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In the past it has been customary to always use the drag coefficient 2.2 for satellites of compact shapes when calculating atmospheric densities. This constant value is not applicable for use in computing decays as the satellite descends down to 100 km heights. In this analysis drag coefficient variability for different shaped rocket bodies is determined as a function of satellite altitude. A new density determination method was used to compute drag coefficients from the orbit decay. Atmospheric temperature and density corrections were first determined on a daily basis using up to 79 calibration satellites in the height range of 150-500 km. These corrections were then applied to special perturbation differential orbit corrections for all the decayed rocket bodies. The resulting ballistic coefficient (B) values were then used to deduce the variation of the fitted drag coefficient values during the last few hundred days of decay.

Introduction

The US Air Force has long supported efforts to improve satellite orbital predictions. The Air Force's recent prediction efforts have evolved along the line of the High Accuracy Satellite Drag Model (HASDM)[1] program, which uses many orbiting satellites to monitor the atmosphere and update an atmospheric model in real time. A major objective of this program is to measure and predict absolute atmospheric densities. Improvement in the knowledge of drag coefficients contributes directly to that goal. Another objective of this

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program is to improve the prediction accuracy of the decay of the numerous rocket bodies left in low earth orbit. Defining the variability of the drag coefficients for these rockets is essential to achieving this improved prediction accuracy goal.

Determination of better drag coefficients will also contribute to the improvement of thermospheric density models. A landmark in the effort to improve models was achieved by Marcos[2] in 1985 when he compared and evaluated 14 models against accelerometer measurements from seven satellites. Recent analysis[3] of sphere drag coefficient variability as a function of altitude has made much progress in defining drag coefficient changes in the 200 to 300 km altitude region.

Further recent progress[4] in the analysis of orbital drag data has refined the semiannual density variation along with other parameters of the Jacchia 70 thermospheric density model[5]. This new development has presented an opportunity to use the improved Jacchia model with data from rocket bodies to refine our knowledge of drag coefficients plus improve the absolute densities in the model.

Analysis Method for Fitted Drag Coefficients

The method developed to determine accurate drag coefficient (C_D) values is to obtain accurate ballistic coefficient (B) values from special perturbation orbit fits using a corrected atmospheric model. In standard least squares orbit fits the solution B values, equal to the drag coefficient times the area to mass ratio (C_DA/M), also contain unmodeled density variations from orbit fit aliasing, as well as contain other variations due to frontal area changes plus C_D changes. However, if a corrected atmospheric model can be used in the orbit fit then this removes the aliasing of the unmodeled density variations into the B solution. The corrected model used for the analysis is based on calibrating the atmosphere on a daily basis from analysis of daily temperature and density corrections on many satellites over the time period of interest. Once the atmospheric model has been corrected the model can then be used to obtain accurate B values. The resulting B variations can then be attributed solely to C_D variations for the rocket body if it has been established that no observable frontal area problems have occurred.

Atmospheric Model Corrections

Daily temperature corrections to the Jacchia 1970 atmospheric model have been obtained on 79 calibration satellites for the period 1994 through 2004, and 35 calibration satellites for the solar maximum period 1989 through 1990. All the “calibration” satellites are moderate to high eccentricity, with perigee heights ranging from 150 to 500 km. No frontal area variations were observed at any time on any of the calibration satellites.

The daily temperature correction values were obtained using a special energy dissipation rate (EDR) method[6], where radar and optical observations are fit with special orbit perturbations. It has been shown that using this method results in daily average density values (representing drag close to perigee) accurate to 2-4% during solar maximum conditions. The daily temperature correction equations obtained from the EDR method were then used in the modified Jacchia 1970 atmospheric model to compute density values at every integration step during the orbit fits of the rocket bodies of interest.

Validation of this method has been previously published in the description of the EDR method paper.

Ballistic Coefficient Analysis of Rocket Bodies

B values obtained from the orbit corrections (using the daily atmospheric temperature corrections) of numerous types of rocket bodies were plotted as a function of perigee height for this analysis. The decayed rocket bodies used in this analysis are listed in Table 1, which include the physical and orbital characteristics[8] of each rocket type.

RB	Launch Type	Len m	Dia m	Incl deg	Per Ht km	Apg Ht km
Ariane	Geosyn	11.6	2.7	7	200	36000
PAM-D	GPS	2.0	1.2	35	190	20000
SL-3	Meteor	2.8	2.6	81	600	680
SL-6	Molniya	3.2	2.6	62	600	40000
SL-8	Varied	6.0	2.4	83	400	2000

Table 1. Rocket body types used in the analysis. Payload launch type, orbit characteristics, and body sizes are listed.

The same method[3] that was previously used to validate the temperature correction field was used to compute the B values for the analyses of the decayed rocket bodies. The daily temperature correction equations were used in the special perturbation orbit fits to correct the atmospheric model. Differential orbit correction fitted B values were then obtained each day using the optimum observation span based on the amount of observable drag. The delta B (DB) values were then computed as a percent difference between the fitted B solution values and the long term (> 5 year) B average value for each rocket body. The long term B averages were almost always obtained from time periods when the perigee heights were above 300 km. Numerous rocket bodies within each type listed above were used to be able to determine least squares average decay curves for each rocket type. These curves are displayed on the figures as solid lines. The summary at the end of the paper displays all the least squares curves together to show the consistent B variability of all the different rocket bodies due to the change in the drag coefficient as the perigee altitude decreases.

SL-3 Rocket Body Analysis

Figure 1 shows the variability of the B value from 350 to 200 km from the decay of SL-3 rocket bodies. The SL-3 rocket bodies are normally used to launch payloads, such as the Meteor satellites, into near circular 500-900 km orbits. All these rocket bodies, with a length to diameter ratio of almost one, show a very high consistency in the variation of B, which is really a variation in the drag coefficient since none of these short cylinders has exhibited any previous frontal area variations. The linear least squares average decay for all the SL-3 objects is shown in the figure.

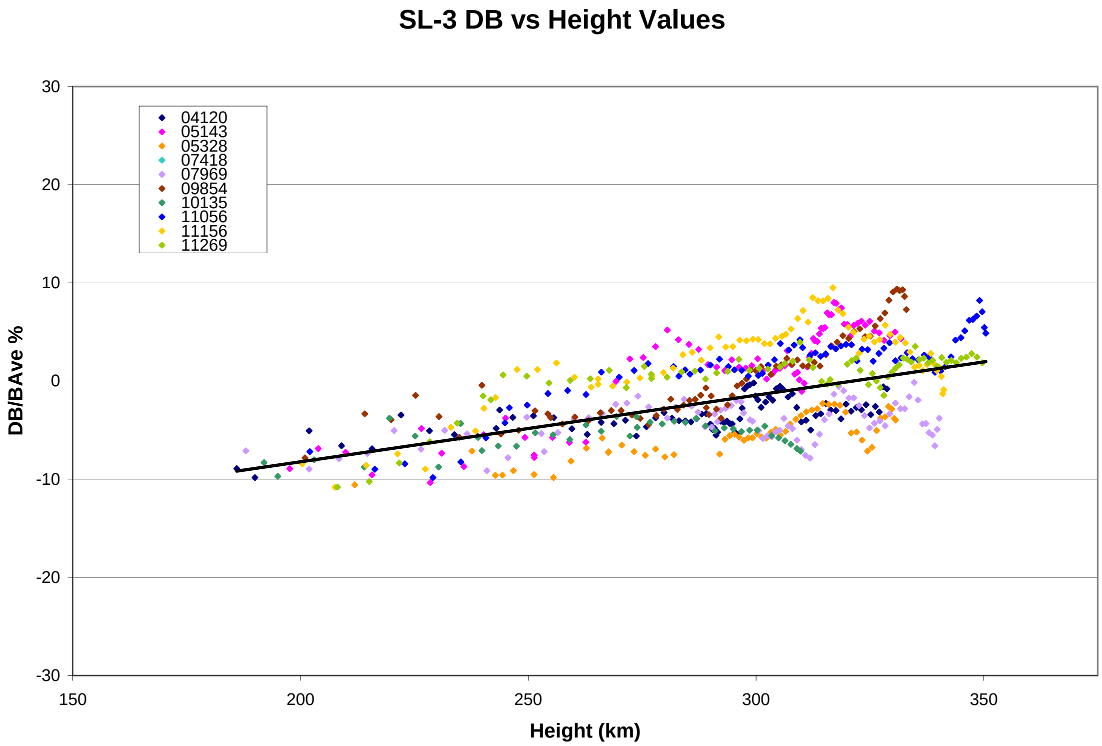

Figure 1. DB values as a function of orbit altitude for a group of decayed SL-3 rocket bodies. Different rocket bodies, with their different NORAD catalog numbers, are plotted in different colors.

PAM-D Rocket Body Analysis

Figure 2 shows the altitude variations of a typical GPS PAM-D rocket body from launch to decay. The PAM-D rocket bodies considered in this analysis were all used to launch GPS satellites into 12 hour circular orbits. These rocket bodies are left in high eccentricity 35-39 degree inclination transfer orbits, with launch perigee heights close to 200 km and initial apogee heights at approximately 20,000 km. Figure 2 shows the large drop in the apogee height during the decay, while the perigee height only changes by about 50 km during the majority of the decay time. The cyclic variation observed in the perigee height is due to lunar-solar 3-body gravitational perturbations.

These GPS PAM-Ds are almost spherical in shape and are solid fueled, which means that the on-orbit burn-out mass is the same (to within a small percent) for all the rocket bodies. This also means that the true B value is the same for this entire class of rocket bodies. An analysis of the decay of a number of PAM-D rocket bodies was previously[7] detailed in the analysis of the semiannual density variation at low altitudes. Figure 3 shows the very consistent DB values during the last stage of decay. Since the perigee height never gets above the 200-225 km launch perigee height the long term average B value corresponds to a lower drag coefficient value than would be obtained for the other rocket bodies starting at higher perigee altitudes. Therefore, the DB values were adjusted to start at a zero value at the 150 km altitude. This means that the least squares curve shown in Figure 3 must be adjusted downward as a whole when combined in the summary with the curves from the other rocket body types.

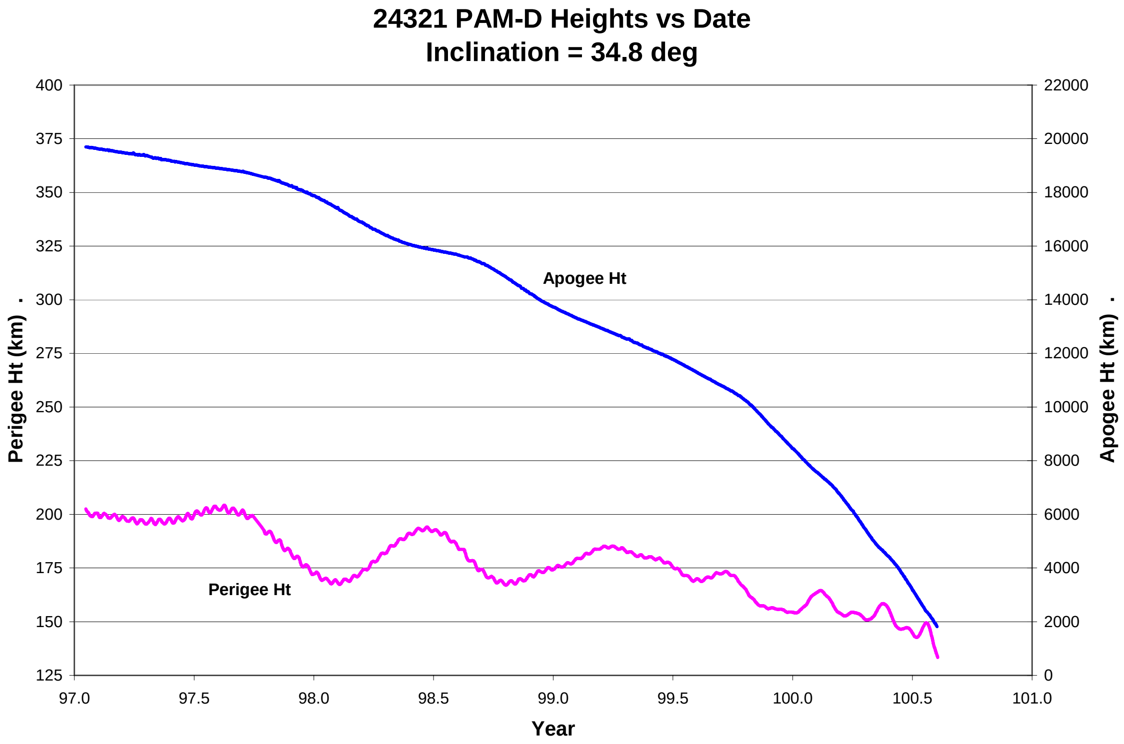

Figure 2. Plot of perigee and apogee heights for 24321 from 1997 to decay in 2000.

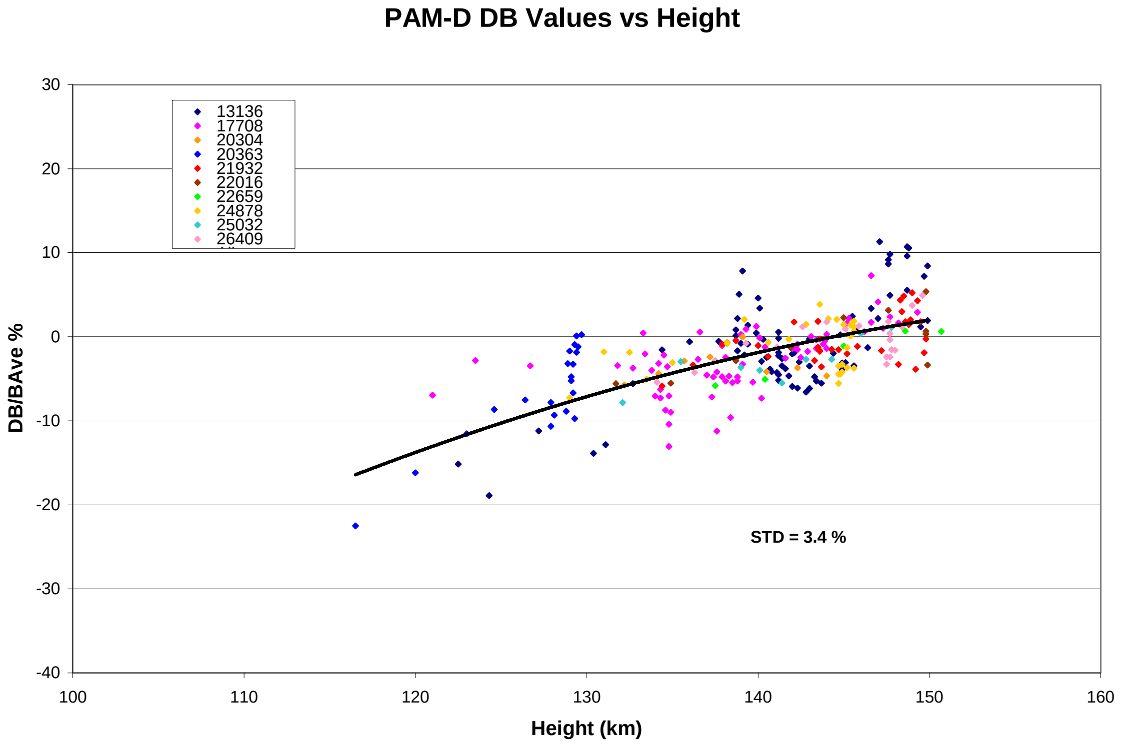

Figure 3. DB values as a function of perigee altitude for a group of GPS PAM-D rocket bodies.

Ariane Rocket Body Analysis

Figures 4 and 5 show the orbit characteristics and B variations of typical Ariane upper stage rocket bodies used to launch geostationary satellites into orbit. The Ariane upper stage remains in a geostationary low inclination transfer orbit with an initial perigee height around 200 km and an apogee height of approximately 36,000 km. The interesting thing about the decay of the Ariane rocket body 23782 shown in Figure 5 is the increase in the B value that occurs only a few months prior to decay. There is a sharp steady increase in B for a couple of months, then a sharp decrease representing the last stages of decay. The only reason for an increase in B is an increase in the frontal area or a decrease in mass. The B decrease starts when the perigee height drops below 150 km. It is possible that the rocket body is heating up so much through each perigee passage that any remaining fuel on board is being vented to relieve the excess pressure buildup in the stage. This scenario will lower the mass on a regular basis until all fuel is exhausted. The final stage of decay will then be driven by a steady decrease in B due to the decreasing drag coefficient value.

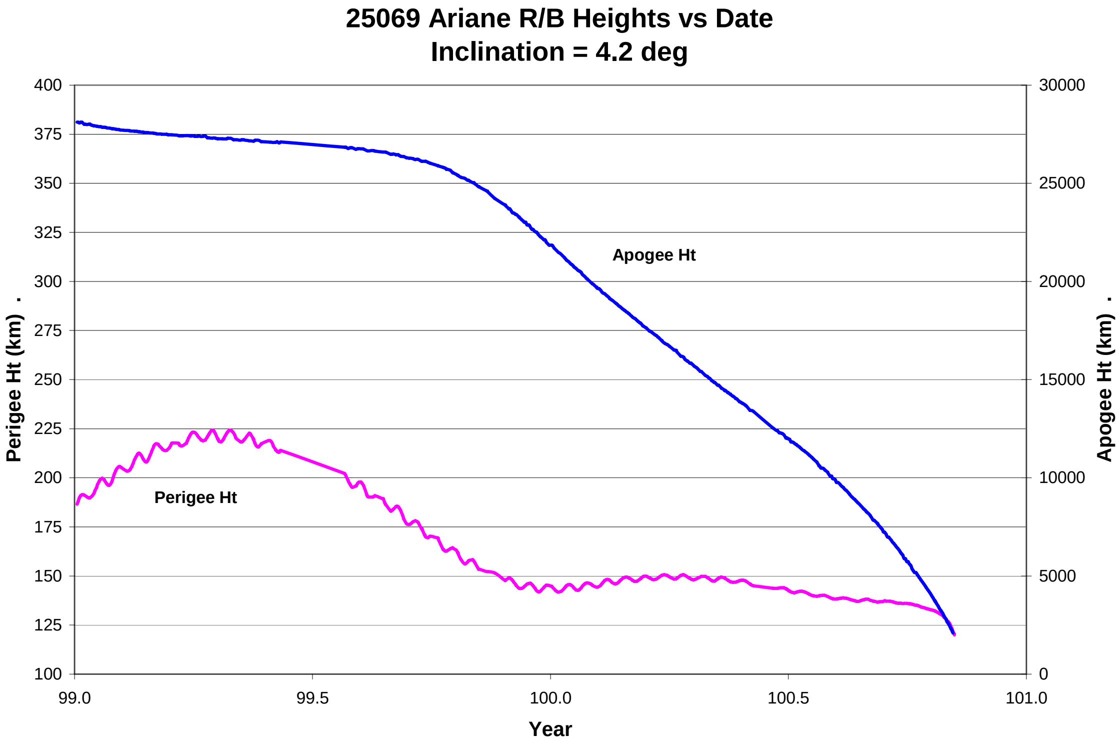

Figure 4. Plot of perigee and apogee heights for 25069 from 1999 to decay in 2000.

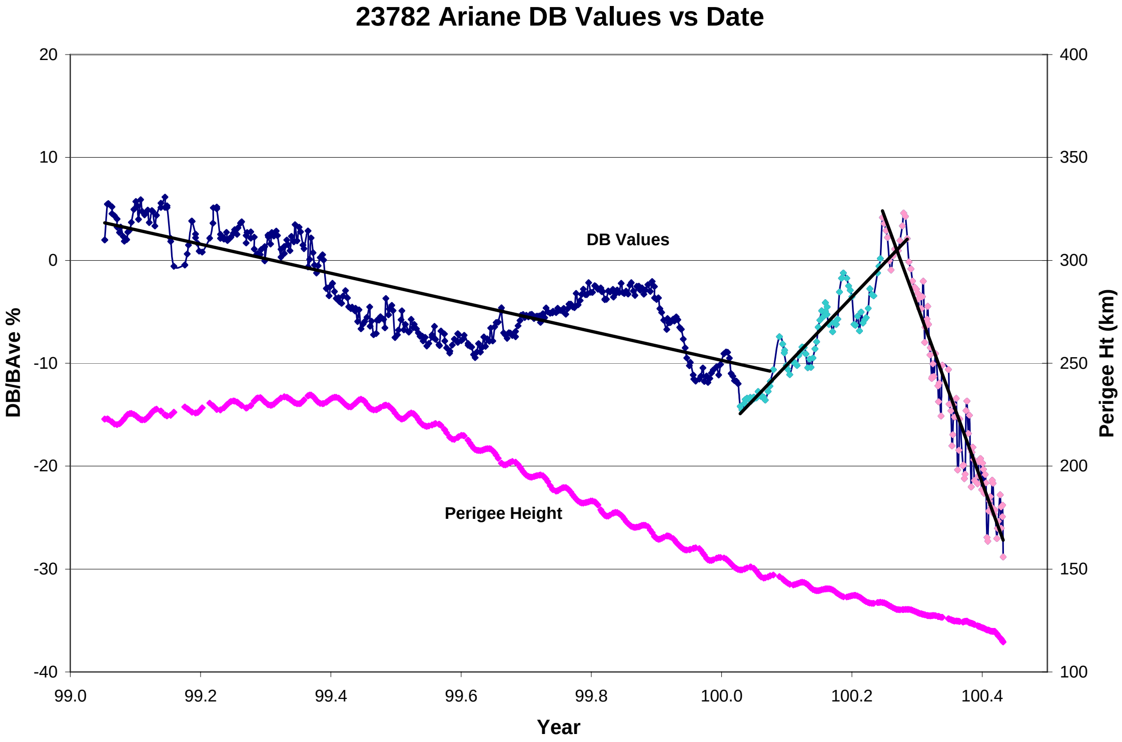

Figure 5. DB values of 23782 as a function of time from 1999 to decay in 2000. Perigee height along with the display of the linear trends in DB are also plotted.

Figure 6 shows the B variations for a number of Ariane upper stages as a function of time prior to decay. The individual plot days have been adjusted to start at 100 days prior to decay (Day 0), and finish at the decay date (Day 100). Note that approximately 30 days before decay the B values increase dramatically for almost all the Arianes shown, which indicates a decreasing mass (fuel leak) occurring until the B values turn around and start decreasing again because of C_D variations. An example of an Ariane rocket body, 26625, that was launched in a later year than all the others did not exhibit the fuel leakage that is shown for the earlier launched rocket bodies. The Ariane rocket bodies are supposed to have vented all remaining fuel just after launch, and this appears to be the case for 26625, while the earlier launched rockets appear to have remaining fuel that started venting much later as the upper stage heated up during the lower perigee passages. The venting appears to be very consistent for the group, with approximately the same rate of venting and same total mass being vented just prior to decay.

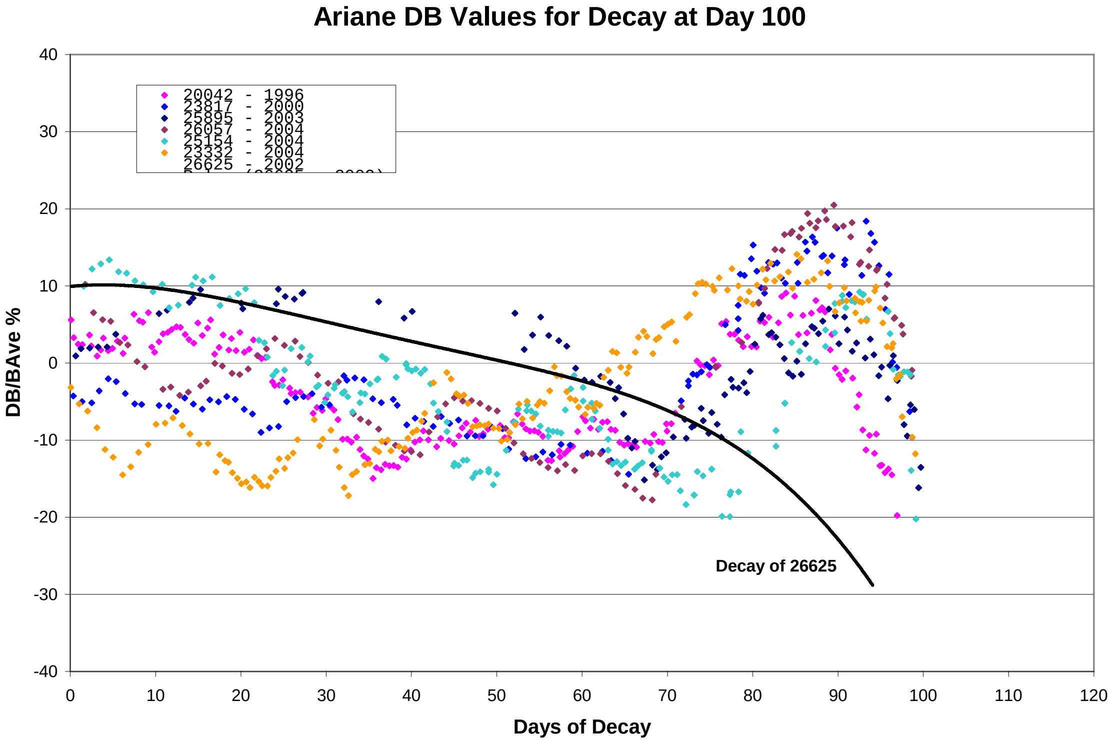

Figure 6. DB values plotted from 100 days prior to decay up to decay (set at Day 100) for a group of Ariane upper stage rocket bodies. The year of decay is listed in the legend.

Figures 7 and 8 show the B variations of rocket bodies before the leakage begins, and then after the leakage has stopped. The curve for rocket body 25313, which showed no leakage, is shown in Figure 7 and is also plotted on Figure 8. The after leak DB data points on Figure 8 have been adjusted vertically to have the initial DB points intersect with the 25313 curve. The consistency of the decay after the cessation of the leakage is remarkable. The reason for the difference between the curves before and after the leakage is unclear at this time.

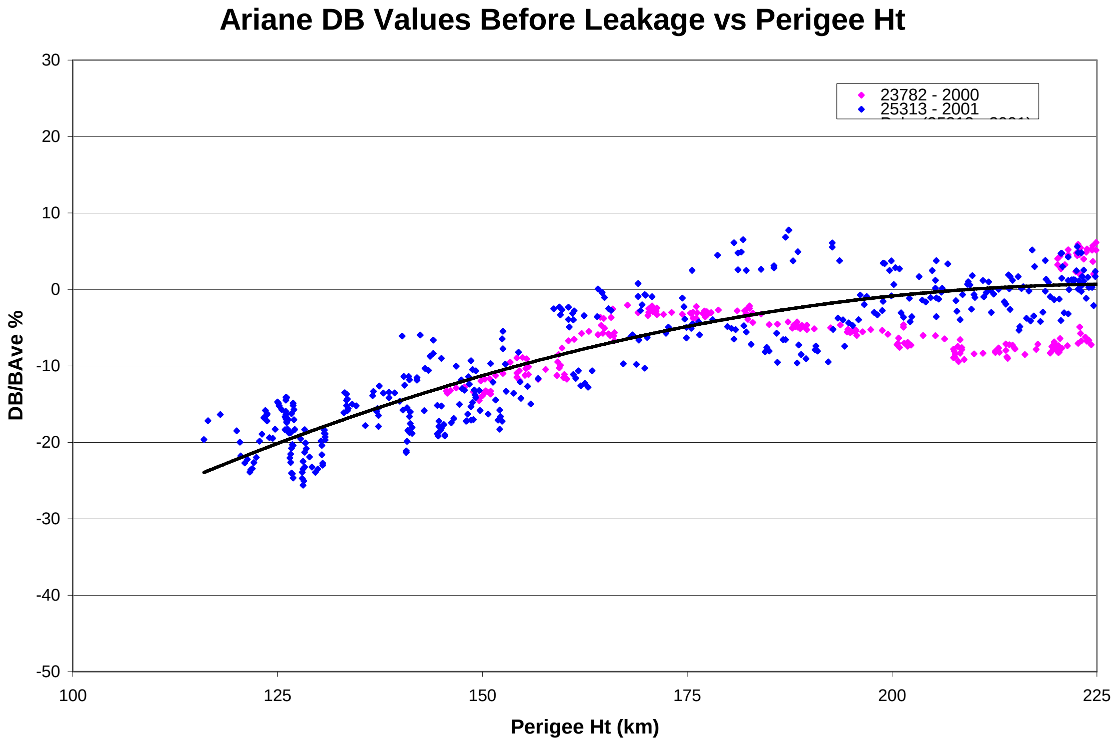

Figure 7. DB values as a function of perigee height for two Ariane upper stage rocket bodies.

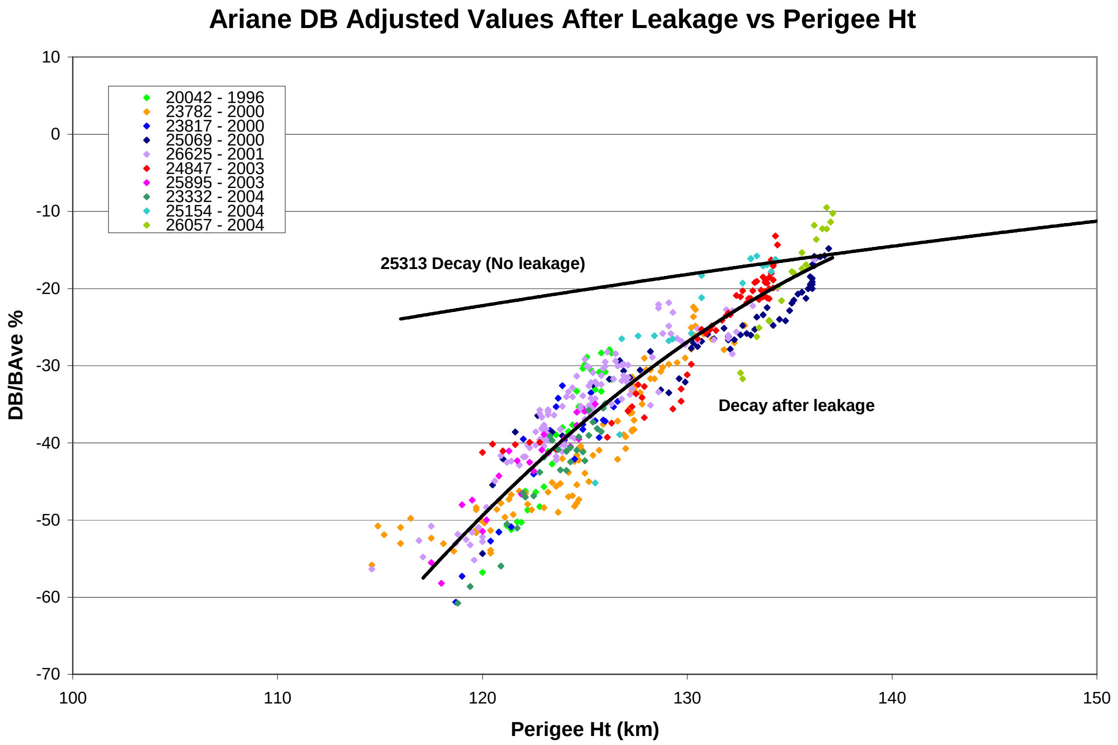

Figure 8. DB values, adjusted for height, plotted as a function of perigee height for the time period following the cessation of leakage of the rocket bodies.

SL-6 Rocket Body Analysis

Figures 9 and 10 show the orbit decay altitudes of two different SL-6 rocket bodies. The SL-6 rocket bodies are used to launch Molynia satellites into high eccentricity 12-hour orbits, with initial apogee heights of approximately 40,000 km. Because of the 63 degree inclination lunar-solar gravitation perturbations force the perigee height to increase or decrease by as much as ~ 1 km per day. Height predictions, with prediction epochs initialized at the beginning year of the chart scale, are plotted in Figures 9 and 10 along with the observed heights. For satellite 11556 (Fig. 9) the predicted and observed perigee heights are the same throughout the majority of the apogee drop, while for satellite 12519 (Fig. 10) there appears to be a significant jump in the observed perigee height as it reached its lowest value. This observed jump can be possibly attributed to out-gassing, which will later be shown to have occurred. The perigee heights decrease to values as low as 105 km for these rocket bodies, with the apogee heights decreasing by over 1000 km per day as the perigee altitudes level out at these very low values. At these heights the rocket body is being heated drastically as it passes through every perigee point.

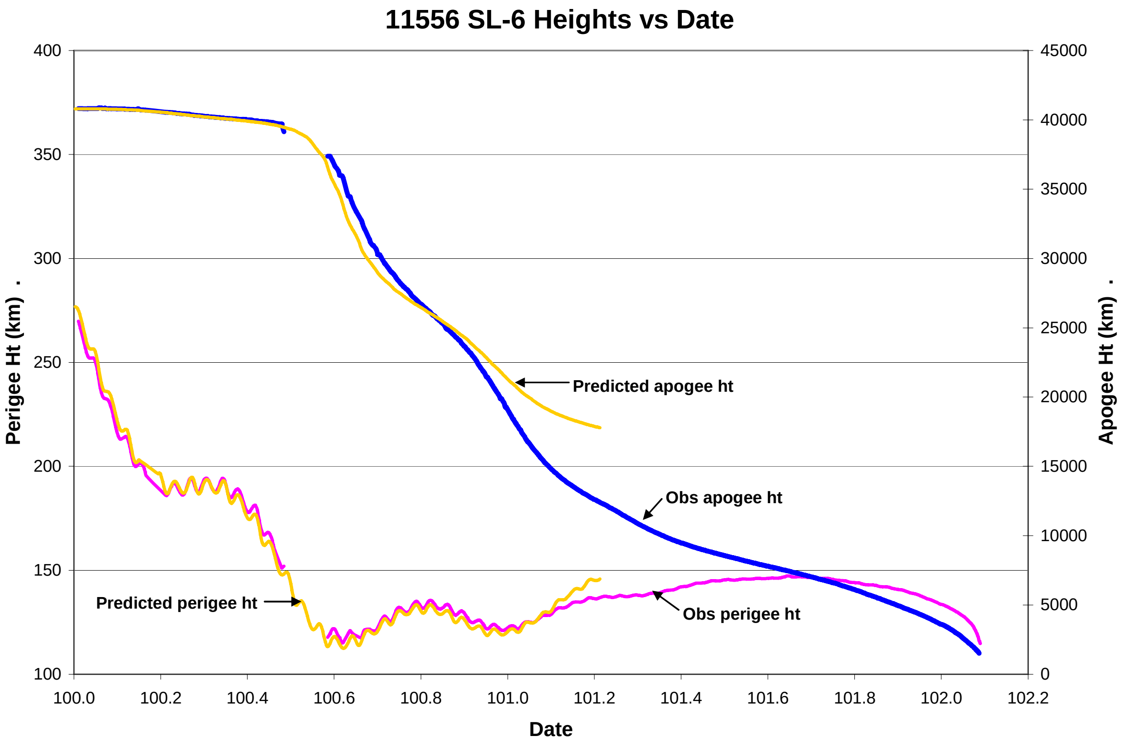

Figure 9. Perigee and apogee heights as a function of time for the SL-6 11556. The predicted and observed values are shown.

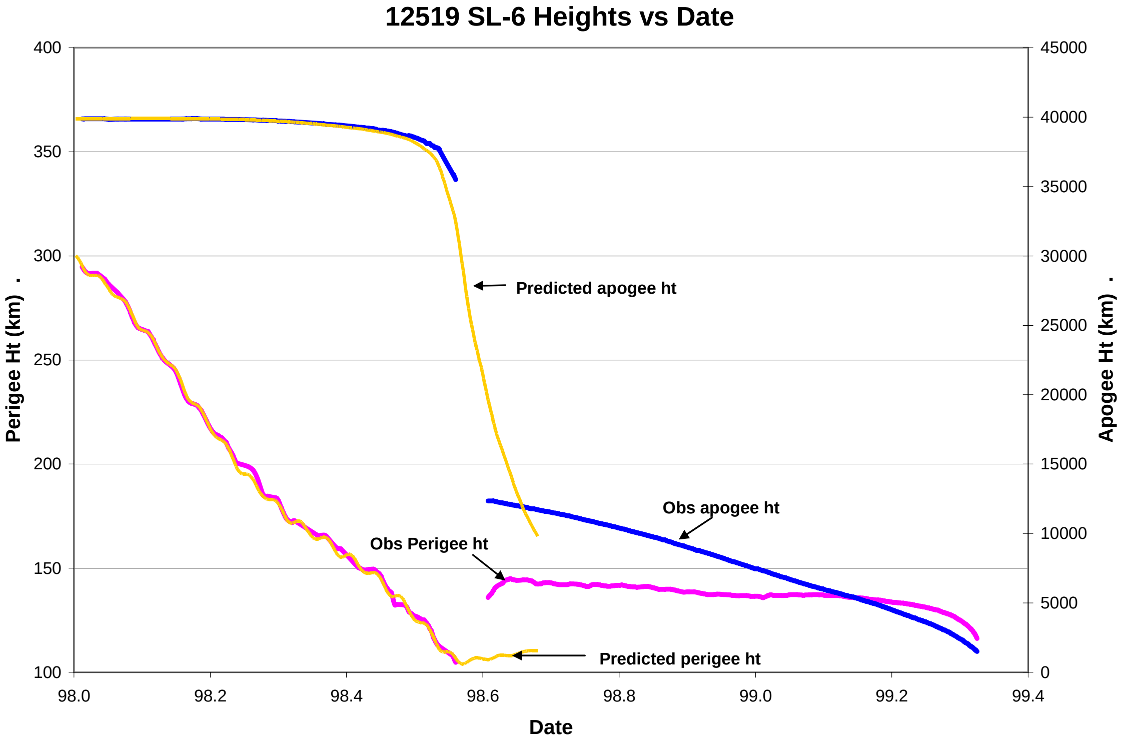

Figure 10. Perigee and apogee heights as a function of time for the SL-6 12519. The predicted and observed values are shown.

Figure 11 and 12 show the altitude and B variations for a group of SL-6 rocket bodies starting from the point where the perigee height drops below 300 km. The time period in years is included in the legend. For the first approximately 200 days the perigee heights and B values decrease steadily, with the B values dropping by as much as 50% by the time the perigee height has dropped from 300 km to 105-140 km. This represents a realistic change in the drag coefficient, which will be shown in a later figure. At this point all the B values start a steady rise, most increasing by over 100% until a maximum is reached. This increase can only be attributed to a loss in mass since these rocket bodies have length to diameter ratios near 1, which means a 100% change in frontal area is not possible to explain the 100% increase in the B values. This increase in B only starts when the perigee height drops below 150 km. The atmospheric drag heating at these altitudes is tremendous, and it is postulated that the internal pressure buildup from the remaining fuel onboard reaches critical levels during each perigee passage, where pressure relief values are then opened to vent the excess pressure buildup. This scenario would explain a steady decrease in mass over a 100 to 200 day time period. For most rocket bodies all the remaining fuel appears to have been vented following the cessation of the B increase. The B values then decrease again due to drag coefficient variability until decay occurs. For a couple of rocket bodies the perigee height rises about 20 km during this venting. This allows for decreased heating and apparently not all the fuel is vented because there appears to be a second series of ventings a couple of hundred days later. At this point the B values again increase but only by as much as 30-50% before they start decreasing again to finally decay.

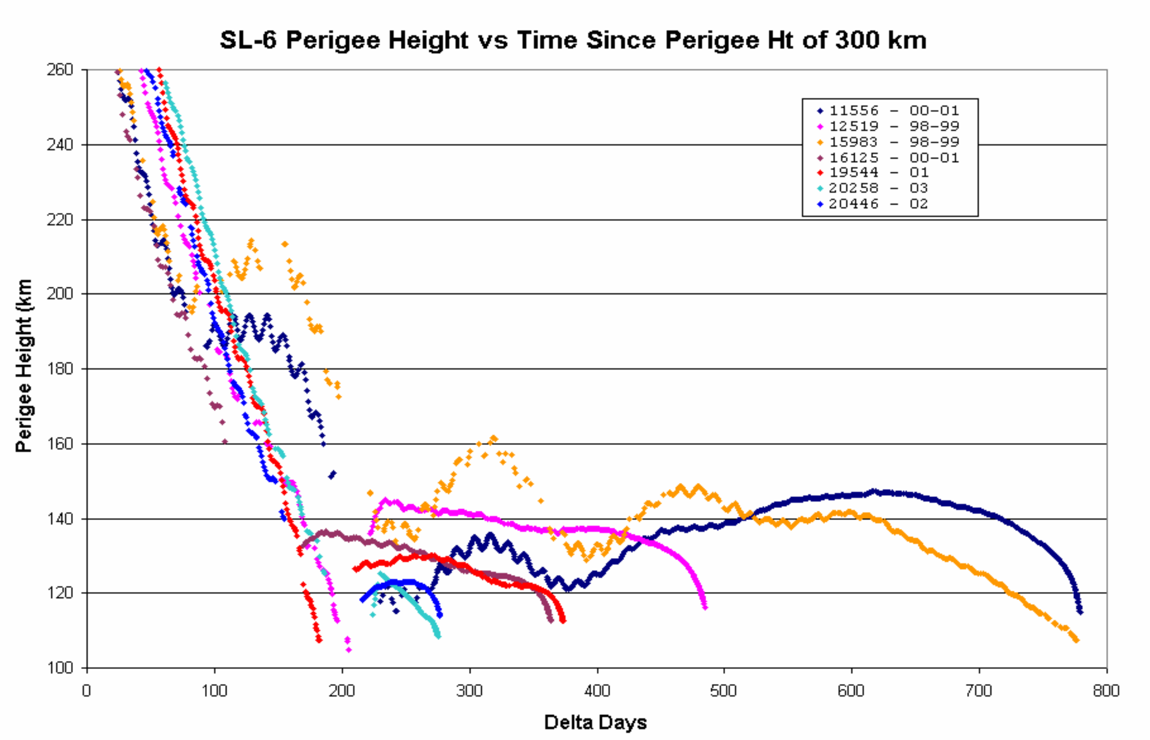

Figure 11. The perigee heights for a group of SL-6 rocket bodies are plotted as a function of days since a perigee height of 300 km. The legend indicates the year(s) of decay.

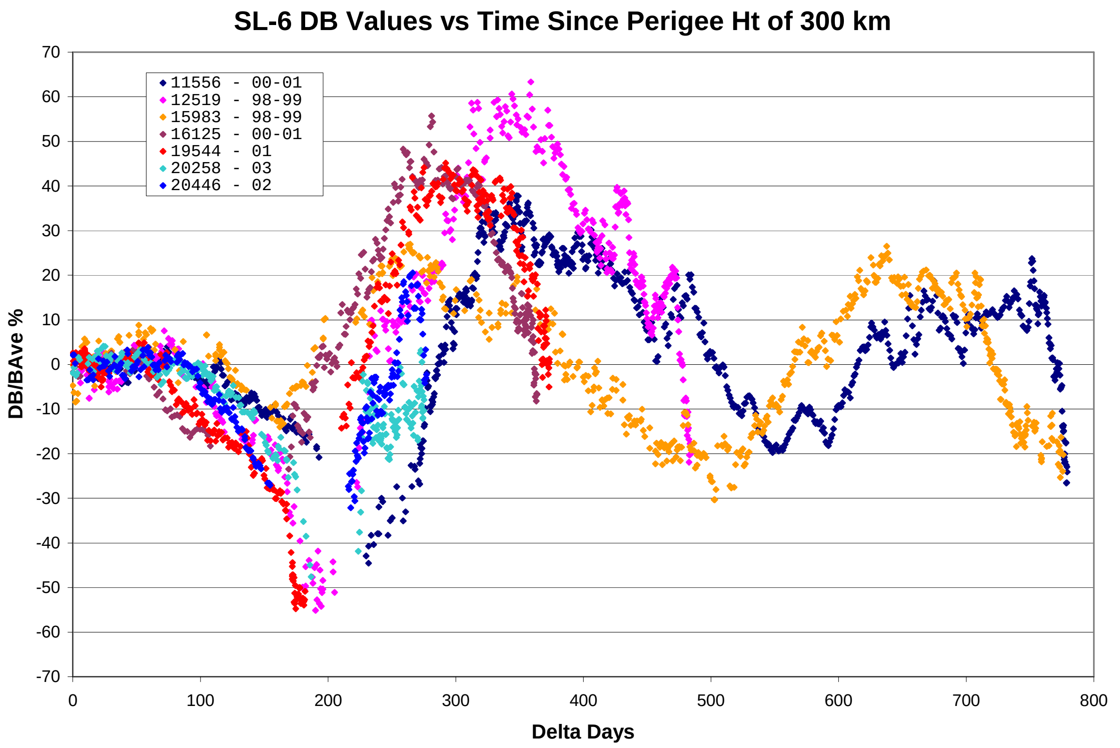

Figure 12. The DB values for a group of SL-6 rocket bodies are plotted as a function of days since a perigee height of 300 km. The legend indicates the year(s) of decay.

Figure 13 shows the plot of the B decrease for 6 SL-6 upper stages prior to any leakage occurring. The decrease in B is due to the decrease in the drag coefficient as the altitude decreases from 300 km to below 120 km. Figure 14 converts the B values to drag coefficient values. This is done by setting the drag coefficient value to 2.10 at the 250-300 km height range, and then computing the changing C_D values as a function of the drop in the B value. The resulting C_D values will need to be raised proportionally if future analyses show that the initial 250-300 km C_D value should be higher than the 2.1 value used here. Figure 14 also shows the values of the atmospheric mean free path for the lower altitudes. The transition region between the free molecular flow region and the slip-flow region occurs as the mean free path drops below approximately twice the length of the rocket body. This point occurs at approximately 125 km for these SL-6 upper stages with lengths of 3.2 m. The drag coefficient has dropped to a value of 1.0 by the time the rocket body enters the slip-flow region of the atmosphere, which is in agreement with theoretical values for drag coefficient changes.

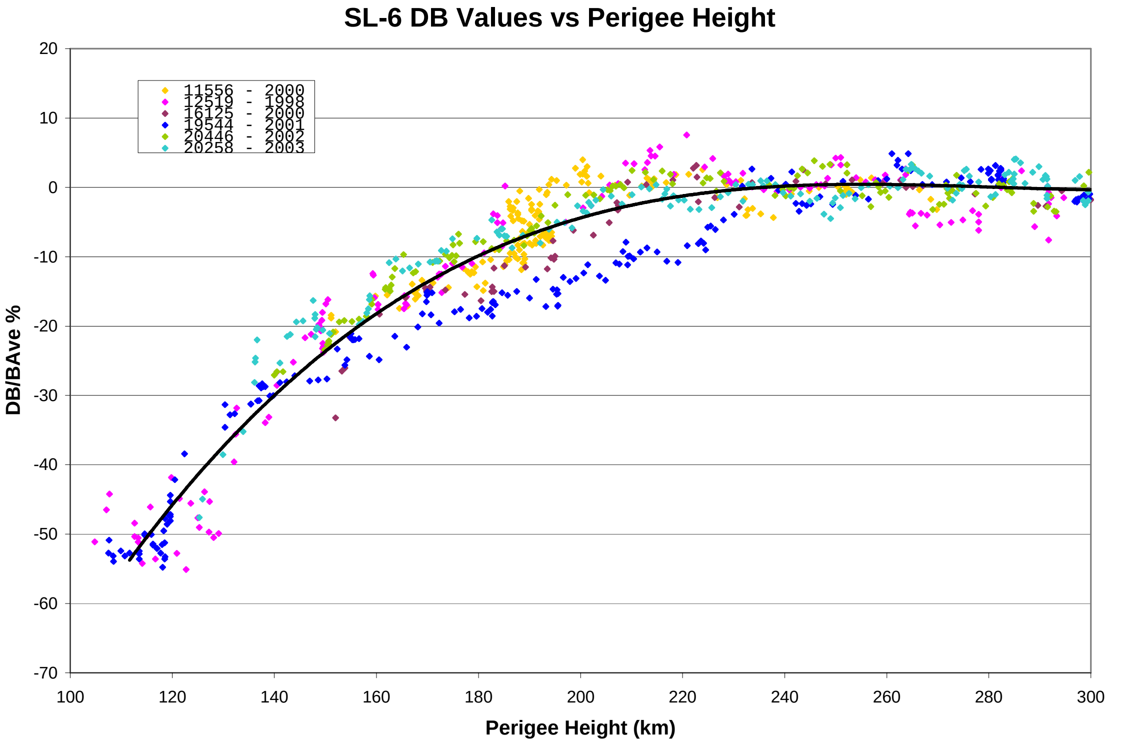

Figure 13. DB values as a function of perigee height are plotted for a group of SL-6 rocket bodies. These values are for the time period prior to any observable leakage.

Figure 15 shows the plot of the B variations for the values obtained after the final observed fuel leakage has occurred. Also included is the curve obtained from fitting the values in Figure 13 prior to any observable leakage. As can be seen from the figure the decrease in B, and thus the decrease in the drag coefficient, is much steeper after the leakage occurs than before any is observed. This same phenomenon was observed with the leakage from the Ariane rocket bodies, and is unexplainable at this time.

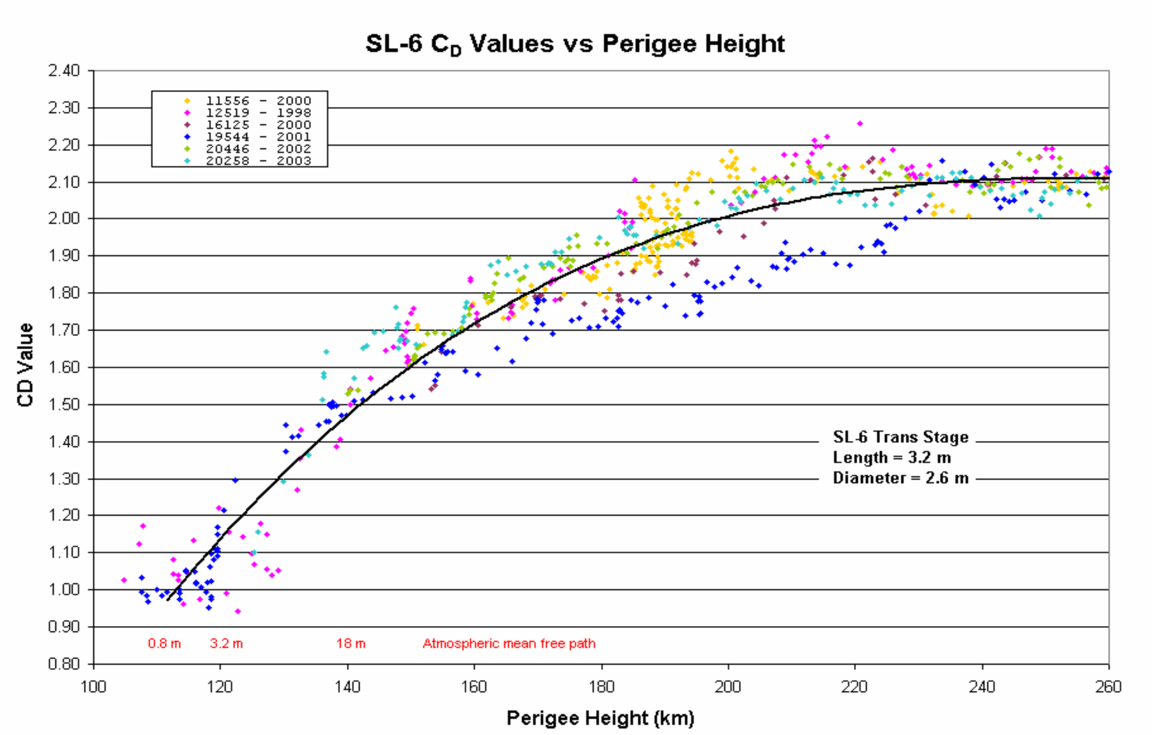

Figure 14. C_D values as a function of perigee height are plotted for a group of SL-6 rocket bodies. The atmospheric mean free path vs height is also listed.

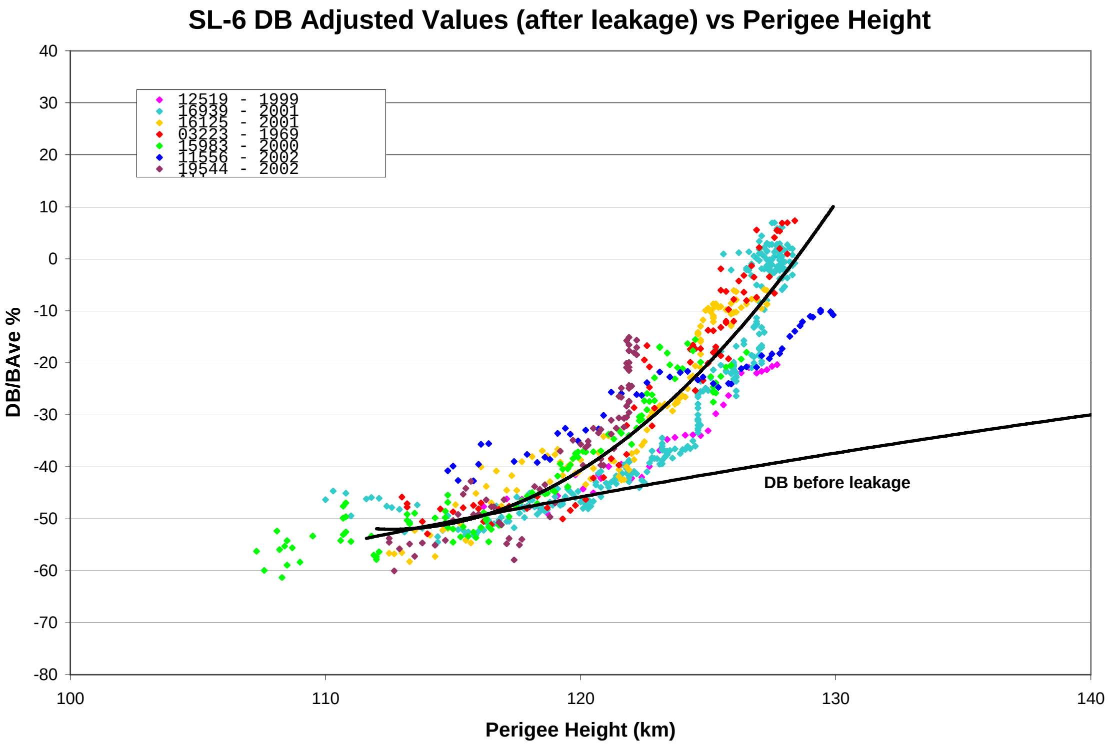

Figure 15. DB values for a group of SL-6 rocket bodies following the final leaking of the rocket bodies.

Summary

Figure 16 is a plot of the B variations of the least squares fitted curves for each set of rocket body types. Since the PAM-D heights started at 150 km it was necessary to adjust the PAM-D curve down by approximately 25%, where all the other curves could be based upon a long term B average value obtained at the 250-300 km height range. The curves acquired prior to any observable fuel leakage all appear to be very consistent as a function of altitude. The two curves obtained from post-leakage values both have significantly higher DB decay rates than the other curves for the same altitude. It is not know what is causing the different rates of B change, and needs to be researched further in future work.

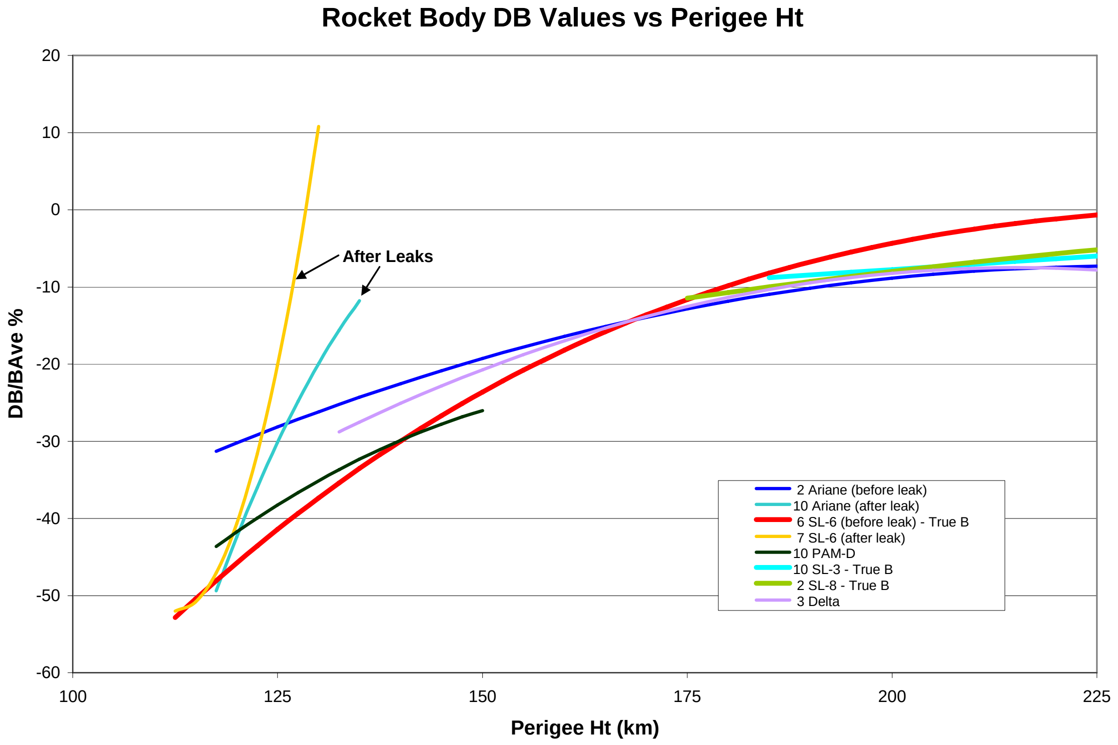

Figure 16. Least squares curve fits of DB values plotted as a function of perigee height for different rocket bodies. The number of rocket bodies used in the analysis are listed for each rocket body type.

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