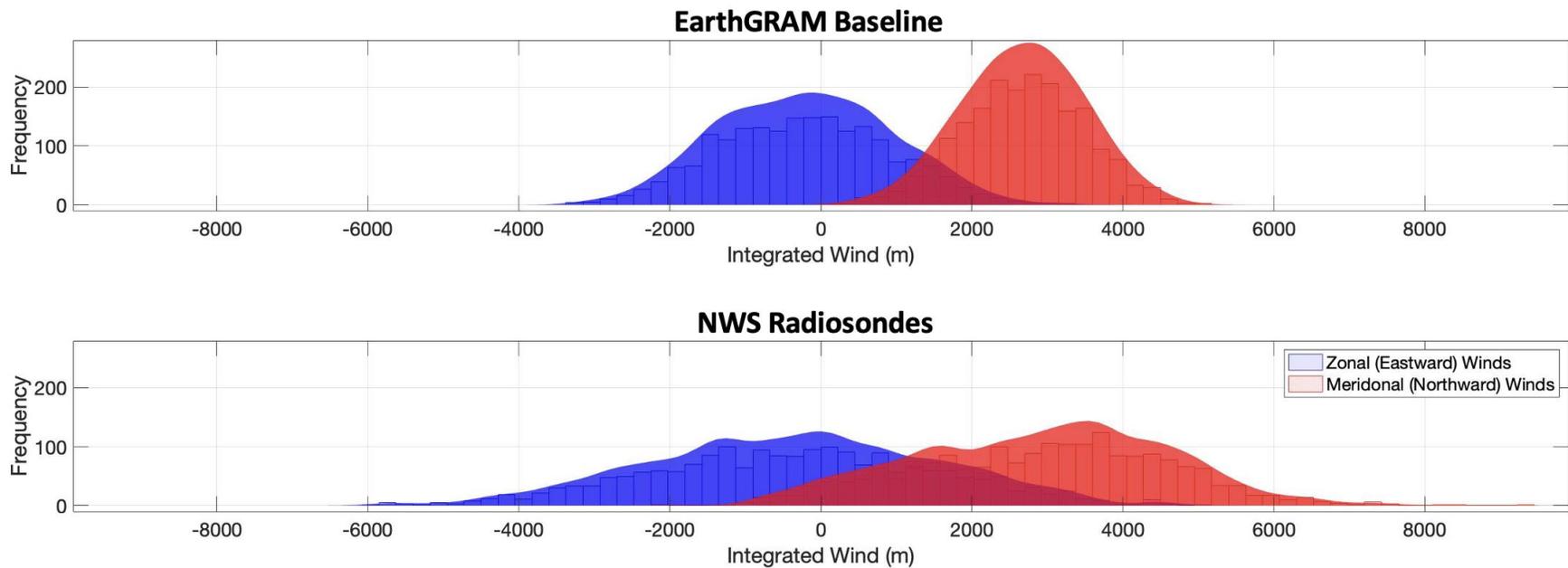
Wind Integral Example



Wind Distribution: Landing Footprint Performance

Using Wind integrals, the team compared an EarthGRAM baseline dataset against National Weather Service (NWS) balloon radiosondes at similar conditions. NWS radiosondes dataset had a larger integrated wind distribution, meaning that profiles were more consistently exhibiting winds at large magnitudes.

- Flight mechanics (POST2 and DSENDS simulations) Monte Carlo results visualize the performance results of the wind distribution, larger wind integral values resulting in increased landing ellipse area.
- This analysis enabled the team to better understand changes in landing ellipse (not apparent using direct comparison) and improved predicted landing ellipse fidelity for AEDL performance.



Summary

- Enabled a deeper understanding of EDL flight mechanics metrics of dynamic stability, landing ellipse, and horizontal velocity.
- Enhanced atmospheric modeling capabilities, along with more accurate predictions of flight mechanics, has contributed to a more robust design of the EES.
- Analyses such as TKE, vertical wind shear, or integrated wind have proven to be critical in revealing intricate details about wind profiles that were previously unexplored.

Future Work

- Utilization of higher fidelity atmosphere data within model through development of Custom Atmosphere Model (CAM) enabling merging of datasets and engineering models over specific regions of interest.
- Integration of atmosphere metrics of TKE, vertical wind shear, or integrated wind within flight mechanics simulation scorecard process for more efficient investigation.



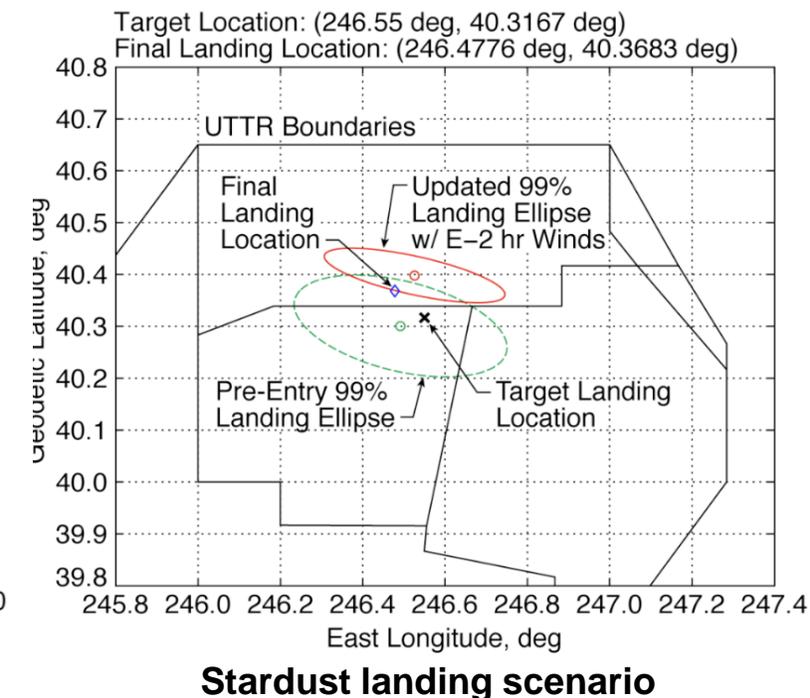
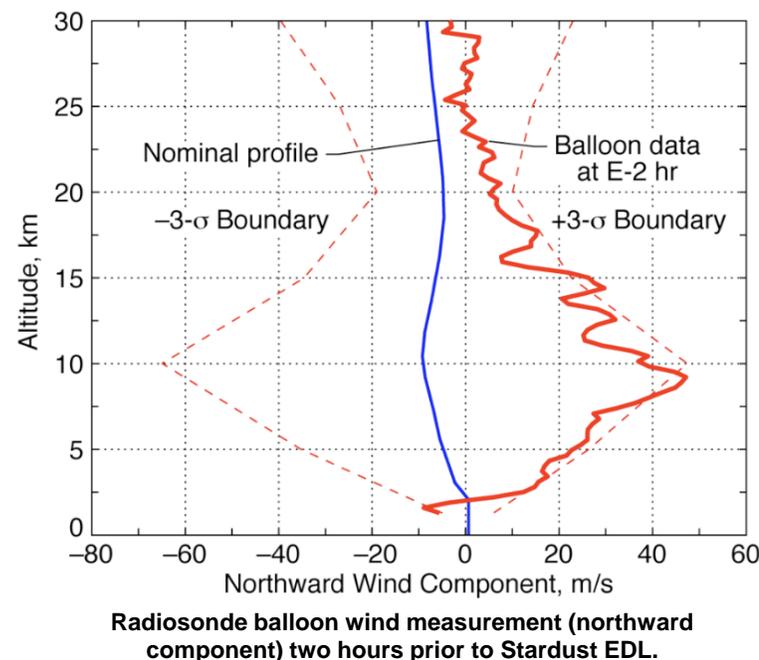
Questions & Comments?

Stardust Sample Return Capsule Lesson Learned

- A high southerly wind developed prior to Stardust entry on January 15, 2006.
- This profile still was within the +3-sigma boundary from the Earth-GRAM 95 model, but the predicted landing position was outside the planned +3-sigma ellipse.

Why?

- The wind reduced prior to touchdown and the vehicle landed within the original planned ellipse.



Reference: Desai and Qualls, AIAA-2008-1198

“...compounded with an anomalous scenario where some of the navigation criteria might have been borderline, the failure to acknowledge the effect of the wind could have led to approval for entry when indeed it should not have been”
–D-37294 Sample Return Primer, Earth Targeting and Entry Safety Plan Volume 2: Decision Criteria Lessons Learned

The AEDL Phase is assessing additional wind data sources and wind model implementations in order to account for any plausible wind scenario.

Earth-GRAM Background and AEDL Phase Implementation



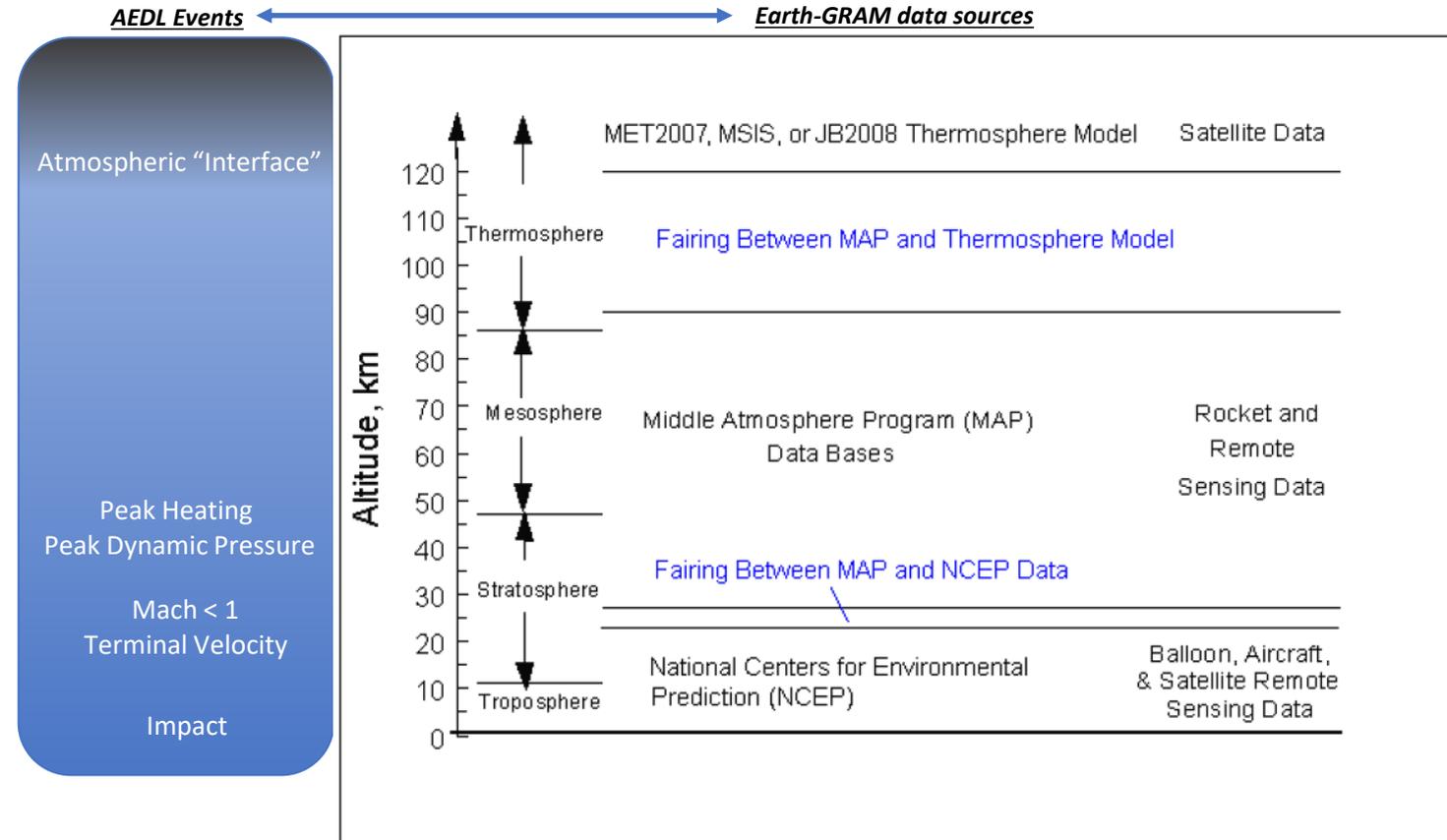
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• Earth-GRAM Background and Overview

- The NASA Global Reference Atmospheric Model (GRAM) was originally developed in response to the need for a design reference atmosphere that provides complete global geographical variability, altitude coverage (surface to orbital altitudes), and seasonal and monthly variability of the thermodynamic variables and wind components.
- A unique feature of GRAM is that, in addition to providing the geographical, height, and monthly variation of the mean atmospheric state, it includes the ability to simulate spatial and temporal perturbations in these atmospheric parameters

• Earth-GRAM Basic Description

- Earth-GRAM is a collection of empirically based models that represent different altitude ranges and the geographical and temporal variations within these altitude ranges.
- A perturbation model then computes variations about these means if dispersions are desired.



Schematic summary of the atmospheric regions in the Earth-GRAM program, sources for the model, and data on which the mean monthly Earth-GRAM values are based.
Source: NASA/TM-20210022157

The AEDL Phase Earth-GRAM implementation integrates several atmospheric data sets and models including the 2019 Dugway Proving Ground Range Reference Atmosphere.