Reconstruction of the Genesis Entry

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An overview of the reconstruction analyses performed for the Genesis capsule entry is described. The results indicate that the actual entry prior to the drogue deployment failure was very close to the pre-entry predictions. The capsule landed 8.3 km south of the desired target at Utah Test and Training Range. Analysis on infrared video footage (obtained from the tracking stations) during the descent estimated the onset of the capsule tumble at Mach 0.9. Frequency analysis on the infrared video data indicates that the aerodynamics generated for the Genesis capsule reasonably predicted the drag and static stability. Observations of the heatshield support the pre-entry simulation estimates of a small hypersonic angles-of-attack, since there is very little, if any, charring of the shoulder region or the aftbody. Through this investigation, an overall assertion can be made that all the data gathered from the Genesis entry is consistent with flight performance that was close to the nominal pre-entry prediction. Consequently, the design principles and methodologies utilized for the flight dynamics, aerodynamics, and aerothermodynamics analyses have been corroborated.

I. Introduction

GENESIS, the fifth of NASA's Discovery class missions, was launched on August 8, 2001. It is the first mission to return samples from beyond the Earth-moon system. Genesis was inserted into a halo orbit about the sun-Earth libration point (L_1) where it collected solar wind particles over a period of approximately 29 months. Upon Earth return, the Genesis entry capsule containing the solar wind samples entered the Earth's atmosphere on the morning of September 8, 2004 at 15:52:47 UTC. Reference 1 provides an overview of the Earth return trajectory strategy.

Trajectory correction maneuvers and targeting procedures prior to entry interface were nominal and placed the capsule on the expected flight path required for a successful entry profile for a mid-air recovery using a helicopter over the U.S. Air Force's Utah Test and Training Range (UTTR) in Northwest Utah.[2,3] Figure 1 illustrates the nominal entry sequence.

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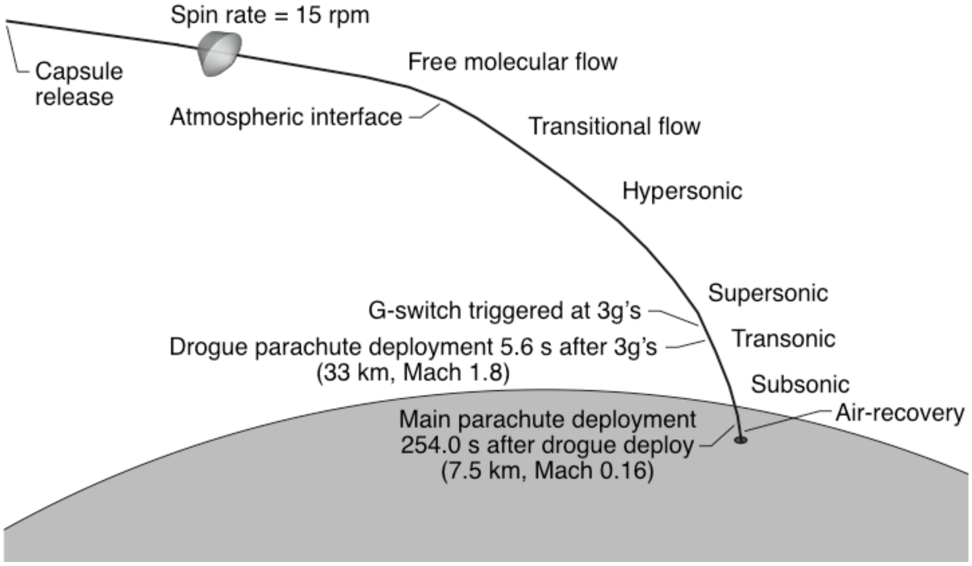

Fig. 1 Nominal Genesis capsule entry sequence.

Four hours prior to entry, the 205.6 kg Genesis capsule was spun-up to 15 rpm and separated from the main spacecraft. The capsule had no active guidance or control system, so the spin-up was required to maintain its entry attitude (nominal 0 deg angle-of-attack) during coast. Throughout the atmospheric entry, the passive capsule relied solely on aerodynamic stability for performing a controlled descent through all aerodynamic flight regimes: free molecular, hypersonic-transitional, hypersonic-continuum, supersonic, transonic, and subsonic.[4] Therefore, the capsule must possess sufficient aerodynamic stability to minimize any angle-of-attack excursions during the severe heating environment. Additionally, this stability must persist through the transonic and subsonic regimes to maintain a controlled attitude at drogue and main parachute deployments. The inertial entry velocity and flight-path angle for Genesis were 11.04 km/sec and –8.0 deg, respectively.

Unfortunately, due to a design flaw (the G-switch utilized for drogue deployment was installed upside down), the signal to initiate drogue parachute deployment failed and the capsule subsequently tumbled and impacted the surface. Following the failure, a reconstruction effort was initiated in an effort to assess how well the flight dynamics, aerodynamics, and aerothermodynamics predictions (performed during the development phase) compared to the actual entry.

This paper provides an overview of the findings from a reconstruction analysis of the Genesis capsule entry. First, a comparison of the atmospheric properties (density and winds) encountered during the entry to the nominal profile utilized is presented. The analysis performed on the video footage (obtained from the tracking stations at UTTR) during the descent is then described from which the Mach number at the onset of the capsule tumble was estimated following the failure of the drogue parachute deployment. Next, an assessment of the Genesis capsule aerodynamics that were extracted from the video footage is discussed, followed by a description of the capsule hypersonic attitude that must have occurred during the entry based on examination of the recovered capsule heatshield. Lastly, the entry trajectory reconstruction that was performed is presented.

II. Final Landing Location

The impact point of the Genesis capsule was 8.3 km south of the desired target as seen in Fig. 2. Also, shown in Fig. 2 is the pre-entry predicted nominal landing location, as well as the final 99% landing ellipse calculated during final approach.[3] The overall 99% landing ellipse was calculated to be 41.9 km by 21.1 km having an azimuth orientation angle of 137.2 deg (measured clockwise positive from north). The 8.3 km downrange distance of the final impact point from the target represented approximately a 1-σ dispersion.

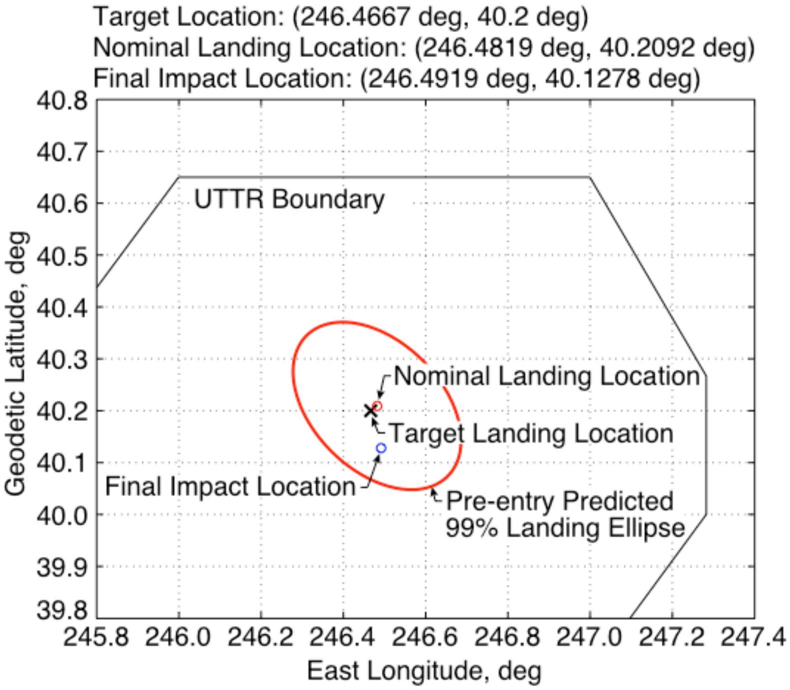

Fig. 2 Final Genesis capsule landing location.

Although, the Genesis capsule landed very close to the pre-entry predicted landing location, an understanding of the hypersonic flight was of great interest. Specifically, assessing the aerodynamics, flight dynamics, and aerothermodynamic performance of the capsule was desired to gain confidence in the design principles and methodologies that were utilized for the design and development phases of entry vehicles. The subsequent sections provide an overview of each discipline.

III. Atmosphere Comparison

The Earth atmosphere model utilized by Genesis for the entry trajectory design and analysis was the Global Reference Atmospheric Model – 1995 Version (GRAM-95).[5] This model is an amalgam of three empirically based global atmospheric data sets of the Earth that can produce an atmosphere profile of density, temperature, pressure, and winds (northward, eastward, and vertical wind components) as a function of altitude for a given date, time, and positional location about the Earth. GRAM-95 produces a representative atmosphere taking into account variations in diurnal, seasonal, and positional information for a given trajectory to produce nominal density, temperature, pressure, and wind profiles along the trajectory flight track. GRAM-95 is not a predictive model, but rather provides a representative atmosphere profile for the given date, time, and positional inputs. A nominal profile was generated using the GRAM-95 model (which is anchored by historical data) for a given date, time, and location. In addition, GRAM-95 also provides statistical perturbations for all the atmosphere parameters.

Four hours prior to the capsule entry, a balloon was launched from UTTR to obtain measurements of the atmospheric properties over the range. The balloon measured density data is plotted in Fig. 3 as a percentage of the nominal profile obtained from the GRAM-95 model. Note, measurements were only available for altitudes up to 34 km. Also depicted in Fig. 3 are the upper and lower 3-σ boundaries of the possible density variation (as a percentage of the nominal profile) produced by the GRAM-95 model for the Genesis entry date and time. As seen, the measured density for altitudes below 34 km was very close to the nominal profile produced by the GRAM-95 model and falls well within the 3-σ bounds; a variation of approximately ±2.5% is observed. For altitudes above 34 km, no measurement data is available. However, an estimate of the density that must have occurred above 34 km is presented in the Trajectory Reconstruction Section.

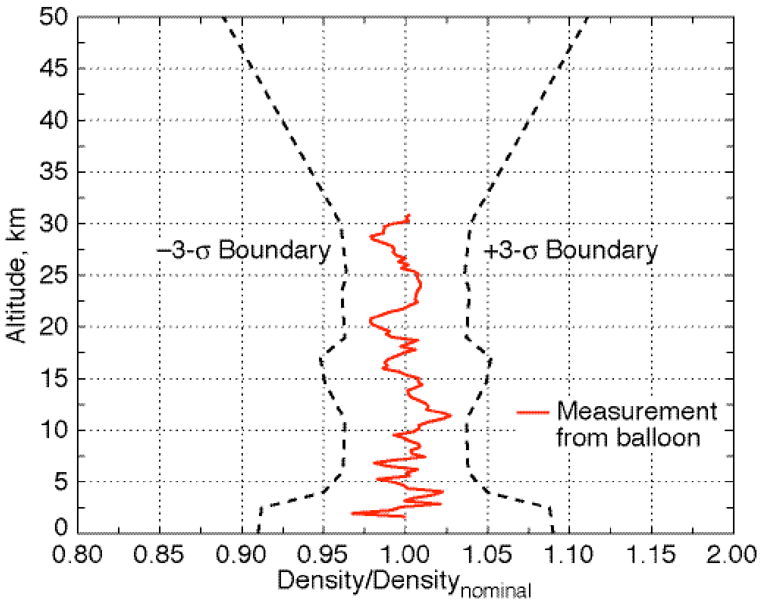

Fig. 3 Density comparison to GRAM-95 model (expanded view).

Similarly, Figs. 4 and 5 show balloon measured wind data for the northward and eastward wind components. Also shown are the nominal profiles generated by the GRAM-95 model, as well as the respective upper and lower 3-σ boundaries. As seen, the balloon measured northward and eastward wind components both fall well within the upper and lower 3-σ bounds produced by the GRAM-95 model. The measured northward wind component varied between ±5 m/sec throughout the altitude band, and was lower in magnitude than the nominal profile produced by GRAM-95. The measured eastward wind component shows a sustained wind speed to the east similar to the nominal profile obtained from GRAM-95. However, the measured wind speed at 12 km (altitude of the jet stream) was higher than the nominal profile having a magnitude of approximately 27 m/sec to the east. This measured eastward wind component corresponds to approximately a 1.5-σ profile from the GRAM-95 variations.

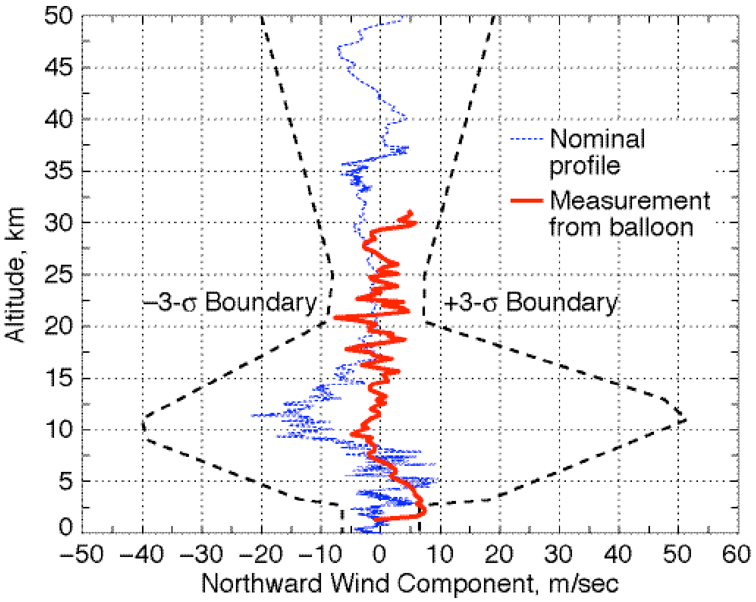

Fig. 4 Northward wind component comparison to GRAM-95 model.

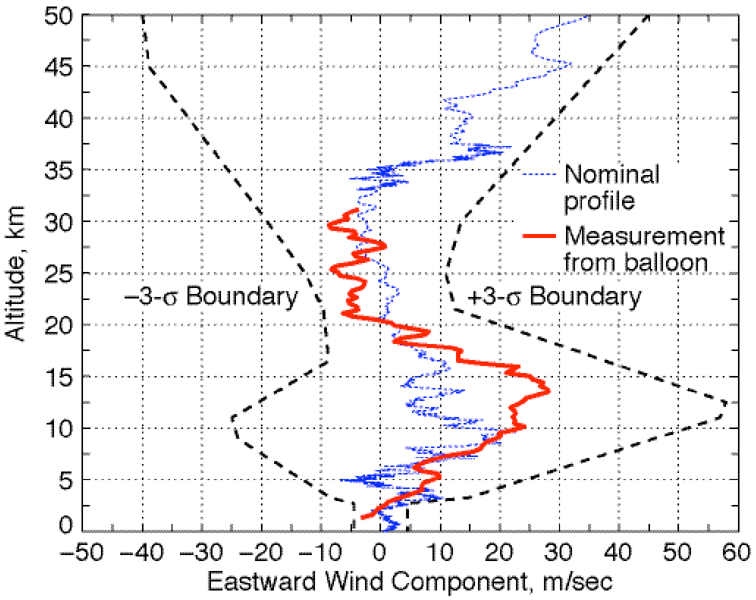

Fig. 5 Eastward wind component comparison to GRAM-95 model.

IV. Video Analysis of Tumbling Capsule

Since there was no on board sensor data from which to perform an attitude reconstruction for the capsule during entry, video footage obtained from the UTTR radar tracking stations was employed to assess the onset of the capsule tumble. This section describes the video analysis that was performed.

Several visible and infrared cameras that are a part of the UTTR infrastructure videotaped the Genesis capsule descent and impact. Videotapes from all of the cameras were reviewed to determine whether they would provide insight into technical details of the capsule's flight. Two videotapes were selected for analysis, one from an infrared video camera and the other from a visible light (color) video camera. Both cameras were actively tracking the capsule and each had an uninterrupted view for the final four minutes of flight. The two videotapes were recorded with different reference timing signals. However, they all were synchronized with each other, as well as other UTTR range data, using the impact event as the common reference. Time depicted in the figures for the video analysis is arbitrary and arises from the video digitization process. Also shown are the capsule descent Mach numbers (M) obtained from the UTTR radar tracking station data.

Software was developed to locate the capsule in the video frame and measure its total infrared luminance as recorded by the video camera. The video signal was recorded at 29.97 frames per second. However, each frame was composed of "fields" which were the even and odd raster lines of the frame. The video fields were recorded at twice the frame rate, or 59.94 fields per second. The software used to recover the luminance information measured the data on a per-field basis and, therefore, produced data at 59.94 Hz.

The extracted luminance data is shown in Fig. 6a. When the high frequency noise is removed (see Fig. 6b), the underlying variation of the capsule's luminance is more obvious. For the purpose of this analysis, the variation of luminance is assumed to correspond to capsule attitude motions that change the area of the forebody that is visible to the camera. There was no attempt to correlate magnitude of the luminance variation with capsule attitude. However, the observed frequencies of the luminance variation should correlate with natural frequencies predicted by pre-entry simulation predictions of the capsule attitude dynamics.

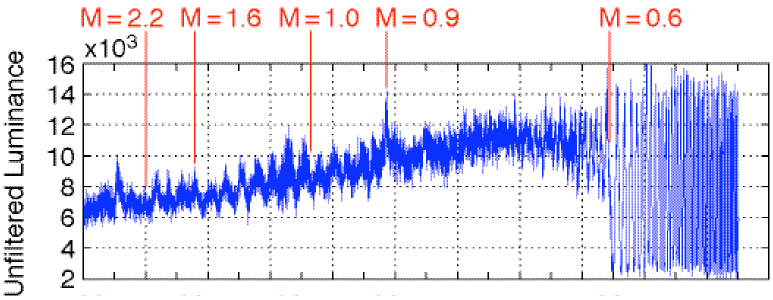

Fig. 6a Unfiltered infrared luminance.

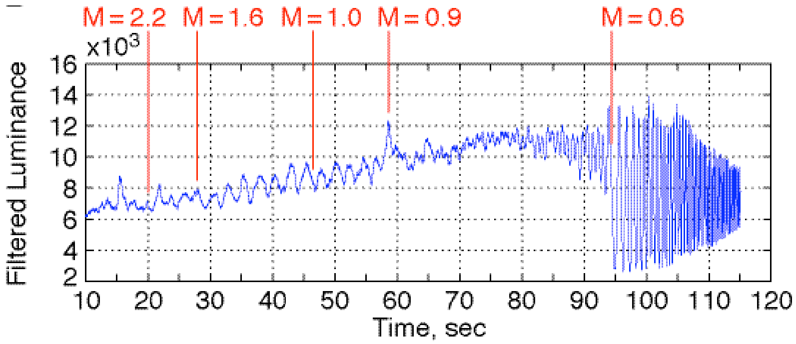

Fig. 6b Filtered infrared luminance.

The frequency content of the extracted luminance data was analyzed using a Fast Fourier Transform (FFT) analysis. The results are shown in the contour plot in Fig. 7, which depict the variation over time of the frequency distribution in the infrared signal. The contours depict FFT magnitude, which is however not of significance to this discussion; only the frequency variation shown in Fig. 7 is of importance. Between 20 sec and 55 sec, the dominant frequency is 0.42 Hz. This frequency oscillation is also clear in Fig. 6b. This oscillation is undetectable to the naked eye due to the low frequency and the large amount of noise in the video signal.

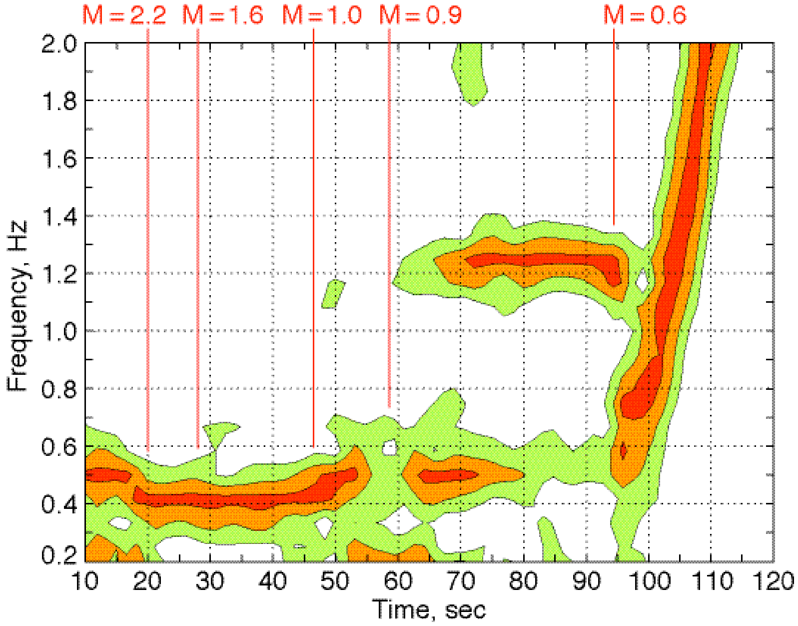

Fig. 7 Frequency contours of luminance signal.

At 59 sec (M = 0.9), there is an excursion in the luminance data that interrupts the 0.42 Hz oscillations that had dominated the signal for the previous 30 sec. Following this peak in brightness, the 0.42 Hz signal is again apparent, but a 1.25 Hz signal is present and increases until it begins to dominate at 72 sec. This higher frequency continues to dominate until 95 sec ($M = 0.6$), when the infrared video shows a target that is clearly tumbling with an increasing rate.

When examining the visible wavelength video at several times between 60 sec and 80 sec, the capsule appears to be tumbling, even though it is still small and faint within the frame. At roughly 80 sec, the brightness settings of the camera change making the tumbling unmistakable, because the dark forebody and white aftbody alternately come into view at a frequency that matches the 1.25 Hz observed in the infrared wavelength video.

Since the 0.42 Hz signal in Fig. 7 persists after the excursion at 59 sec, the appearance of the 1.25 Hz signal indicates a new mode that is superimposed on the previous 0.42 Hz capsule motion. Over the next 10 sec, the higher frequency motion begins to dominate the capsule's dynamics and continues to do so beyond 90 sec. The appearance of this higher 1.25 Hz frequency is interpreted as being the onset of tumbling. The time of this event corresponds to a Mach number of 0.9 when the video signal timeline is correlated with the UTTR radar tracking station data.

V. Aerodynamics Assessment

The results from the video analysis, in conjunction with the use of the trajectory simulation[4] employed for the pre-entry predictions, can be used to corroborate the capsule aerodynamic database in the supersonic regime (between Mach 2.2 and 1.0). Plotted in Fig. 8 is the capsule angle-of-attack history from the trajectory simulation without the deployment of the drogue parachute, where specific Mach numbers are highlighted. As the Mach number decreases, the capsule angle-of-attack increases from a few degrees at Mach 2.2 to very large angles shortly after Mach 0.9. Since there are no data points in the aerodynamic database above 30 deg, extrapolation would occur and the validity of the simulation would be in question. As seen, the angle of attack increases from ~70 deg to over 100 deg over a few seconds. This point (approximately at Mach 0.85) is assumed to be the location in the simulation when the capsule tumbles. This value of Mach 0.85 for the onset of tumbling from the simulation compares well with the Mach 0.9 estimate from the video analysis.

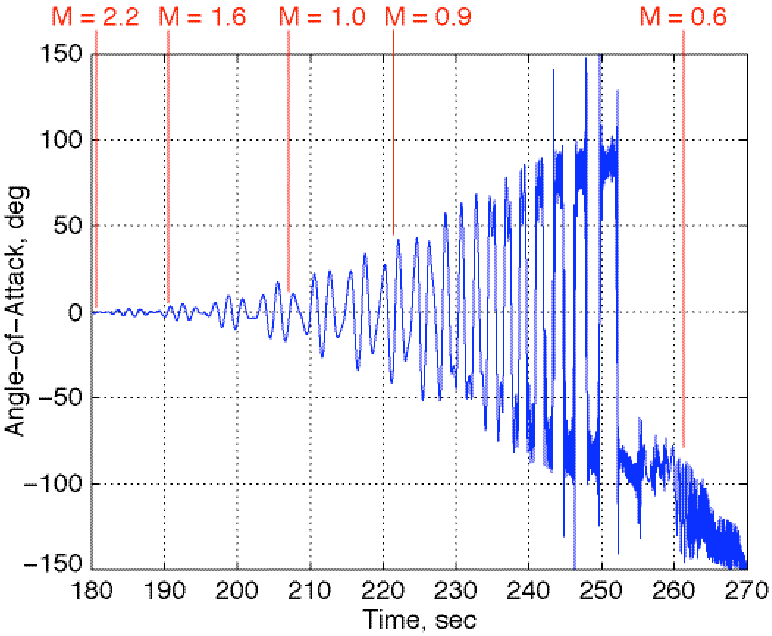

Fig. 8 Time history of angle-of-attack from simulation.

Figure 9 shows the comparison of the capsule deceleration, in terms of Mach number versus time, for the trajectory simulation data and tracking data obtained from the UTTR radar tracking stations. Note, the timelines of the trajectory simulation and the tracking data were aligned at Mach 1.0. A very good agreement is observed with differences between 0%-5% for the available Mach number range. This good agreement indicates that the aerodynamic database accurately captures the drag of the Genesis capsule from Mach 2.2 down to Mach 0.9. For these deceleration profiles to agree across the Mach range visible to the ground tracking stations suggests that the capsule was closely following the pre-entry predicted trajectory.

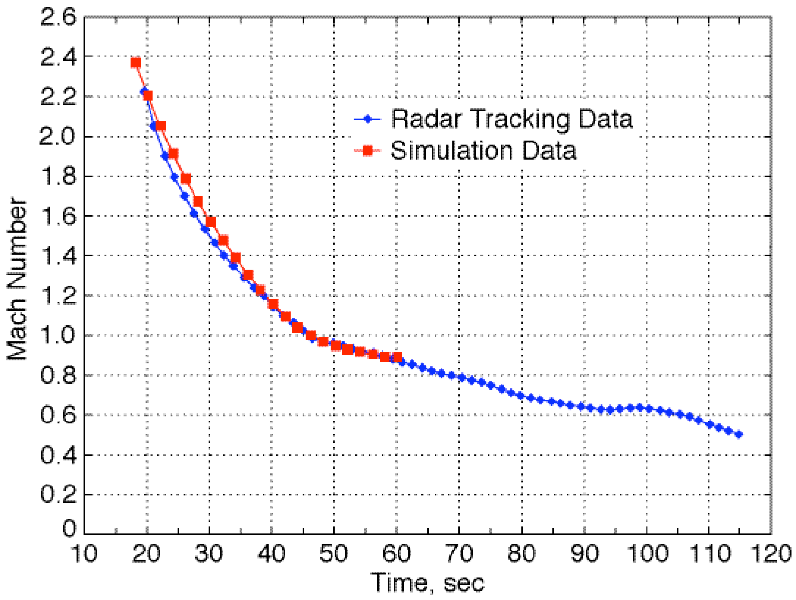

Fig. 9 Mach number comparison.

Figure 10 shows a comparison of the frequency content of the simulated angle-of-attack data of Fig. 8 from the pre-entry trajectory simulation and the measured infrared data presented in Fig. 7. Again, the timelines of the measured infrared signal and the trajectory simulation were aligned at Mach 1.0. As seen, the dominant frequencies correlate well over the range of Mach numbers where both data are present (differences within 1% between Mach 1.6 and Mach 1).

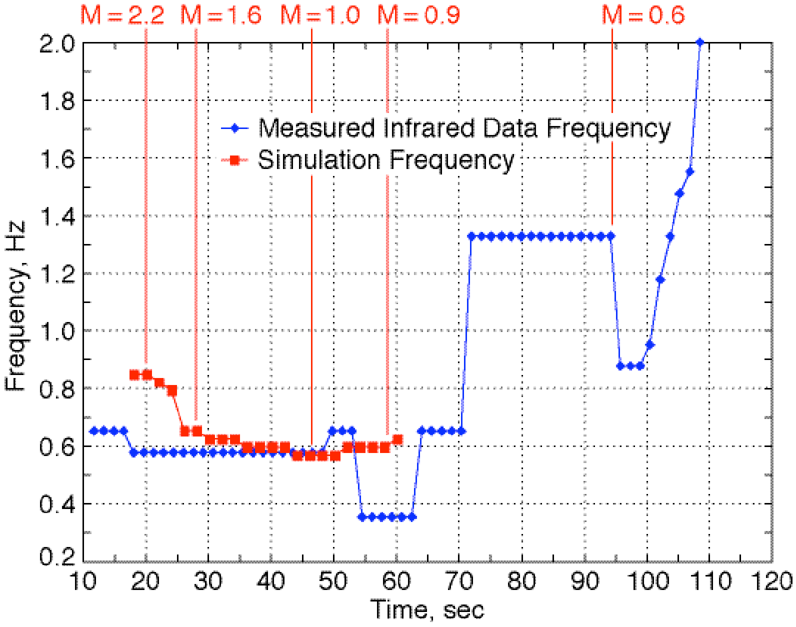

Fig. 10 Frequency comparison.

With confidence in the oscillation frequency, an assessment of the Genesis capsule static stability can be made, since the frequency of oscillation (f) is proportional to the square root of the pitching moment slope (Cm_{α}) multiplied by the local dynamic pressure (q), $f \propto q * \sqrt{Cm_{\alpha}}$.[6] There appears to be good agreement between measured data and the pre-entry predicted dynamic pressure variation. This assertion depends on an agreement between the pre-entry predicted drag and measured drag, as well as agreement in the atmospheric density profile. The accuracy of the drag was detailed in Fig. 9, and Fig. 3 shows that the density profile on the entry day (for the range of altitudes where frequency comparisons can be made) deviated by less than 3% from the nominal atmosphere profile used for the pre-entry trajectory simulation. Therefore, the agreement in frequencies in Fig. 10 between the pre-entry trajectory simulation data and the measured infrared data from the video analysis indicates that the aerodynamic database generated for the Genesis capsule reasonably predicted the static stability in the supersonic flight regime. In summary, while no definitive claims can be made because of the limited flight data, there are no indications in the available data to suggest that the Genesis capsule aerodynamic performance deviated significantly from the pre-entry predicted nominal trajectory.

VI. Hypersonic Attitude Assessment

Since there was no on-board sensor data, the capsule hypersonic attitude behavior cannot be determined. Therefore, the attitude during the hypersonic flight must be inferred from observations of the recovered capsule forebody and aftbody heatshield material response. As seen in Fig. 11, there is very little, if any, charring of the shoulder region or the aftbody Thermal Protection System (TPS) material. Also, inspection of the forebody TPS (Fig. 12) showed charring patterns that imply symmetric heating.

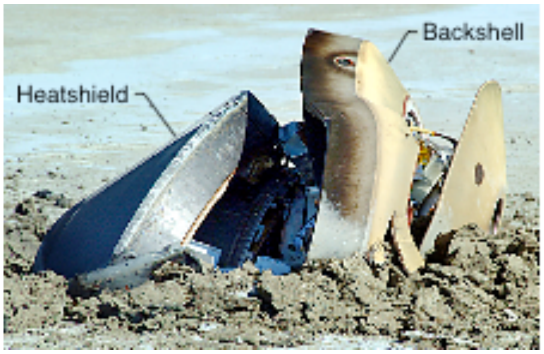

Fig. 11 Image of capsule shoulder region and aftbody heatshield.

Fig. 12 Image of capsule forebody heatshield.

These observations suggest that the capsule attitude must have been only a few degrees during the entry. Based on observed patterns left in wake of the forebody attachment points (seen in Fig. 12), a maximum hypersonic angle-of-attack was estimated to be no larger than 2.1 ± 1.4 deg.[7] The pre-entry trajectory simulations predicted a capsule angle-of-attack during the hypersonic phase near peak heating of 1.3 deg with a maximum of 3.0 deg. Consequently, the observations of the heatshield corroborate the pre-entry attitude predictions and support the estimate of a small hypersonic angle-of-attack and the resulting heating rate and heat loads estimates. These observations support the assertion that the aerodynamic database generated for the Genesis capsule reasonable predicted the static stability in the hypersonic regime.

Also observed on the forebody heatshield (see Fig. 12) is a more intense char pattern (darker regions) just aft of one of the forebody attachment points, which is consistent with a transition to turbulent heating. Such a transition region was predicted by numerical analyses and wind tunnel tests as shown in Fig. 13 using phosphor thermography.[8] The darker regions in Fig. 13 depict higher heating. A comparison of these two figures corroborate the aerothermodynamic predictions of the augmented heating initiated by localized roughness of the attachment points. Reference 8 provides a detailed description of these augmented heating predictions.

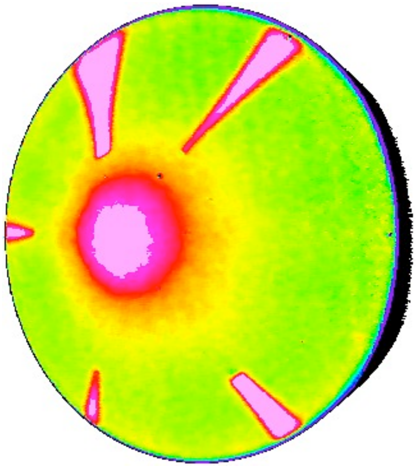

Fig. 13 Sample phosphor thermography heat transfer images.

VII. Trajectory Reconstruction

A. Best Estimated Trajectory

Since, there was no on board sensor data from which to perform a “traditional” trajectory reconstruction for the capsule entry, a best estimated trajectory (BET) has been calculated for the Genesis capsule. The capsule trajectory estimation process is split into two phases: the hypersonic flight and then the terminal (tumbling) flight. The procedure for calculating the BET is described in the following subsections.

B. Hypersonic Flight

For the estimate of the hypersonic portion of the flight, only two data sets were available, namely the final navigation state vector at entry interface and tracking data from the UTTR radar tracking stations. Therefore, the BET is based on using the final navigation state vector at entry interface and the latitude and longitude data (obtained from the UTTR radar tracking stations) at the pre-entry predicted drogue deployment time of Sept. 8, 2004 15:54:53.85 UTC (which was calculated to be 126.7 sec after entry interface). The UTTR radar tracking stations acquired the capsule from approximately an altitude of 34 km through impact. The accuracy of the navigation state vector at entry interface was confirmed by tracking data obtained from Strategic Commend (STRATCOM) to be well within 0.5-σ relative to the predicted dispersion about the target. Similarly, the UTTR radar tracking station data set also had small errors.

With confidence in these two end points (one at entry interface and one at the pre-entry predicted drogue deployment time), a hypersonic trajectory was calculated employing the trajectory simulation utilized for the pre-entry predictions.[3,4] Within this trajectory simulation, a multiplier on the capsule drag (specifically, density times drag coefficient) was applied as the control parameter in an effort to determine what capsule drag variation is needed to match the two end point conditions. This drag multiplier value, if accurate, should produce an altitude that is close to that observed by the UTTR radar tracking station at the pre-entry predicted drogue deployment time. A reduction in the capsule drag of 8.1% (from the baseline nominal value) produces an entry trajectory profile that matches the altitude at the pre-entry predicted drogue deployment time point very well. The altitude difference from this BET is extremely close (within 380 m) to that obtained from the UTTR tracking data set. The UTTR tracking data set indicates an altitude of 33.1 km, while the BET produces an altitude of 32.72 km.

Figure 14 shows the altitude and velocity as a function of time from entry interface to impact from the BET. The hypersonic portion of the profiles (from 0 through 127 sec) is indistinguishable from the pre-entry predicted trajectory profile.

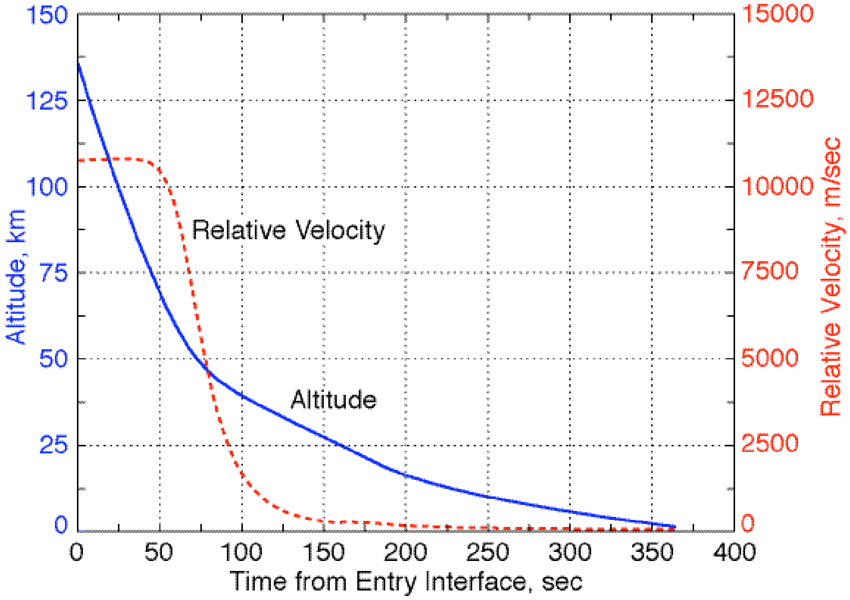

Fig. 14 Altitude and velocity profiles from the BET.

The maximum deceleration obtained from the BET is 27.0 Earth *g* as compared to 27.2 Earth *g* from the nominal pre-flight predicted entry trajectory. Figure 15 shows the deceleration as a function of time from entry interface obtained from the BET. The 3-σ variation in the maximum deceleration from the final pre-entry Monte Carlo analysis was calculated to be ±1.84 Earth *g*.[3] Hence, the actual Genesis capsule entry was very close to pre-entry predicted nominal, and well within the 3-σ dispersions. Consequently, the peak heat rate experienced during the entry was also very close to the nominal environment predicted during the design phase.

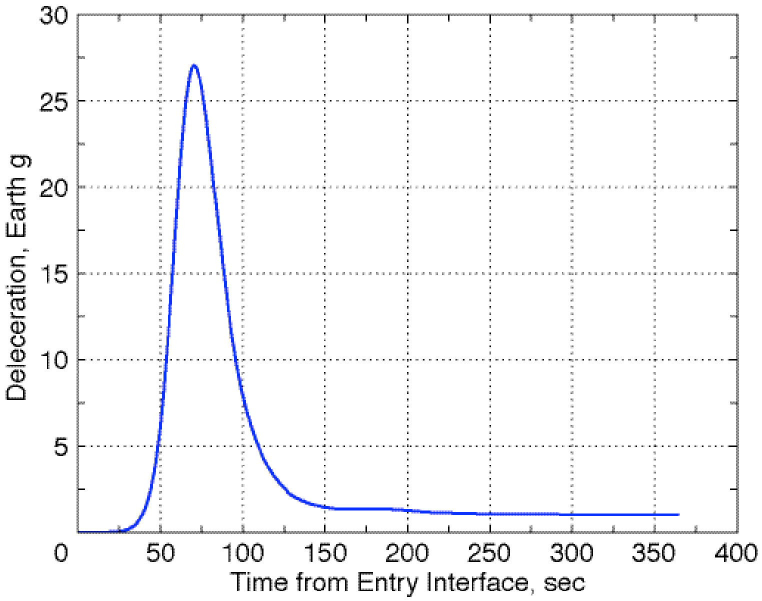

Fig. 15 Deceleration profiles from the BET.

The 8.1% drag reduction can arise from multiple sources; specifically, a mis-predication in the navigation state vector at entry interface, capsule drag coefficient (C_D), or atmospheric density. A sensitivity of the BET to these three parameters was performed to quantify their respective contributions to the overall 8.1% drag reduction.

A 1-σ error in the entry flight-path angle would account for approximately 1.5% of this 8.1% drag reduction. However, as stated previously, the error in the state vector at entry interface compared to the nominal was confirmed by STRATCOM to be very small (well less than 0.5-σ). Such a small error in the state vector at entry interface would account for less than a few tenths of a percent of the overall 8.1% drag reduction. Therefore, the uncertainty in the capsule C_D and atmospheric density account for nearly all of the 8.1% drag reduction.

Since there is no measurement data of the atmospheric density above 34 km, the relative contributions to the 8.1% drag reduction between the capsule C_D and the atmospheric density cannot be determined. However, an estimate for the atmospheric density encountered during the hypersonic portion (between 34 km and 80 km) can be approximated if an uncertainty is assumed for the capsule C_D in the hypersonic regime.

During the development of the capsule aerodynamics, the uncertainty in the hypersonic flight regime C_D was estimated to be ±4% (3-σ), which was based on historical practices and engineering judgment.[4] If the capsule C_D uncertainty is arbitrarily assumed to be 1-σ low (corresponding to approximately 1.5% low) as an illustration, a reasonable assumption in light of the corroboration of the aerodynamics in the hypersonic and supersonic flight regimes as described in the preceding two sections, an estimate of the density above 34 km can be calculated. With such an assumption, the atmospheric density encountered during hypersonic flight (altitudes above 34 km) of the Genesis entry can be approximated to be 6.6% (8.1%-1.5%) lower than the nominal profile produced by the GRAM-95 model. Referring back to Fig. 3, this density estimate correlates to approximately a 1.5-σ low profile from the GRAM-95 variations.

C. Terminal (Subsonic) Flight

Once a good estimate for the hypersonic portion of the entry was calculated and the Mach number for the onset of the capsule tumble identified, the terminal portion (below 33 km) of the entry was estimated using the end condition of the hypersonic flight portion (at the predicted drogue deployment time) as the starting point. Given this starting point and the landing (impact) time September 8, 2004 15:58:52 UTC, a tumbling C_D value for the capsule was estimated for these end conditions. A tumbling C_D value of 0.63 for the capsule results in the observed impact time (which was 238.3 sec after the pre-entry predicted drogue deployment time). This tumbling C_D value, if accurate, should produce a landing position that is close to the final impact location. Indeed, the difference between the landing position obtained from this BET and the final impact location was 420 m. Since this difference is very small, the BET methodology employed for the trajectory reconstruction corroborates very well within all the available data.

VIII. Conclusions

On September 8, 2004, the Genesis capsule entered and descended through the Earth's atmosphere. Unfortunately, due to a design flaw (the G-switch utilized for drogue deployment was installed upside down), the signal to initiate drogue parachute deployment failed and the capsule subsequently tumbled and impacted the surface. The capsule landed 8.3 km south of the desired target at Utah Test and Training Range (UTTR).

An overview of the reconstruction analyses performed for the Genesis capsule is described. The results indicate that the actual entry prior to the drogue parachute deployment failure was very close to the pre-entry predictions. Atmospheric properties (density and winds) encountered during the entry based on balloon measurements were well within the variations predicted by the GRAM-95 model. The aggregate density during entry was estimated as a 1.5-σ low profile from the GRAM-95 variations. The northward wind component was fairly benign varying between

±5.0 m/s, while there was a sustained eastward wind component that corresponded to approximately a 1.5-σ high profile from the GRAM-95 variations. Analysis of infrared video footage obtained from the radar tracking stations at UTTR during the descent estimated the onset of the capsule tumble at Mach 0.9. Comparison of the frequency between the pre-entry trajectory simulation data and the measured infrared data from the video analysis indicates that the aerodynamic database generated for the Genesis capsule reasonably predicted the drag and static stability. Since there was no on-board sensor data, attitude during hypersonic flight must be inferred from observations of the recovered heatshield. Observations of the heatshield support the pre-entry simulation estimate of a small hypersonic angle-of-attack, since there is very little, if any, charring of the shoulder region or the aftbody.

In summary, while no definitive claims can be made because of the limited flight data, there are no indications in the available data set to suggest that the Genesis capsule flight performance deviated significantly from the pre-entry predicted nominal trajectory. Through this investigation, an overall assertion can be made that all the data gathered from the Genesis entry (tracking data, balloon measurement, video footage, and post-landing capsule hardware inspection) is consistent with flight performance close to the nominal pre-entry prediction. Consequently, the design principles and methodologies utilized for the Genesis flight dynamics, aerodynamics, and aerothermodynamics analyses have been corroborated.

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