

OPERATIONAL EXPERIENCE WITH HYPERSONIC FLIGHT OF THE SPACE SHUTTLE 17_5259

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INTRODUCTION AND OVERVIEW

Hypersonic flight is, by its nature, high altitude flight. Adverse effects due to drag including both propellant consumption and heating, and flight control instabilities can only be avoided by significantly higher altitude flight than typical current commercial or military aircraft experience. It is of significant note that the only operating supersonic airliner, the Concorde, cruises at altitudes typically 25% higher than subsonic airliners. The most advantageous flight regime for hypersonic vehicles is even higher. Unfortunately, the region of the atmosphere between 18 km (60,000 ft) and 120 km (400,000 ft) has been rightly termed the “ignosphere” due to the relatively low number of direct measurements available. These altitudes are too high for virtually all winged aircraft, and too low for satellite observation. Balloons may penetrate the lowest regions up to 30 km (100,000 ft) but only widely scattered measurements by rocketsondes reach the higher regions. Blunt body reentry vehicles penetrate this region but can gather little data during their brute force rapid transition of the regimes of interest. Of the handful of winged vehicles flown at hypersonic speeds and high altitude, only the space shuttle regularly traverses this region in controlled aerodynamic flight. Over 100 hypersonic entries by the space shuttle in 20 years have provided a wealth of information about hypersonic flight at very high altitudes. This data has direct applicability to the design and operations of future hypersonic winged aircraft.

Operationally significant lessons have been learned about the meteorology of high altitudes as well as aspects of hypersonic flight control that will be crucial to the development of future hypersonic aircraft. These include the so called “density shears” or deviations from global average atmospheric conditions; the effect of charging or lightning at high altitudes, the so called “red sprites” and “blue jets” directly observed by the space shuttle; and the effect of high altitude so-called “noctilucent” clouds on vehicle structure, flight control and navigation. Operational concerns include the peculiar role that the environment plays on navigation including seldom considered GPS and inertial navigation effects; communications issues at these altitudes and speeds; and real world airframe effects including asymmetric boundary layer transition from laminar to turbulent flow, which results in abnormal drag, heating, and flight control.

DESCRIPTION OF SHUTTLE ENTRY

The space shuttle entry corridor is more constraining than that of earlier crewed vehicles. It is limited by thermal, load factor, dynamic pressure and equilibrium glide boundaries [1]. The thermal and load factor constraints in particular result in a more extended high-altitude glide as compared to other vehicles.

The space shuttle entry phase begins at an altitude of 122 km (400,000 ft) at Mach=25 and ends at the terminal area energy management (TAEM) interface at an earth-relative velocity of 762 m/s (2500 ft/s) or M=2.5. During hypersonic entry, the range to the landing site of the Space Shuttle decreases from a maximum of 8564 km (4624 nm) to approximately 111 km (60 nm) at TAEM interface. Orbit inclinations have varied from 28.5 to 62 degrees, and the crossrange from the orbital flight path to the landing site has varied from 6 km (3 nm) to 1465 km (791 nm). Landings have been made at the Kennedy Space center (KSC) in Florida, Edwards Air Force Base (EDW) in California and White Sands Space Harbor (NOR) in New Mexico. This wide range of reentries has provided a rich database of high-altitude hypersonic flight information. Figure 1 shows typical Space Shuttle hypersonic flight parameters.

DENSITY SHEARS AND HOW THEY AFFECT THE SHUTTLE

The standard upper air models such as the 1976 US reference atmosphere are useful in design of aircraft and planning trajectories and flight conditions. However, these models generate a smooth density profile as a function of altitude. Nature is rarely so well behaved and significant deviations have been observed by the space shuttle. On several flights, the drag – which is a direct function of atmospheric density at a given altitude for a specific vehicle – has varied up to 19% over a few seconds (Figure 2). The aircraft designer must recognize these variations occur, as they will highly influence engine performance, specific fuel consumption, drag, and flight control.

Since the Space Shuttle is an unpowered glider, energy control is critical during aerodynamic flight. The Space Shuttle entry guidance computes a reference drag acceleration profile that satisfies the ranging requirements and the entry constraints. To maintain the drag

acceleration on this reference profile, a drag error feedback is added to the roll command, which is the primary trajectory control. Because the trajectory response to the roll angle is slow, a drag error term is also added to the angle of attack command for short-period control. One consequence of the density shears and resulting drag excursions is to cause frequent fluctuations in the angle of attack profile (Figure 3). These large fluctuations were one of the major surprises from the first shuttle test flights. They could aggravate the heating and also contribute to the saturation of the angle of attack at its corridor limits during maneuvers, which could deteriorate the drag control and the ranging accuracy.

However the most significant impact is on the roll command response to the drag error (Figure 4). The entry flight control system uses a combination of aerodynamic control surfaces and reaction control system (RCS) thruster rockets down to $M=1$. The abrupt changes in the roll command substantially increase the RCS propellant usage (Figure 5); sufficient propellant must be budgeted to cover all expected maneuvers and potential atmosphere dispersions.

UPPER ATMOSPHERE VARIATIONS FROM STANDARDS

Four major differences have been observed between the shuttle flight data and the standards.

The first difference is between the steady-state component of the actual atmospheres and the reference standard atmospheres that are used by the navigation and guidance systems. During most of entry, navigation updates the altitude by extracting the atmosphere density from the drag and comparing it to one of three standard tables of density versus altitude (nominal, hot and cold). Deviations from the standards have resulted in significant altitude errors. Guidance uses the 1962 standard atmosphere to compute a reference altitude rate profile as a function of the reference drag profile. The actual atmospheres have been found to differ substantially from that standard. This often contributes to a negative angle of attack bias from the reference angle of attack profile, which can have adverse thermal consequences.

The second and most significant difference is in the modeling of the density shears. The Global Reference Atmospheric Model (GRAM) was used to estimate the original RCS propellant budget. After two flights exceeded the RCS budget (STS-50 and STS-57), an analysis was undertaken to assess the adequacy of the GRAM atmosphere dispersion model for RCS budget development. When compared with those observed in the flights, the density shears predicted by the GRAM model were found to be of higher magnitude, but lower frequency, which did not sufficiently stress the flight control system in the simulations. As a result of this comparison, the GRAM model was modified to allow the use of smaller altitude increments to better match the high frequency of the flight density shears. However this resulted in RCS usage predictions much larger than those of the flights, because in GRAM the density shears occur almost constantly, instead of in discrete patches separated

by more quiescent intervals as observed in the flights. The recommendation was made to develop a "patchy density shear" model. Because the next version of GRAM was still not sufficiently patchy, the decision was made not to use the GRAM model for RCS budget development and to rely instead on atmospheres reconstructed from the flight data. Unfortunately the atmosphere reconstruction process was found to have a smoothing effect on the atmospheres, which can result in under-prediction of the RCS usage. So at this time no completely accurate method exists for the modeling of density shears. The third potential difference is in the effect of latitude and season. The GRAM model predicts significantly larger atmosphere dispersions at higher latitudes in the winter, and small dispersions at low latitudes. However, the two flights with the highest RCS usage flew low latitude trajectories during the month of July. For the other flights no conclusive trend has been determined at this time, possibly because not enough flights have been flown at high latitudes in the worst months. As a result of the flight experience the inclination dependency has now been eliminated from the RCS propellant budget.

The fourth difference is the absence of longitude dependency for the random perturbations in the GRAM model. In the shuttle flight data, the longitude and geography have a significant effect, possibly larger than the effect of latitude. For example, flights that land at EDW, and therefore fly the entire entry trajectory over the Pacific Ocean, seem to have a lower probability of encountering severe atmosphere dispersions than those that fly over land, in particular Mexico and Texas. A possible trend is also beginning to emerge for strong winds or wind gusts over the Gulf of Mexico for flights that land in Florida.

A first attempt has been made by the GRAM developers to incorporate data from the first 22 space shuttle flights into the GRAM model (in GRAM 95) [2]. Much progress has been made in the modeling of the atmosphere at high altitude; however more work remains to be done to produce a high-fidelity atmosphere model for future hypersonic vehicles.

NOCTILUCENT CLOUD PHENOMENON

Noctilucent clouds are the highest clouds observed in the atmosphere which often appear to the eye as very thin cirrus clouds blue or silver in color. It is believed that Otto Jesse first observed noctilucent clouds in 1885 in Berlin [3]. Noctilucent clouds may appear to shine and their name is derived from Latin words meaning night and luminous. The clouds are observed at high latitudes, generally above 50° although observations as low as 42° latitude have been recorded. The altitude of noctilucent clouds seems confined to 81 to 87 km (265 k ft to 290 k ft) with most occurring at 82-83 km [4]. The clouds are typically only a few kilometers thick [5]. Techniques to observe noctilucent clouds using satellites have been developed and when viewed from space they are often referred to as polar mesospheric clouds. Polar mesospheric clouds have been observed by satellite to cover much of the Earth above 60° latitude during the

summer season. It is generally agreed that noctilucent clouds are the fringes of polar mesospheric clouds visible to the human eye. Noctilucent clouds are only visible to the human eye near twilight when the sun illuminates the clouds and the ground and lower atmosphere are dark. Lidar techniques have been developed to allow for observing noctilucent clouds in full sunlight [6]. The noctilucent cloud season occurs from 3-5 weeks before to 7-9 weeks later of summer solstice. A peak of occurrence occurs about 3 weeks after summer solstice. It is during this season that temperatures in the polar mesosphere become cold enough to support the super saturation of ice and nucleation onto the small dust or proton hydrate ion particles believed to compose the clouds.

For certain Space Shuttle re-entry trajectories hypersonic flight from May to August flight through noctilucent clouds is possible. Lidar and rocketsonde investigations in the past 10 years have shed new light upon the composition and electrical properties of noctilucent clouds and polar mesospheric clouds that are of interest to hypersonic flight. A review of the literature suggests that the median particle radius in noctilucent clouds ranges from 30 to 70 nm. Distribution width of the particle size is on the order of $\sigma = 1.4$ to 1.6 assuming a log normal distribution and number concentrations range from 25 to 610 particles cm^{-3} [6], [7]. Maximum particle sizes of 0.5 μm with number concentrations on the order of 10^{-4} per cm^{-3} have been estimated by particle collisions with rocketsondes [8]. For comparison, typical values for tropospheric cloud ice crystals are 1-8 mm radius and a number concentration of 0.01-0.001 particles per liter (1000 cm^3). Rocketsondes have measured the electric field in the vicinity of noctilucent clouds. Electric fields reach maximums for the mesosphere in noctilucent clouds with reported values of over 1 V m^{-1} and a maximum during one flight of 12 V m^{-1} [8]. The values are considered very low and a tolerable environment for Space Shuttle flight.

Recent research into what causes noctilucent clouds suggests that vertically propagating gravity waves (buoyancy waves) originating in the troposphere are responsible for the vertical motions needed to lift air parcels in mesosphere to the cold heights required for ice nucleation. The possibility then exists for meteorologists to forecast areas of greater likelihood of noctilucent cloud formation. If phenomena such as thunderstorms, jet streams, and mountain waves that may result in vertically propagating gravity waves are forecast skillfully then the location of noctilucent clouds may be predictable.

NOCTILUCENT CLOUD EFFECTS ON HYPERSONIC VEHICLES

At hypersonic speeds these clouds may present a corrosion/abrasion hazard to forward surfaces including airfoils and windows. These clouds would certainly increase drag and may result in abnormal operation of turbojet or scramjet engines. Abrasion of the windshield is possible, but in the shuttle the windshield would probably be shielded by the 40-degree angle of attack. Density shear effects – in this case due to the concentration of ice

particles - could upset guidance, with roll and angle of attack transients, increased RCS propellant usage and ranging errors. The magnitude of these effects could vary from trivial to catastrophic depending on the cloud particle size, number density and composition. Simulations with extreme density shears show the vehicle actually skipping off the cloud. However, these disturbances are more likely to be mild enough to be survivable. Heating rates would be unpredictable, because of potentially off-nominal laminar-to-turbulent flow transition, chemical reactions in the plasma that might increase the heating by a factor of two, and energy absorbed by the vaporization of ice. However, the most severe effect of entry through a noctilucent cloud would probably be the erosion of the thermal protection system during the most critical heating region. Depending on the particle size, sufficient damage could be done to result in loss of vehicle.

SPACE SHUTTLE OPERATIONAL CONSTRAINTS DUE TO NOCTILUCENT CLOUD PHENOMENON

Due to the threat posed by noctilucent clouds, the Space Shuttle program has elected to avoid them entirely, with the only exception for emergency conditions. Therefore, the Space Shuttle has never flown through a noctilucent cloud as far as can be determined. For shuttle purposes, this means that atmospheric entry is never planned for descending node orbits for high-inclination flights. This means that the shuttle does not fly through the altitudes where noctilucent clouds are sometimes present at high latitudes. For ascending node deorbits, the altitude regime where these clouds exist is flown through at low latitude, thus avoiding the clouds. While this restriction is technically in place only for the summer months (June through August), shuttle flight dates are frequently delayed, with the practical result that no flights are ever planned to descend through the high northern latitudes no matter what time of year. This restricts about half of the landing opportunities the shuttle has every day to a given landing site. Since the crew must be awake and well rested for entry, this restriction causes a significant planning and operational constraint on the entire mission timeline and impacts many operations on almost every flight. The threat of noctilucent clouds has greatly impacted the operation of the space shuttle.

HIGH ALTITUDE CHARGING

Electrical charging and especially the high voltage discharge of electricity in the form of lightning has been a concern for aircraft operation since time immemorial. Since thunderstorms and their associated lightning strike potential rarely exceed 13 km (45,000 ft) it might appear that electrical discharge would not be a problem for high-flying hypersonic aircraft. On rare occasions pilots and other eyewitnesses reported lightning-like discharges emanating from the tops of thunderstorms extending into the stratosphere and mesosphere. These reports were often considered fanciful or simply meteorological oddities and were not the subject of serious study. Franz et al [9] was the first to report low light television imagery of these upward discharges. Direct observation by the space shuttle payload bay television cameras shortly after provided additional evidence of electro-optical phenomena

in the stratosphere and mesosphere above thunderstorms [10]. Research during the 1990's discovered other types of electro-optical phenomena and are now referred to collectively as Transient Luminous Events (TLE). These have been classified by their appearance as "red sprites," "blue jets," and "elves". While details of their charging potential are not well understood, these conceptually present a significant design and flight operation consideration to high altitude hypersonic aircraft should TLE's be proven hazardous to hypersonic vehicles in flight. TLE's have been observed across much of the globe. At the very least, the avoidance of regions of disturbed weather may have very serious impact on the routing of hypersonic aircraft traffic.

Sprites are large, but weakly luminous electro-optical events that form from 30 to 100 km altitude and above active thunderstorm clusters. Sprites are generally associated with large positive cloud-to-ground (+CG) lightning flashes. Although difficult for the human eye to see because they occur quickly (a few milliseconds) and are very dim compared to lightning they are generally red in color. The width of sprite is typically 5-10 km covering a volume around 100 km³. Blue jets appear as beams or jets of blue light that come directly from thunderstorm cloud tops and extend to 50km altitude. Elves are diffuse and luminous phenomena also usually associated with large +CG flashes. Elves appear as thin disks around 80 to 100 km and expand quickly outward sometimes achieving diameters of 200 km or more. Elves appear to be created by the electromagnetic pulse of large lightning discharges.

Since TLE's are frequently associated with thunderstorm clusters containing radar echo areas > 7500 km² and large +CG lightning flashes [11] a hypersonic vehicle would need to avoid over flying these large thunderstorm clusters if TLE's are likely and hazardous. In the United States the high plains is climatologically a favorable location for large thunderstorm clusters and +CG lightning flashes. Lyons et al [11] stated, "...the U.S. High Plains may represent one of the highest TLE producing regions in the world." This area may be over flown by the Space Shuttle for descending node de-orbits and landings at the Kennedy Space Center. Internal studies by NASA have estimated the risk of encountering a sprite given over flight of a sprite-producing thunderstorm cluster. The risk is estimated at 1 in 100 or less. Expert panels so far have concluded that sprites, blue jets, and elves do not pose a hazard to the Space Shuttle, which is designed to withstand a harsh electrical environment. Further research into TLE's will refine and measure any possible hazards, but nonetheless hypersonic vehicles should be designed to withstand high electric fields or bear a possible burden of avoiding thunderstorm over flight.

COMMUNICATION ISSUES DURING HYPERSONIC FLIGHT

During hypersonic flight from about M=23 to M=12, a plasma layer envelops the shuttle orbiter. This plasma layer is particularly thick on the lower surface of the vehicle. Early in the space program when only ground stations supported communications including voice, telemetry, and command, contact with the shuttle was not

possible during this flight phase. Currently, most communication with the shuttle is conducted using the Tracking and Data Relay Satellite System in geosynchronous orbit. The view angle to these high altitude satellites is generally from the upper surface of the shuttle. When this is the case, communications are not impaired and normal exchange with the ground can take place. However, on many trajectories, the shuttle is required to make a high bank angle s-turn which puts the bottom of the vehicle in the general direction of the TDRS satellites high over the Earth's equator. When this occurs, communications are cut off until a different geometry is obtained or the vehicle speed decreases so that the plasma sheath is moderated. Careful operational planning is required to ensure that important landing site data is on board prior to any loss of communications. Predictions concerning loss of communications in this period are difficult due to the significant changes in plasma blockage with small geometry changes. If future vehicles are expected to cruise in plasma sheath conditions, special consideration for communications must be made.

GPS OPERATIONS AT HIGH SPEEDS

The use of the Global Positioning Satellite system for navigation has come into maturity in the last few years of Space Shuttle flights. The receiver used by shuttle is a modified US military receiver [12]. Among its other features, the GPS unit computes a Figure of Merit (FOM) based on the number of satellites being tracked, the geometry of the tracked satellite constellation, etc. The FOM is typically low when a good set of satellites are being tracked. However, as described in the communications issues above, there are periods during hypersonic entry when the plasma sheath interferes with GPS signal reception. At these times the computed FOM climbs sharply indicating a degraded navigation output. The periods of poor GPS performance have been experienced to last for up to three or four minutes, which is a nontrivial period of time. For a shuttle entry, this effect begins for GPS signals at about 97 km (320,000 ft). Continuous carrier frequency tracking of four GPS satellites ends at about 82 km (270,000 ft). The shuttle receiver does not experience a total "blackout" of GPS signals. Code tracking of from one to four GPS satellites occurs during plasma, with frequent loss of lock and reacquisition cycles. Tracked satellites tend to be in a cone whose centerline is opposite the velocity vector. Continuous carrier frequency tracking of four satellites usually resumes around 67 km (220,000 ft), with some lower antenna plasma effects manifesting down to 56 km (185,000 ft) or about M=15 on some flights [13]. As hypersonic vehicles are designed, it may be necessary to augment GPS navigation considering that good reception from well spaced satellites may not always be available. The shuttle GPS receiver computed state vector excursions during plasma have not been excessive. Inertial state vector aiding greatly assists tracking during plasma. On a recent flight of an unaided GPS receiver on the shuttle, the receiver was not able to maintain track during plasma as well as the aided receiver [14].

Ionospheric scintillation effects on velocity calculations have been observed while on-orbit. The variation of GPS

signal phase due to irregularities in ionospheric electron density have resulted in velocity noise of up to 3 m/sec (11 ft/sec) [15]. These noise events have clustered in geographic regions susceptible to instability and disturbed ionospheric conditions, typically within 20 degrees of the magnetic equator; they also occur in the polar regions [16]. Scintillation-induced velocity noise is a linear function of vehicle velocity, and therefore should not be as severe for hypersonic vehicles as for orbiting vehicles. Another potential manifestation is amplitude scintillation of GPS signals, which can cause signal fading leading to loss of lock, signal acquisition failure, and therefore an increasingly inaccurate GPS state vector. Amplitude scintillation has not been observed on shuttle missions, although it is frequently seen by ground based GPS receivers. Receivers that perform carrier phase tracking may be more vulnerable to ionospheric scintillation than the shuttle GPS receiver, which performs carrier frequency tracking. Receiver response to ionospheric scintillation is a function of tracking loop and navigation algorithm design, and will vary from one type of GPS receiver to another.

ASYMMETRIC BOUNDARY LAYER TRANSITION (ABL T)

Under normal conditions, boundary layer transition from laminar to turbulent flow occurs approximately at the same time on both sides of the vehicle (left/right), usually around Mach 8 for a space shuttle entry. However, it occasionally occurs early (as early as Mach 19 on STS-73). Transition causes a sharp rise in the heating rate and the thermal protection system (TPS) temperatures. This is magnified when transition occurs early, which has resulted in slumped tiles and other damage to the shuttle TPS. The higher heating has also aggravated the effect of ascent debris impacts. This TPS damage has required additional TPS refurbishment work during the turnaround for the next flight.

Transition can also begin on one side of the vehicle, which temporarily causes asymmetric drag, and rolling and yawing moments. The primary consequence of this rolling and yawing moment disturbance is an increase in RCS propellant usage at the onset of asymmetry, followed by a second, smaller increase when transition occurs on the other side of the vehicle, which eliminates the asymmetry. In vehicles with limited aileron trim capability, this could also contribute to aileron trim saturation in the presence of airframe and center of gravity asymmetries.

The time of transition is affected by the angle of attack and the surface roughness. Transition can be triggered slightly early by a roll reversal, which temporarily increases the angle of attack in response to the decrease in drag caused by the increasing altitude rate. However when transition occurs very early, the cause is usually a protruding gap filler. There are gaps between the TPS tiles to allow for thermal expansion. The gap fillers are installed between the tiles to reduce hot gas flow to the filler bars underneath these gaps. They occasionally become dislodged and protrude in the flow, which can trigger early, and often asymmetric, transition. This phenomenon caused some surprise when it was first analyzed after STS-28. Visual

inspection of the tiles and temperature measurements permitted reconstructing the spread of turbulent flow from a small area at the back of the left wing, to the entire left wing and finally to both sides of the vehicle. The responsible gap fillers could be seen during the post-landing vehicle inspection. However, occasionally no protruding gap filler can be seen, and no cause can be determined for the asymmetric transition. It is hypothesized that in such a case the gap filler has fallen off during entry. Improved TPS installation techniques seem to have decreased the incidence and severity of ABLT recently.

The modeling of ABLT has evolved over time. The model currently used in the statistical simulations, which is based on flight experience, predicts that early transition (before Mach 10.9) will occur in 20% of the flights, and be asymmetric in 60% of those flights. However, if transition occurs after Mach 10.9, it only has a 10% probability of being asymmetric. This reflects the high correlation between early and asymmetric transition.

The occurrence of the earliest transition, and the hottest entry, on the 72nd flight (as well as the occurrence of the most severe density shears on the 48th and the 56th flights) illustrate the importance of maintaining sufficient safety margins in the design and operation of hypersonic vehicles, even after the end of the test flights.

Another lesson learned is the desirability of installing a sufficient number of thermocouples on both sides of the vehicle. Every flight is an opportunity to refine the understanding of aerothermodynamics.

CONCLUSION

During over 20 years of space shuttle operations, more than 100 hypersonic entries of the earth's atmosphere have been experienced. Many lessons have been learned from shuttle hypersonic flight concerning meteorology, atmospheric variations, real flight control effects, and other matters. These lessons will provide the designers of future vehicles with the knowledge necessary to build robust and economical vehicles that will safely fly in the unusual conditions experienced in hypersonic flight at high altitudes.

ACKNOWLEDGEMENTS

This paper represents the work of a multitude of dedicated people in the space shuttle program. The authors wish to give special recognition and thanks to Messrs. David P. Dannemiller and John L. Goodman of the United Space Alliance for their invaluable contributions to this paper regarding GPS navigation.

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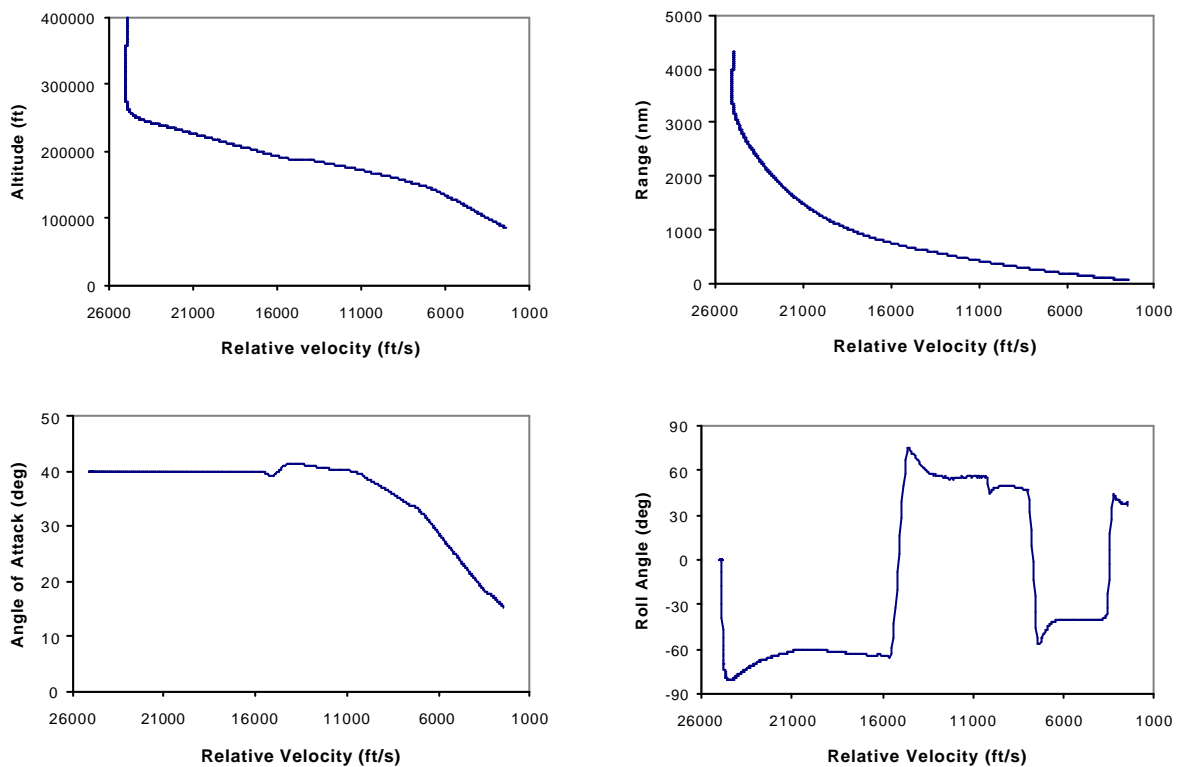


Figure 1 Typical Space Shuttle Hypersonic Flight Parameters

Drag Acceleration:
Actual vs. Reference
(ft/s²)

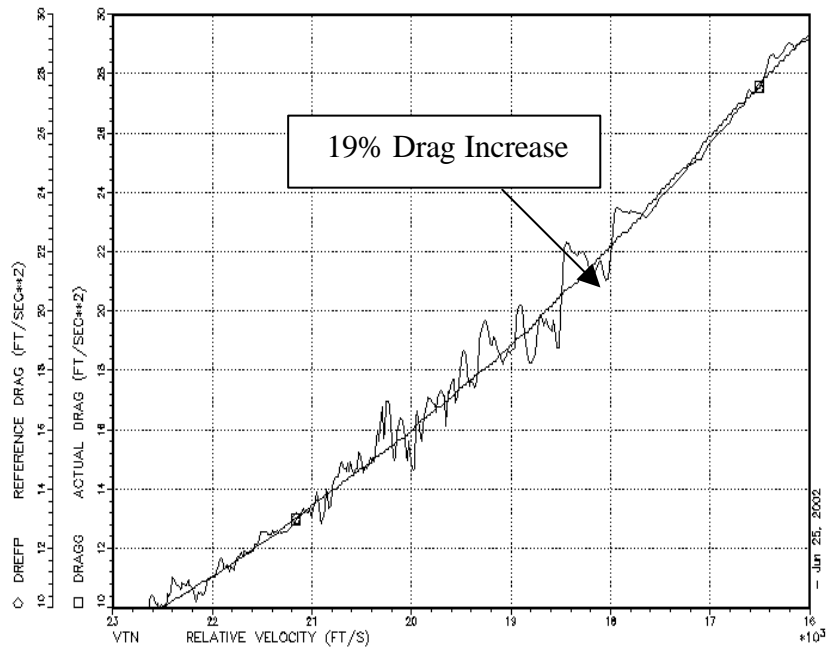


Figure 2. STS-57 Drag Acceleration vs. Relative Velocity

Angle of Attack:
Actual vs. Reference
(Degrees)

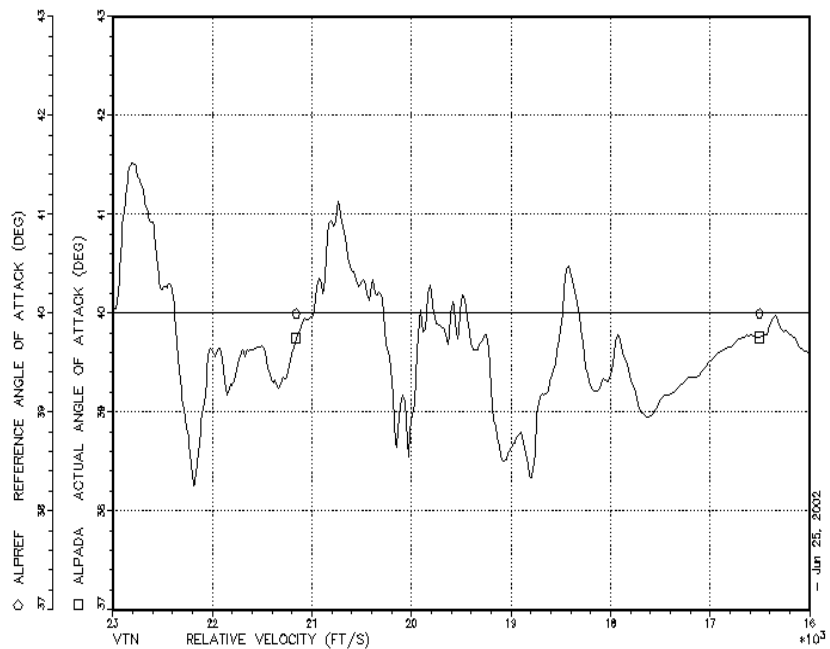


Figure 3. STS-57 Angle of Attack vs. Relative Velocity

Roll Command
(Degrees)

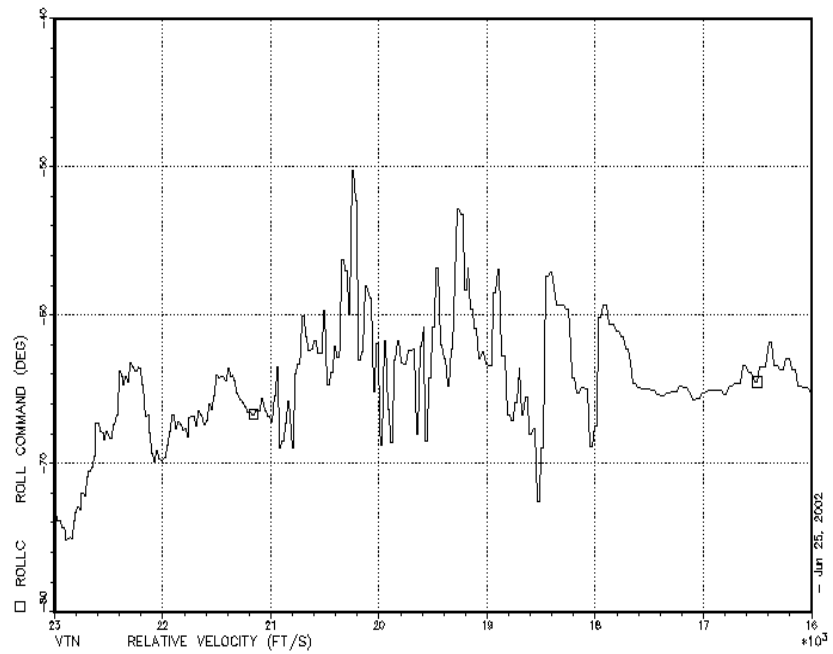


Figure 4. STS-57 Roll Command vs. Relative Velocity

RCS Propellant
Usage (lb)

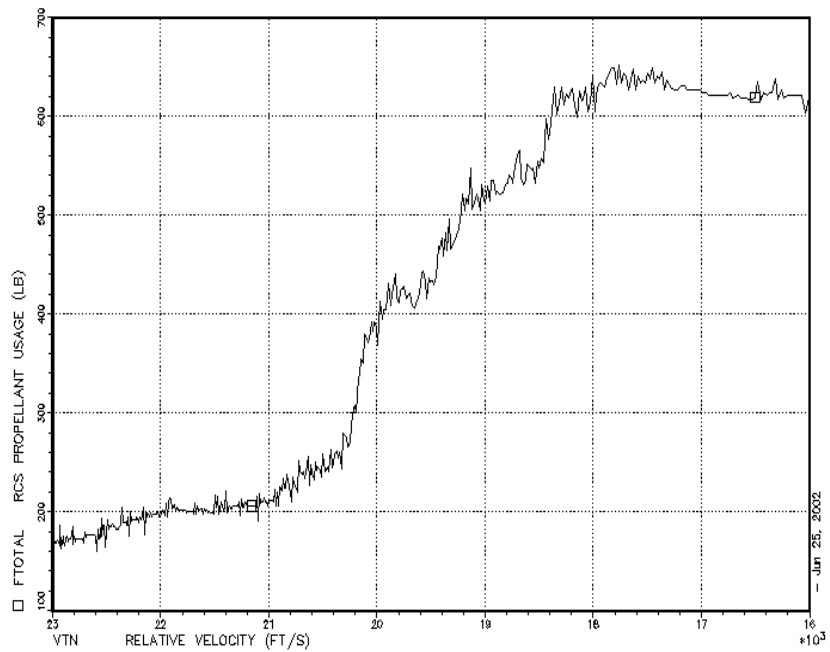


Figure 5. STS-57 RCS Propellant Usage vs. Relative Velocity