



Reconstruction of the Stardust Entry

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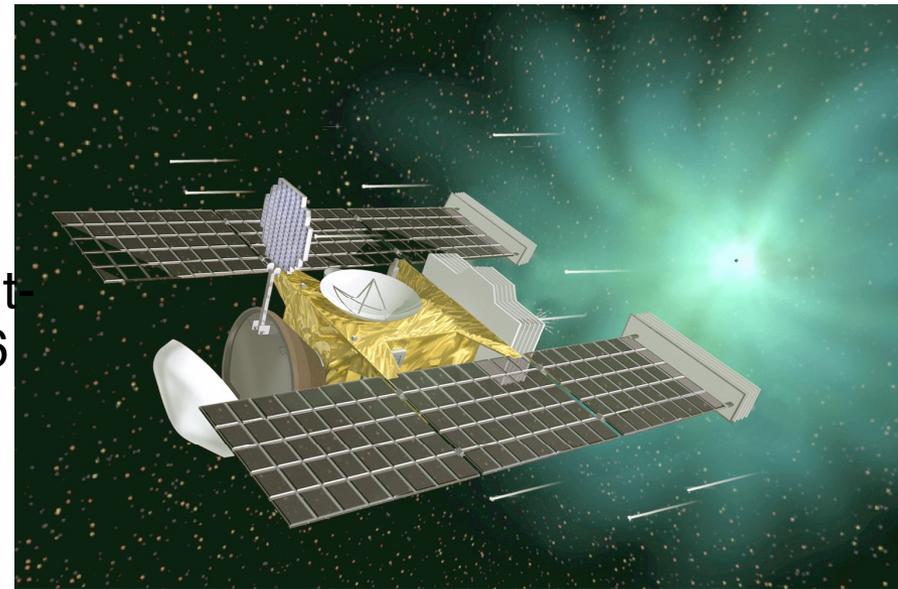
Bordeaux, France



Mission Background

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- Stardust was the Forth of NASA's Discovery Class Mission
 - Launched February 7, 1999
 - Return cometary samples from the comet Wild-2, along with interstellar particles
 - First mission to return samples from a comet
- Maneuver and targeting procedures placed capsule on desired entry flight path on morning of January 15, 2006 at 09:56:42.3 UTC
 - Successfully landed under parachute at Utah Test and Training Range (UTTR)
 - First direct entry from an interplanetary trajectory to fly & land over continental US
- Overview of the entry reconstruction to assess comparison between pre-entry prediction and actual flight

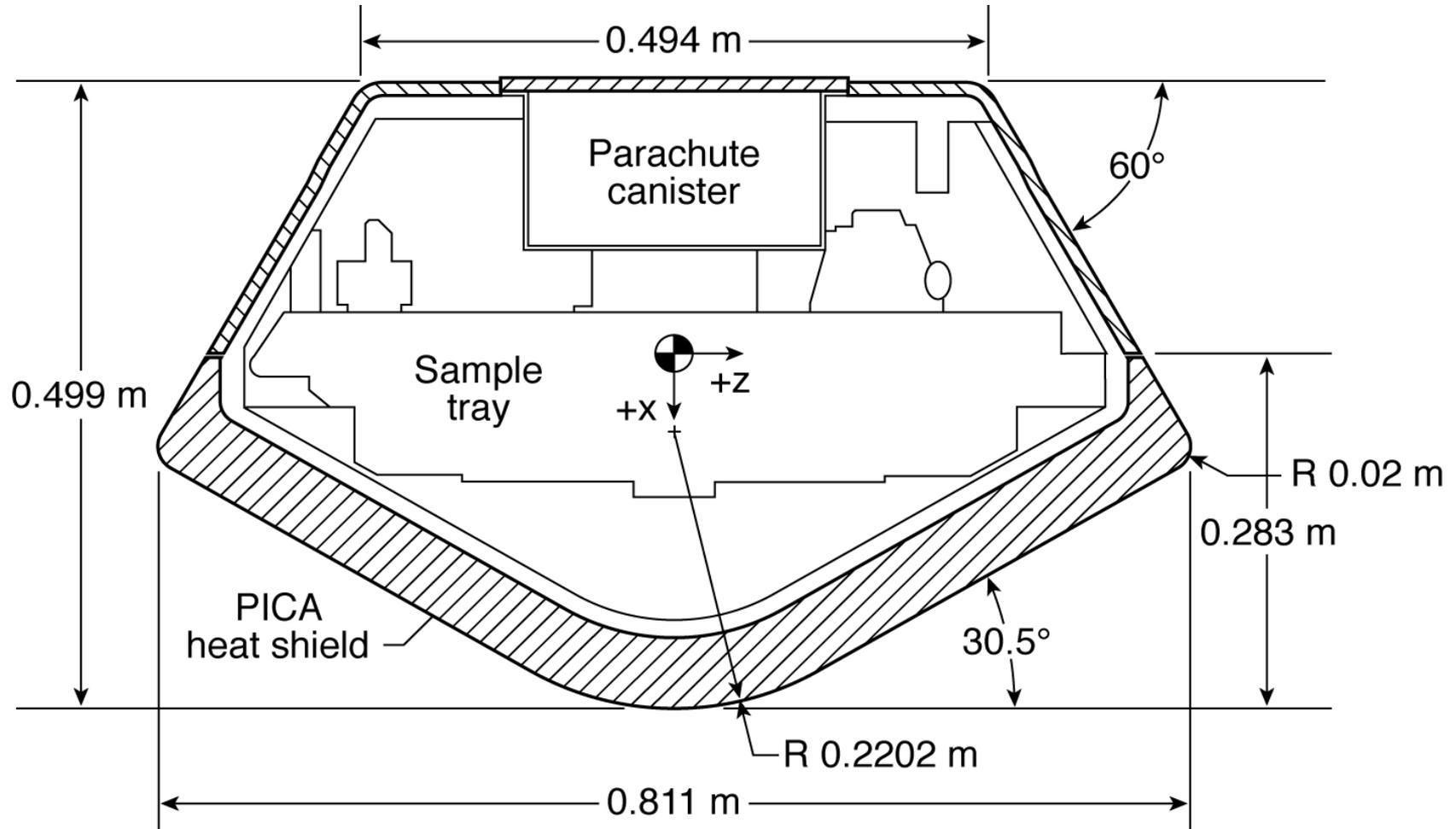




Stardust Sample Return Capsule Configuration

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Capsule mass = 45.8 kg





Nominal Stardust Capsule Entry Sequence

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Entry $V_I = 12.9$ km/s

Entry $\gamma_I = -8.2$ deg

Spin rate = 13.5 rpm

Capsule release

Atmospheric interface

Free molecular flow

Transitional flow

Hypersonic

Ballistic Entry (i.e., no active guidance or control systems)

Supersonic

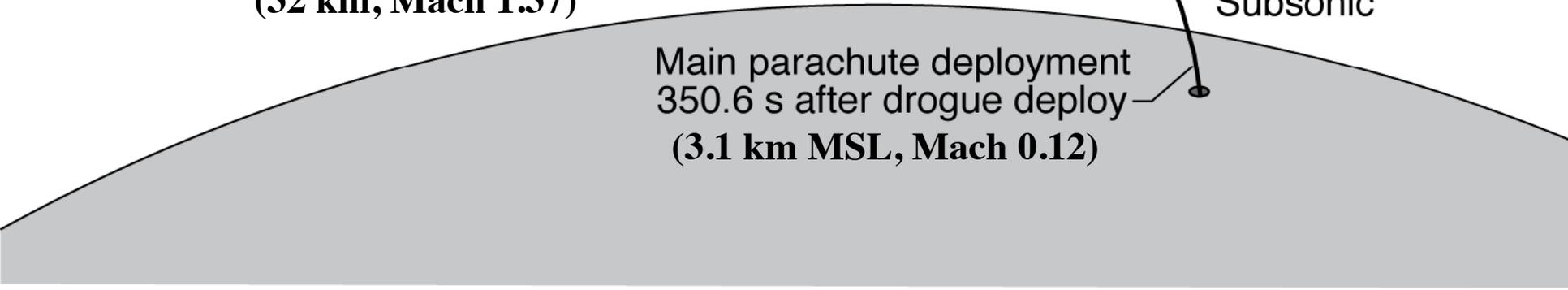
G-switch triggered at 3g's

Transonic

Drogue parachute deployment 15.04 s after 3g's
(32 km, Mach 1.37)

Subsonic

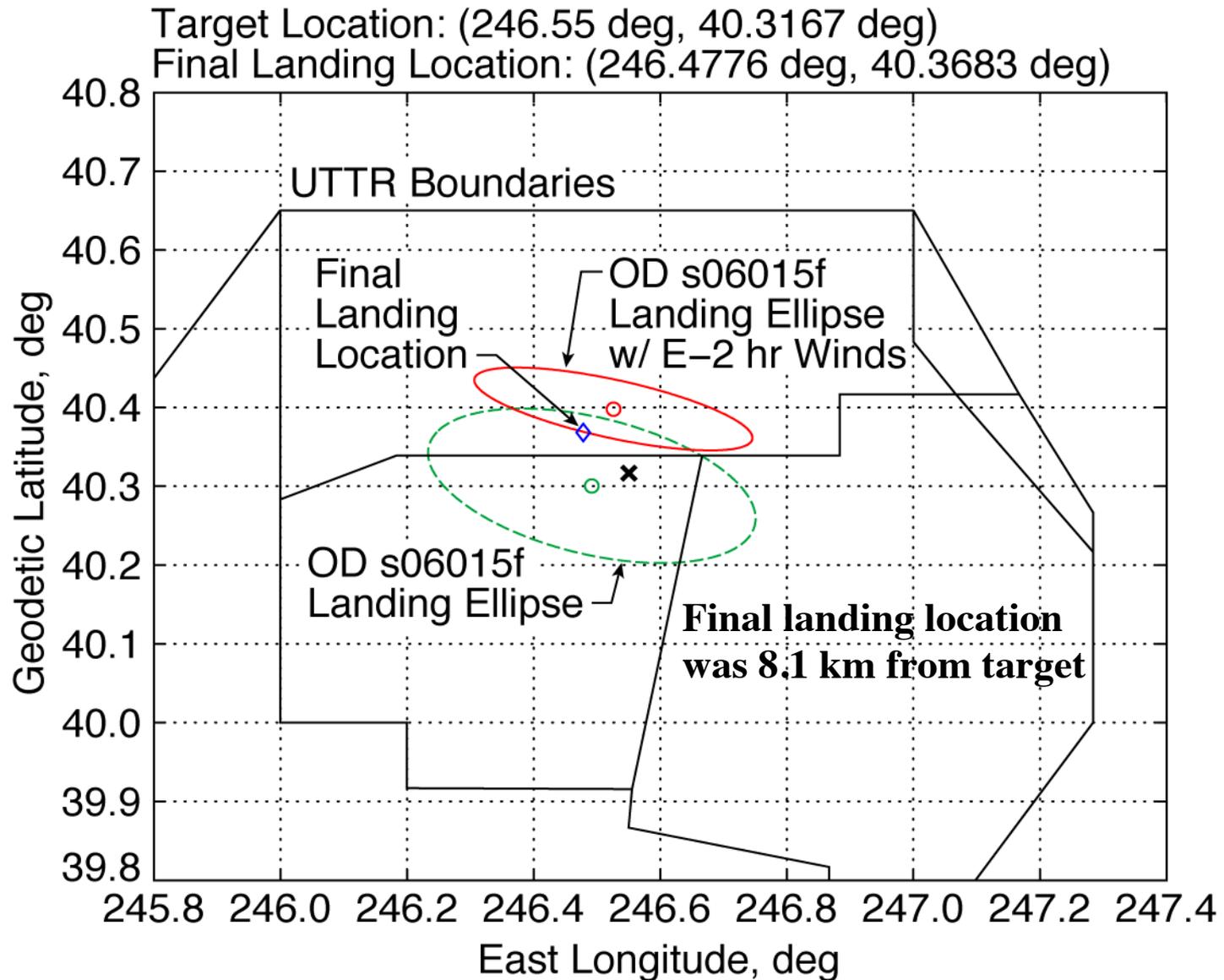
Main parachute deployment 350.6 s after drogue deployment
(3.1 km MSL, Mach 0.12)





Final Capsule Landing Location

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Stardust Reconstruction Effort

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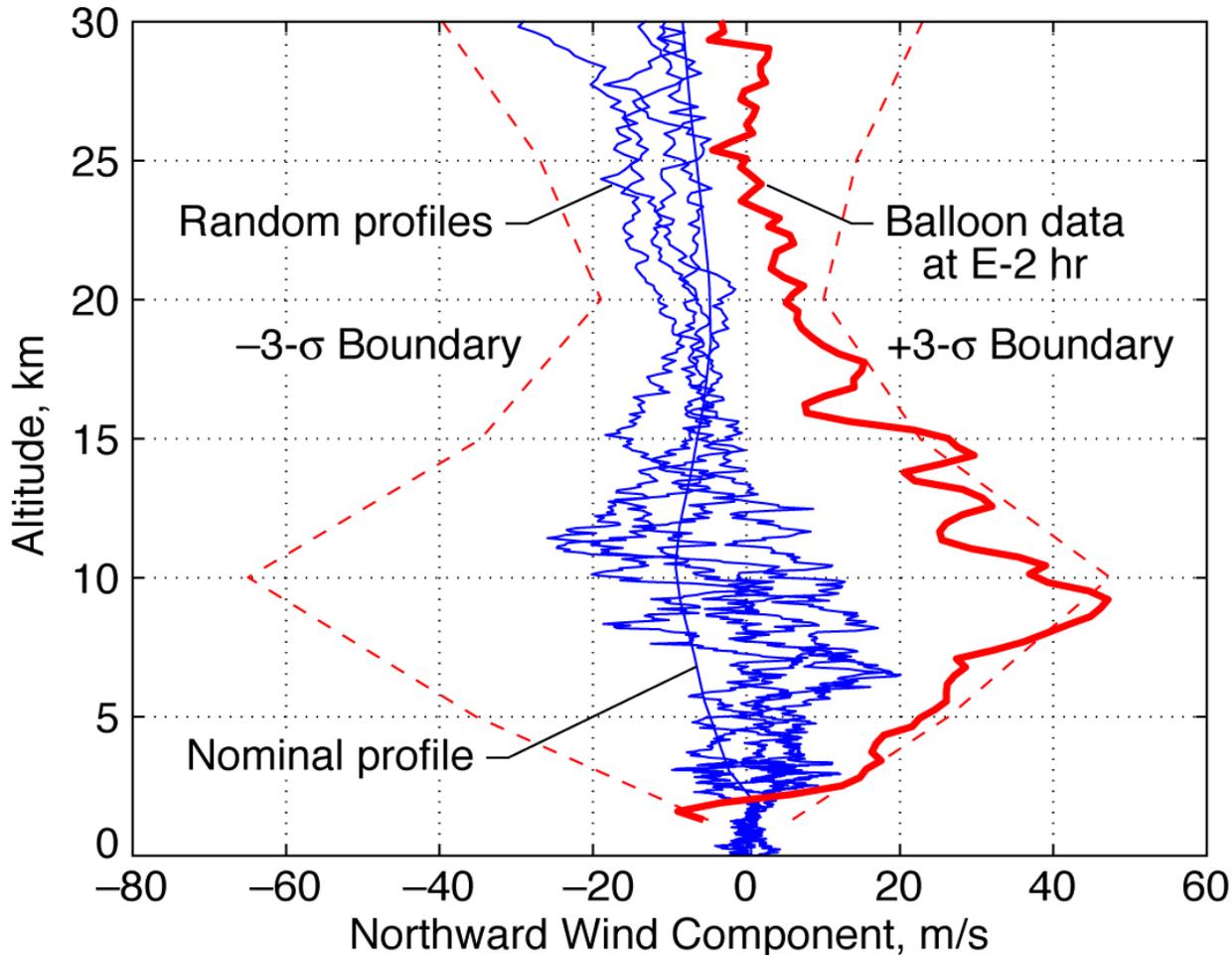
- Stardust capsule landed very close to the desired target
 - Understanding hypersonic flight performance is of great interest
 - Specifically, assessing how the pre-entry predictions of flight dynamics, aerodynamics, and aerothermodynamics
- Only limited data exists to perform reconstruction
 - No onboard sensors on capsule
 - Only available data source is from UTTR radar tracking stations
 - Video and tracking data
 - Balloon measurement of atmospheric properties up to 35 km two hours prior to entry



Northward Wind Component Comparison to GRAM-95 Model

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- Sustained wind to the North observed (~40 m/s at 10 km)
 - Blizzard moving through Utah during landing
- Corresponds to 3- σ profile from GRAM-95 variations

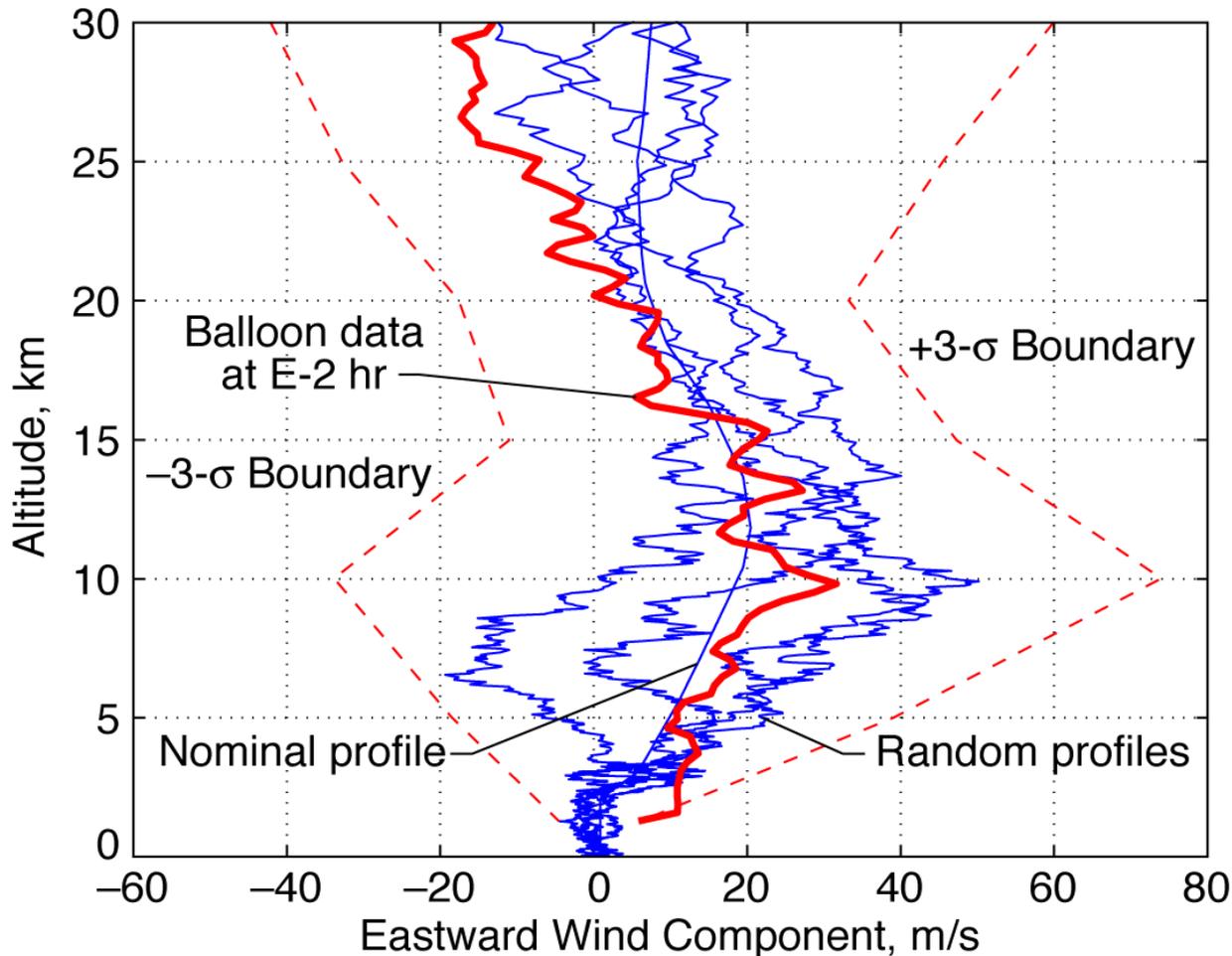




Eastward Wind Component Comparison to GRAM-95 Model

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- Eastward wind observed was a little larger than nominal from GRAM-95





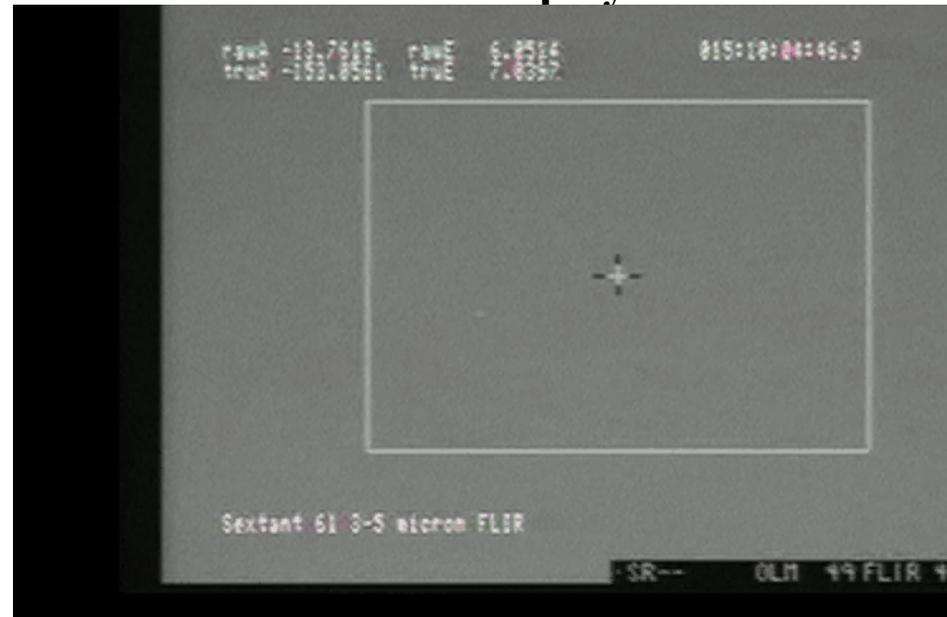
Inferred Video of Stardust Entry

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Drogue Deployment

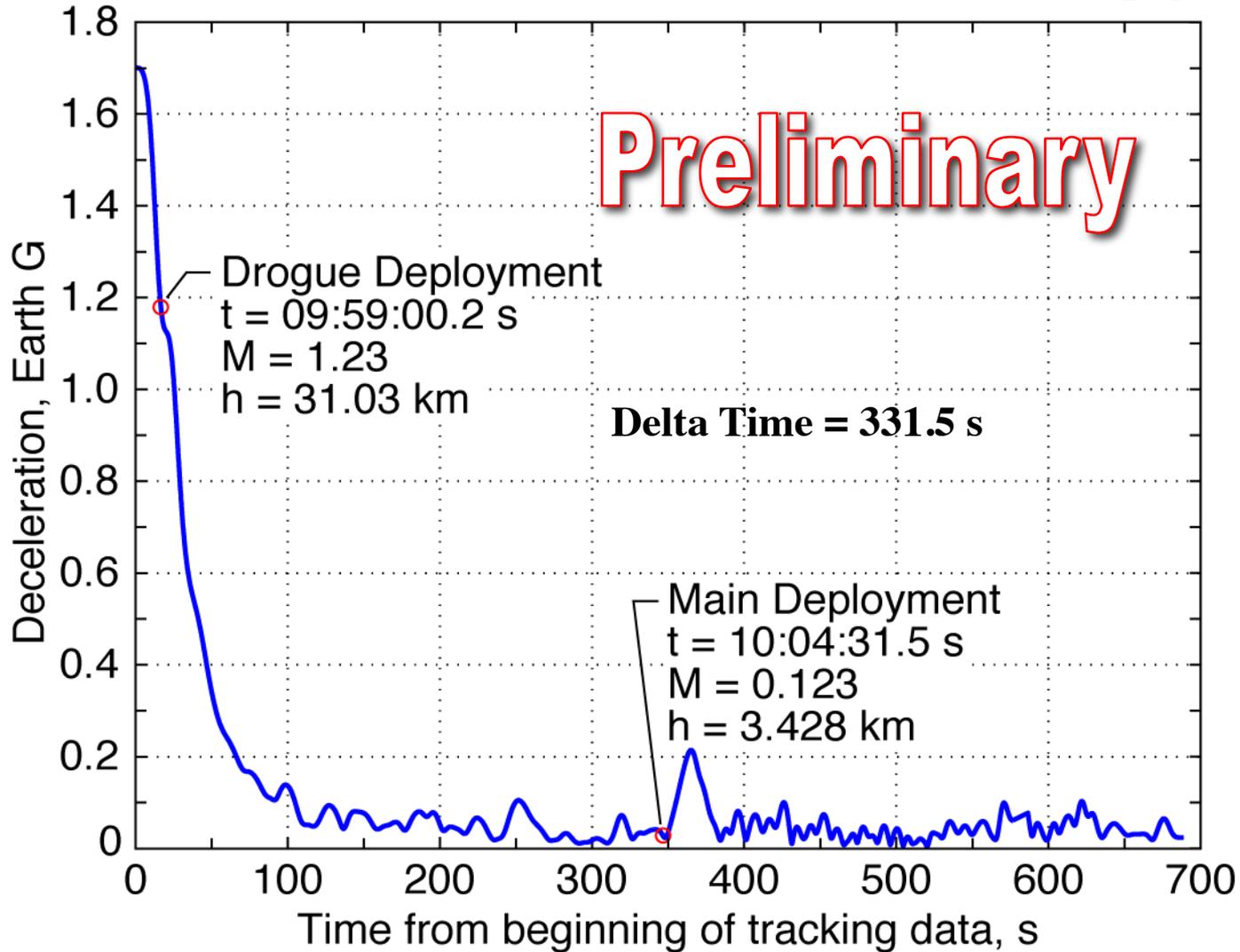
Main Deployment





Deceleration Profile from UTTR Tracking Data

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- Time between drogue and main deployment < timer setting of 350.6 s
Assessment underway to determine if main deployed on backup baroswitch.



Trajectory Reconstruction

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- Since there was no onboard sensor data, a “traditional” trajectory reconstruction cannot be performed
 - Therefore, a Best Estimated Trajectory (BET) is calculated
- For hypersonic flight, only two data sources were available
 - Final Navigation entry state at atmospheric interface
 - Latitude and longitude data from UTTR radar tracking stations at time of drogue deployment (pre-entry prediction of 133 s from entry)
 - Tracking data indicates drogue deployment time at 137.9 s from entry
 - Actual deployment time 4.9 s later than predicted (within pre-entry Monte Carlo dispersion prediction of ± 7.4 s)
- With, confidence in these two endpoints a hypersonic trajectory can be calculated using the pre-entry simulation



Trajectory Reconstruction (cont' d)

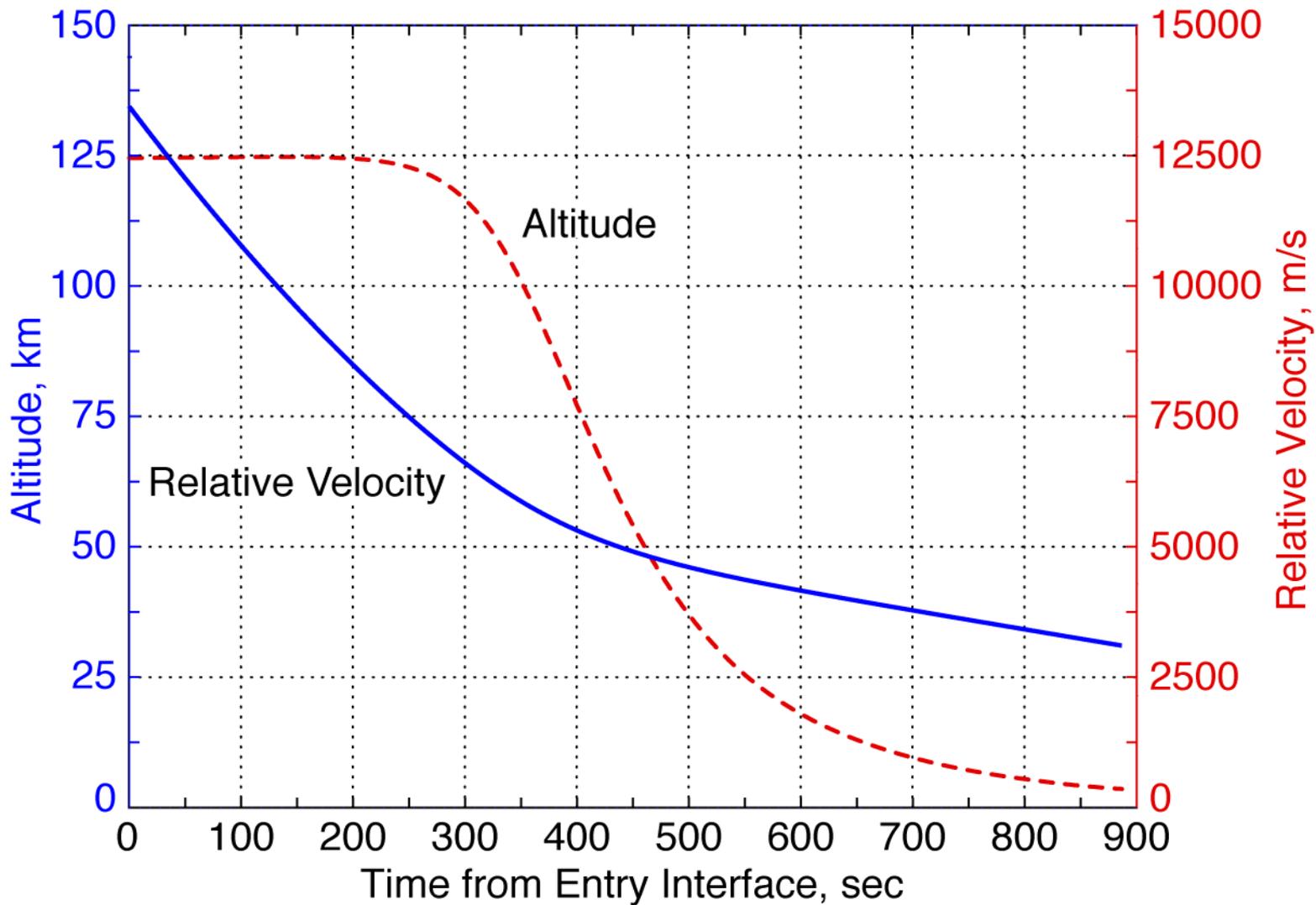
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- Within the trajectory simulation, a multiplier on capsule drag was applied as the control parameter to determine the variation needed to patch the two endpoint conditions
 - An drag increase of 0.83% is calculated
 - Therefore, pre-entry prediction was very close to actual flight
 - Altitude is within 3 m between BET and tracking data
 - Mach number is within 0.02 between BET and tracking data
- The 0.83% increase in drag can arise from multiple sources
 - Mis-prediction in entry state, capsule C_D , or atmospheric density
 - Final entry state was confirmed to be extremely accurate by STRATCOM
 - No measure of density available above 35 km
 - So, relative contributions between density and C_D cannot be determined



Stardust Best Estimated Trajectory: Hypersonic Flight

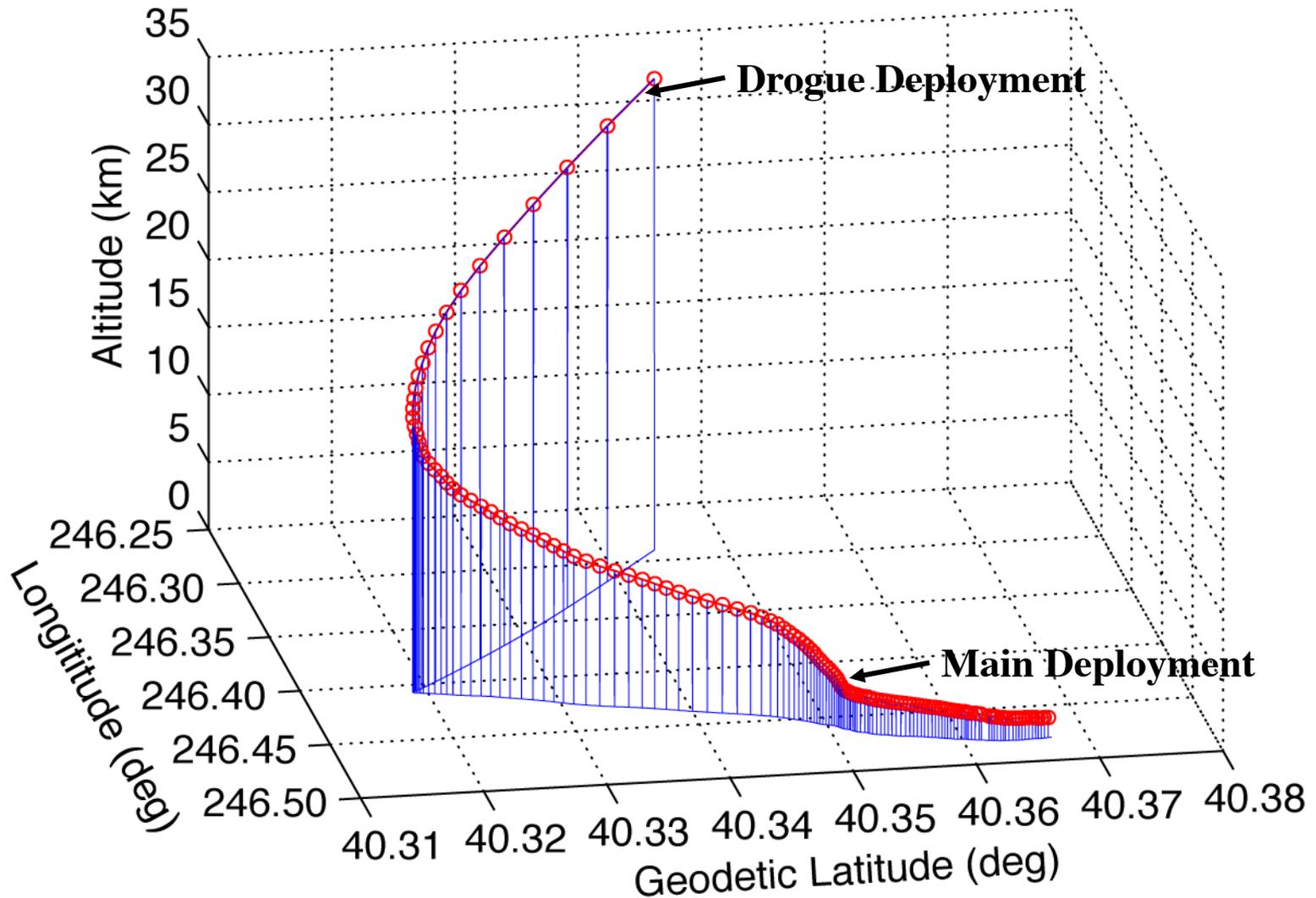
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Stardust Trajectory from Radar Tracking Data: Drogue and Main Parachute Descent

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Hypersonic Capsule Attitude Assessment

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- Since there was no onboard sensor data, capsule hypersonic attitude cannot be determined
 - Attitude must be inferred from observation of recovered heatshield
- There is very little, if any, charring of the shoulder region or aftbody of TPS
 - Inspection of forebody shows charring patterns that imply symmetric heating
 - Observations suggest that attitude must have been small (few degrees)
 - Pre-entry simulation predicted angle-of-attack at peak heating of 2.6° with a maximum of 5.4°
- Overall observations support the assertion that the aerodynamics database reasonably predicted hypersonic static stability



Stardust Capsule Heatshield Inspection

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Very little aftbody charring



**Symmetrical
forebody charring**

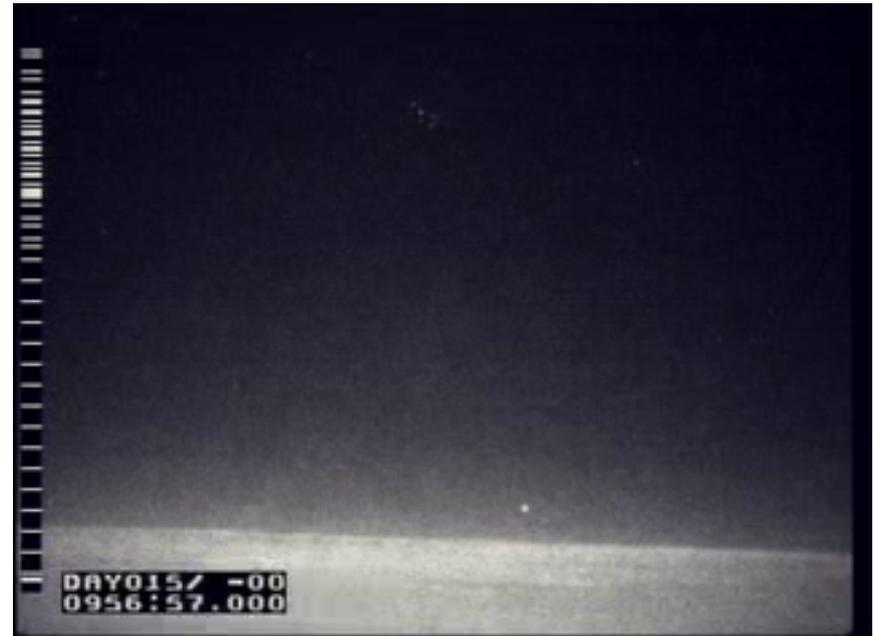


- Heatshield inspection suggests hypersonic attitude must have been small



Successful Entry!!!

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Entry trajectory prediction was used to vector airplane for real-time aerothermodynamic environment observations during entry



Summary

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- An overview of the reconstruction analyses is described
- Reconstructed trajectory was close to pre-entry prediction
 - Drag was within 1%
 - Drogue deployment time was 4.9 s later than predicted (within Monte Carlo pre-entry predicted dispersion of ± 7.4 s)
- Observations of the recovered heatshield indicated small attitude during hypersonic flight
- Overall assertion is that the Stardust entry flight performance was close to the pre-entry predictions
- Consequently, the design principles and methodologies utilized for the flight dynamics, aerodynamics, and aerothermodynamics analyses were corroborated