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Improved Satellite Drag Coefficient Calculations from Orbital Measurements of Energy Accommodation

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Significant discoveries about gas–surface interactions that have been made in 90 years of laboratory experiments and 30 years of orbital measurements are reviewed. This information is used to improve the calculation of drag coefficients for satellites in low Earth orbit for several different satellite shapes and orientations by inserting the appropriate parameters in theoretical models of the drag coefficient. The drag coefficients so calculated provide increased consistency in orbital measurements of atmospheric density by satellites of different shapes near 200 km, where adsorbed atomic oxygen dominates the interaction and causes the energy accommodation coefficient to approach unity. It is essential to improve the numerical value of the drag coefficient so that the density of the neutral thermosphere can be inferred from satellite drag to better than the present 15% uncertainty. The key to this improvement is the calculation of drag coefficients from parameters measured in space, rather than from those measured in the laboratory under conditions very different from the space environment.

Nomenclature

A = reference area of the spacecraft
C_d = drag coefficient calculated from orbital measurements and physical models
D = diameter of the satellite
E_i = kinetic energy carried to the surface by incident molecules
E_r = kinetic energy carried away by reemitted molecules
E_w = kinetic energy that fully accommodated molecules would carry away
e = orbital eccentricity
F_d = drag force
h_p = altitude of perigee, km
k = Boltzmann constant
L = length of the satellite
m = mass of an air molecule
T = absolute temperature, K
T_i = kinetic temperature of the incident molecules
T_r = kinetic temperature of the reemitted molecules
T_w = kinetic temperature of fully accommodated molecules, i.e., wall temperature
V_i = velocity of the incident airstream, km/s
V_r = velocity of reemitted molecules
v_p = orbital velocity at perigee
z = altitude, km
α = energy accommodation coefficient
ρ = air density

Introduction

RECENT efforts to validate new models of the neutral thermosphere have continued to encounter a barrier that has prevented models and measurements from agreeing to better than 15% (Ref. 1). One of the important sources of uncertainty in the neutral measurements is the drag coefficient. Reduction of this uncertainty is the motivation for the present work.

Atmospheric density is often calculated from the drag force on a satellite, using the well-known equation

$$F_d = \tfrac{1}{2}\rho C_d A V_i^2 \tag{1}$$

which also defines the drag coefficient C_d. Here V_i is the velocity of the incident airstream relative to the spacecraft. The area A is usually taken to be the projected area of the satellite normal to the velocity vector. Space experiments measure F_d. The quantities A and V_i are usually known to high accuracy, leaving C_d as the principal cause of uncertainty in determining the density. C_d depends on the satellite shape and on the way in which air molecules interact with the satellite surfaces. Orbit analysts often use the term "drag coefficient" for a fitting parameter that constrains the orbital decay calculated from a thermospheric model to agree with the observed orbital decay of a satellite, but that is a meaning of drag coefficient different from the one used in this paper. Here we are concerned with a physical quantity that measures the actual drag force on a satellite.

Laboratory experimenters have been measuring the reflection of molecules from surfaces for the past 90 years.[2–5] These investigations have contributed to our understanding of such diverse areas of satellite science and technology as drag coefficients,[6–8] mass spectroscopy,[9–11] and spacecraft glow.[12–14] During the first 30 years of this century, the experimenters observed that gases (except the light gases, hydrogen and helium) lost nearly all of their kinetic energy and were reflected with a diffuse angular distribution. In the 1930s, Roberts[15] showed that, by taking extraordinary measures to clean surfaces, he could cause gaseous molecules to rebound with a considerable fraction of their incident kinetic energy. Since the pioneering research of Roberts, an enormous body of information has accumulated on the interaction of molecules with clean and contaminated surfaces. A representative sample of this literature has been cited in a recent paper,[16] in which the drag coefficients of spheres were calculated.

During the past 30 years, satellite experiments using pressure gauges[9,10] and mass spectrometers[11] have revealed that satellite surfaces are covered by adsorbed gases and that this coverage varies continuously as the satellite moves up and down in its orbit: An example[11] from the mass spectrometer on OGO-6 in Fig. 1 shows

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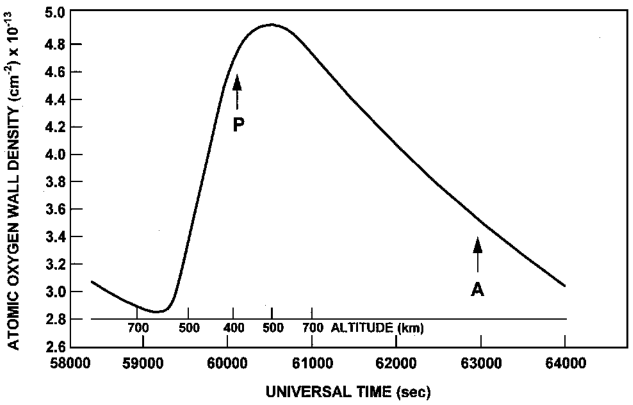


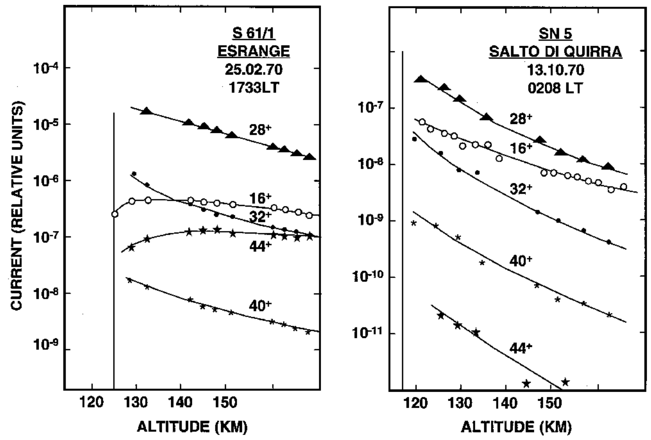
Fig. 1 Surface coverage of atomic oxygen on the walls of a mass spectrometer (after Hedin et al.[11]).

that net adsorption occurs near perigee (point P), whereas net desorption occurs around apogee (point A). The perigee height of OGO-6 was 400 km, and the fractional surface coverage of adsorbed molecules was about 5% of a monolayer near perigee. In the pressure gauge on the SPADES satellite,[10] the fractional surface coverage was about 4% at 400 km, but it was an order of magnitude larger at its perigee, 159 km. The continuous variation in surface coverage around the orbit increases the difficulty of simulating satellite conditions in the laboratory. In fact, the laboratory experiments cited in Refs. 2–5 have shown that the energy exchange on collision depends on at least eight parameters: the molecular composition, roughness, and lattice configuration of the surface; the number and nature of molecules adsorbed on the surface; and the composition, velocity, and angle of incidence of molecules striking the surface. To facilitate theoretical analysis, laboratory experimenters often use inert gases and make strenuous efforts to clean their surfaces. Satellite experimenters, on the other hand, must deal with reactive gases, such as atomic oxygen, which adsorb on satellite surfaces. Because of all of these complexities, we use insights gained from both orbital and laboratory measurements to summarize the present state of knowledge of satellite drag coefficients. However, when calculations of drag coefficients are carried out, they should be based on those parameters describing gas–surface interactions that have been measured in space, rather than those measured in the laboratory under conditions very different from the space environment.

We shall begin by describing the measurements that reveal how molecules interact with surfaces. Then we shall review how orbital measurements of energy accommodation[17] were used in the drag coefficient models of Sentman[18] and Schamberg[19,20] to calculate C_d for satellites of several different shapes and orientations near 200 km, where surface coverage dominates the gas–surface interaction. After that, we shall show how some theoretical models of energy accommodation were proven inapplicable at 200 km by comparing the predictions of these models with orbital measurements on satellites of different shapes. Such models may apply at much higher altitudes, where the surface coverage of adsorbed molecules is lower than it is at 200 km. This possibility is investigated in discussing the work of Harrison and Swinerd,[21] who analyzed the energy exchange at 800–1000 km. Then we shall turn to measurements in a highly eccentric molniya orbit, where the ratio of incident kinetic energy to the binding energy of adsorbed molecules is considerably higher than in low Earth orbit. Finally, we shall discuss Blanchard's[22] measurements of Shuttle re-entry, which can improve our knowledge of the transition from free molecular flow toward continuum flow as the mean free path approaches the satellite dimensions and reflected molecules begin to deflect incident molecules away from the spacecraft.

Processes at Satellite Surfaces

Striking evidence of adsorption and chemical reactions on surfaces at satellite altitudes was provided by the rocket experiments of Offermann and Grossmann.[23] These experimenters flew two mass spectrometers of identical semiopen design. One was cooled to the temperature of liquid helium, so that nearly every molecule that struck its surfaces froze there. Only molecules that did not strike a wall were ionized by an energetic stream of electrons and were measured. The other instrument was uncooled, so that most of the measured molecules had made multiple collisions with its walls. The measurements by the two instruments are compared in Fig. 2. In the cooled instrument (SN 5), the concentration of each species decreased with increasing altitude with its own scale height, as expected. But in the uncooled mass spectrometer (S 61/1), several species showed signs of surface chemical reactions: The curve for atomic oxygen (mass 16) has been severely distorted by reactions of incoming oxygen atoms with carbon and adsorbed oxygen atoms on the walls. This has produced carbon dioxide (mass 44) in amounts that greatly exceed the natural amounts. Carbon monoxide (mass 28) has also been produced on the walls, distorting the curve for molecular nitrogen, which also has mass 28. The curve for molecular oxygen also is distorted. Thermospheric experiments such as this make it clear that laboratory measurements of inert gases striking clean surfaces do not apply to the interactions in low Earth orbit: As many laboratory measurements have shown, adsorbed gases strongly influence gas–surface interactions.[2,3]



Uncooled spectrometer **Cooled spectrometer**

Fig. 2 Comparison of atmospheric gases ionized and measured by cooled and uncooled mass spectrometers at altitudes of 120–170 km (after Offermann and Grossmann[23]).

Confirmatory Laboratory Experiments

Laboratory simulations using atomic oxygen have confirmed the space-based measurements: The sticking probability of atomic oxygen on various metals was measured by Riley and Giese[24] and by Wood.[25] In later laboratory experiments by Lake and Nier[26] and Lake and Mauersberger,[27] a beam of atomic oxygen (the principal constituent of the lower thermosphere) flowed into an uncooled mass spectrometer. Some of the oxygen atoms adsorbed on the surfaces of the instrument and underwent chemical reactions in which carbon monoxide and carbon dioxide were produced. After most of the carbon had been oxidized, molecular oxygen became the main product of the experiments. More recently, Sjolander[28] measured in the laboratory the rates at which adsorption occurs and carbon monoxide, carbon dioxide, and water are produced in a mass spectrometer by a beam of atomic oxygen. Sjolander did not measure the surface coverage, and so his measured rates depended strongly on the number of hours the mass spectrometer had been exposed to the oxygen beam. Now Stein is developing a new method of producing a 5-eV beam of atomic oxygen with a flux that can deposit a monolayer on a surface in minutes instead of hours. This new source is better suited to simulating the environment in low Earth orbit than the older sources, which had lower fluxes and less energetic atoms. The effect of surface coverage on the rate of adsorption can be represented theoretically by Langmuir's adsorption isotherm (see Ref. 29 and many of Langmuir's subsequent papers). The theory of adsorption in satellite instruments, based on the Langmuir isotherm, was developed in a series of papers[9–11,30] in the 1960s and 1970s.

Accommodation Coefficients Measured in Low Earth Orbit

A measure of the kinetic energy lost by molecules on collision with surfaces is the energy accommodation coefficient α. It is defined by the equation

$$\alpha = \frac{E_i - E_r}{E_i - E_w} = \frac{T_i - T_r}{T_i - T_w} \tag{2}$$

where E_i is the kinetic energy transported to the unit area of the satellite surface by incident molecules, E_r is the kinetic energy carried away by reflected molecules, and E_w is the energy that would be transported away if the reflected molecules had adjusted to the surface (or wall) temperature before reemission. The subscripts on the temperatures have the same meanings as those on the energies. A review of satellite measurements has revealed that, in low Earth orbit near 200 km, α is near unity and appears to depend only on the amount of gas adsorbed on the surface.[17]

Accommodation coefficients have been measured in orbit by four satellites of unusual design that had two different measured aerodynamic interactions, such as orbital decay and spin decay or lift and drag. The values measured by several scientists are shown in Fig. 3, which is taken from Ref. 17. The perigee heights h_p, velocities at perigee v_p, and orbital eccentricities e are shown in the box. Each vertical column contains accommodation coefficients calculated from the orbital data by assuming a different angular distribution of reemitted molecules. These angular distributions are shown in Fig. 4. The fourth distribution (a fresh silver surface) could not be verified by experiment. It should be ignored. Angular distribution has been measured in orbit only once: It was 98% diffuse at 225-km altitude,[31] so that the quasispecular case (column 3) is inappropriate at altitudes near 200 km. Therefore, one can assume that all of the incident molecules were diffusely reemitted from S3-1 and Proton 2 at perigee heights below 200 km. One would have expected this because their measured accommodation coefficients were 0.99 and 1.00. Above 200 km, the accommodation coefficients are lower, as Fig. 3 shows. As the altitude increases and the surface coverage of adsorbed molecules decreases, one would expect the fraction of molecules that are diffusely reflected to decrease monotonically, as it does in laboratory experiments.[2]

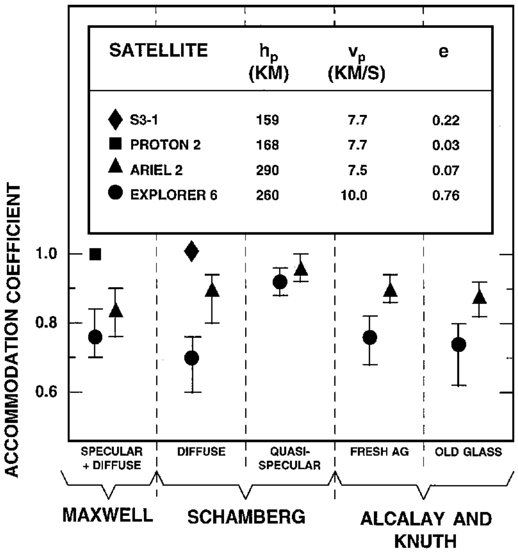


Fig. 3 Accommodation coefficients measured by four satellites.

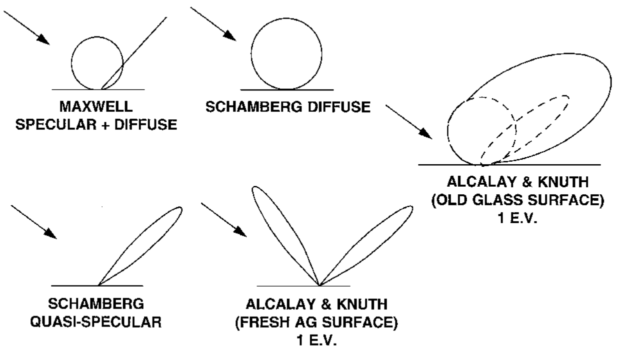


Fig. 4 Models of angular distribution used in Fig. 3, plotted in polar coordinates and projected on the plane of incidence.

Drag Coefficients in Low Earth Orbit

Because of the difficulty of laboratory simulation, we have used the energy loss and angular distribution of reflected molecules measured in orbit to guide us in calculating satellite drag coefficients. As explained in Ref. 16, we have inserted these parameters measured in low Earth orbit into the drag coefficient models of Sentman[18] and Schamberg.[19,20] In Sentman's model, the molecules striking the satellite surface have a Maxwellian velocity distribution (corresponding to the atmospheric temperature) superposed on the negative of the satellite velocity vector. The molecules reemitted from the surface have a diffuse angular distribution and a Maxwellian velocity distribution corresponding to the temperature T_r. In Schamberg's model, the incident molecules have the joule gas velocities superposed on the negative of the satellite velocity vector. The reemitted molecules can have an angular distribution ranging from specular to completely diffuse, depending on an adjustable parameter. All of the reemitted molecules have the same speed, $V_r = (3kT_r/m)^{1/2}$. Therefore, Schamberg's model is capable of representing quasi-specular reemission in which, for example, all of the reemitted molecules might be distributed in a cone of half-angle 15 deg. Sentman's model has the advantage that it gives a more accurate representation of the momentum transferred to the surface at grazing incidence. On the other hand, Schamberg's model, or superpositions of Schamberg models, can represent the entire range of reemitted angular distributions. A superposition of both models can handle almost any physical situation.

The calculated values of C_d vs altitude for a sphere and a stubby cylinder (with a length-to-diameter ratio of 1) are shown in Figs. 5 and 6, which are taken from Ref. 16. The solid curves were calculated using Sentman's model. The dashed curves, based on a combination of Sentman's and Schamberg's models, include a quasispecular

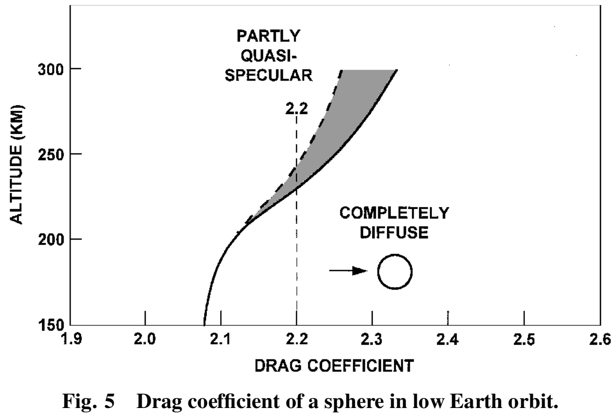


Fig. 5 Drag coefficient of a sphere in low Earth orbit.

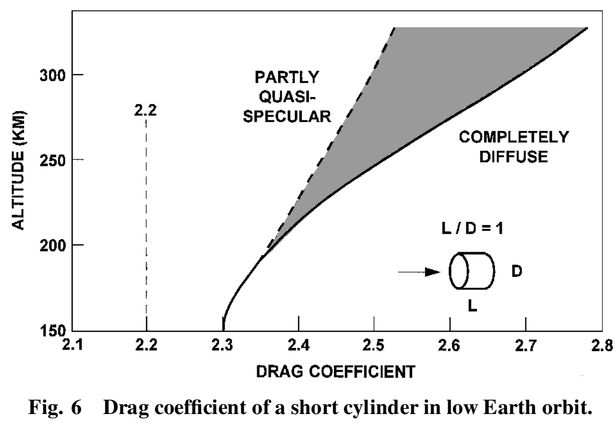


Fig. 6 Drag coefficient of a short cylinder in low Earth orbit.

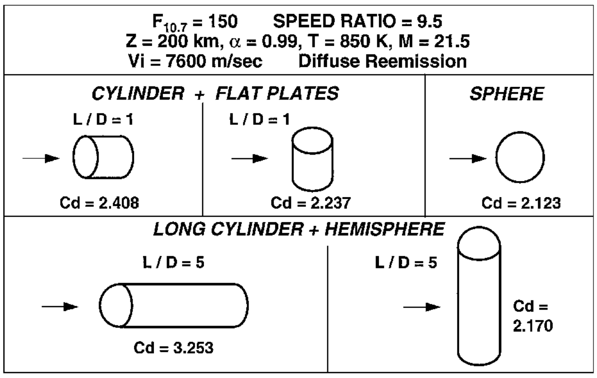


Fig. 7 Drag coefficients of satellites of five different shapes and orientations at 200 km. In all cases, the reference area is the projected area normal to the velocity vector, and the energy accommodation coefficient is 0.99.

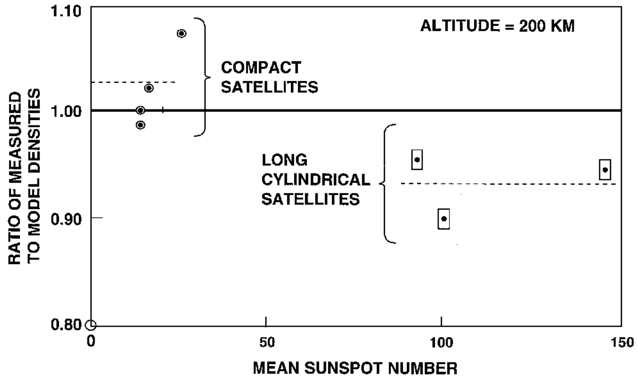


Fig. 8 Ratio of measured densities to model densities for two satellite shapes (data from Ref. 1).

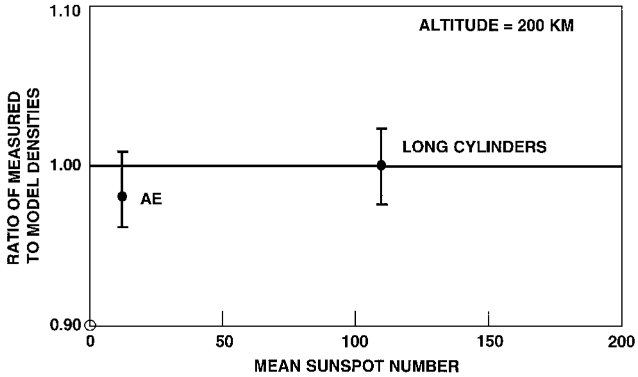


Fig. 9 Data of Fig. 8 recalculated using drag coefficients derived by using the accommodation coefficient 0.99 that was measured in orbit.

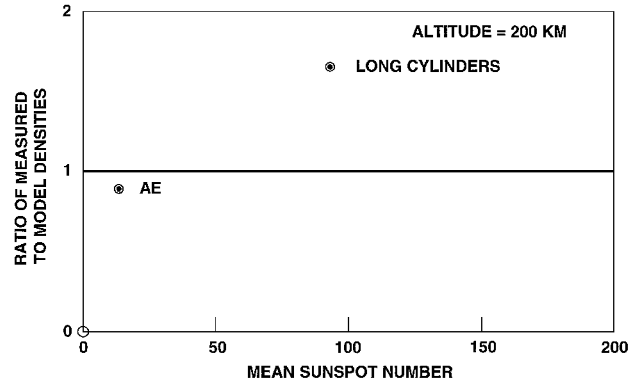


Fig. 10 Data of Fig. 8 recalculated using drag coefficients derived by using static-lattice, hard-sphere models of energy accommodation (note change of scale).

fraction that increases from 2% at 200 km to 21% at 325 km, which is our estimated upper bound on the quasispecular component. The vertical line at $C_d = 2.2$ represents Cook's early theoretical estimate,[6,7] which has been widely used for satellites of compact shapes. Comparing Fig. 5 with Fig. 6, one can see the importance of shape and orientation for precise density measurements.

The increase in C_d in Figs. 5 and 6 as the altitude increases from 150 to 300 km is caused mostly by the decrease in accommodation coefficient (see Table 5 in Ref. 8). This causes the air molecules to rebound with more energy, thus increasing the drag by Newton's third law. The quasispecular fraction used in calculating the dashed curves in Figs. 5 and 6 is an extrapolation intended to encompass the measurement of Gregory and Peters[31] on STS-8, which showed that at 225 km about 2% of the oxygen atoms reflected from a carbon plate were quasispecularly reflected.

Karr et al.[32] calculated drag coefficients for a sphere and a flat plate, using Gregory and Peters'[31] orbital measurements of angular distribution. Karr et al.[32] used Nocilla's[33] drifting Maxwellian model of the reflected molecules, and they assumed all possible values of the accommodation coefficient from zero to one. For a sphere, they obtained drag coefficients ranging from $C_d = 2.02$ or 2.03 for complete accommodation to $C_d = 2.21$ or 2.26 for zero accommodation.[32] They commented that "the lower bound would seem to be more likely since the reflection is nearly a cosine."[32]

We hope that future measurements will remove the uncertainty about reflection at higher altitudes. One way to reduce this uncertainty is to compare the densities deduced from satellites of different shapes flying simultaneously in similar orbits. Harrison and Swinerd[21] have used this method effectively at 800–1000 km, as will be discussed later. The idea can be understood by looking at Fig. 7, which has been calculated from Sentman's model for an altitude of 200 km, an atmospheric temperature of 850 K, and a mean molecular mass of 21.5. The angular distribution of reflected molecules is diffuse, and the accommodation coefficient is 0.99. The speed ratio (the ratio of the satellite speed to the most probable speed of air molecules) is 9.5. In all of these cases, the reference area has been chosen to be the projected area of the satellite normal to the velocity vector. Observe the effect of shape and orientation on C_d. At higher altitudes, where the accommodation coefficient is lower and the fraction of molecules quasispecularly reflected is greater, the drag coefficients of the various shapes will vary even more than in Fig. 7.

Long Cylindrical Satellites

Long cylindrical satellites can eliminate unrealistic models of drag coefficient because of the large area that is exposed to the airstream at grazing incidence. This will be shown in the present section by utilizing Marcos's[1] data for compactly shaped satellites and long cylindrical satellites that fly like an arrow. Marcos[1] compared accelerometer measurements of air density made by seven satellites with more than a dozen thermospheric density models. Four of the satellites were compactly shaped: Three of these were atmosphere explorers (AE), cylinders capped by flat plates, with a length-to-diameter ratio of 0.71 and with the cylindrical axis normal to the airstream. Three were long cylinders that flew like arrows, with a length-to-diameter ratio of 5. In deducing densities from his accelerometer measurements, Marcos[1] used $C_d = 2.2$ for the short cylinders and "about 3.5" for the long cylinders. We have calculated the average ratio of his measured densities to the 11 most recent density models in Fig. 8. The ratios are shown as a function of the sunspot cycle because the compact satellites were aloft at times of low solar activity, whereas the long cylinders flew when the sunspot number was high. On average, densities derived from the compact satellites are about 2% above the models, whereas densities from the long cylinders are 7% below the models. In Figs. 9 and 10 we shall reinterpret these data, using C_d calculated from two very different models of the accommodation coefficient.

Figure 9 shows the average of the density ratios for three of the compact satellites from Fig. 8 (the three AEs) and the average for the three long cylinders; however, in Fig. 9 the ratios have been adjusted by using drag coefficients calculated from Sentman's[18] model using the accommodation coefficient 0.99, which was measured in orbit near 200 km. The calculated C_d for the AEs is 2.297 in place of the conventional value, $C_d = 2.2$, and that for the long cylinders is $C_d = 3.253$ in place of 3.5. These drag coefficients computed from orbital measurements bring the average ratios of densities to models to within 2% of each other and within 2% of the average density model. This confirms Marcos's conjecture[1] that uncertainties in drag coefficient caused the discrepancy. There remains a possible slight bias in the ratio for the long cylinders because the exact shape and the exact C_d used in Fig. 8 for the long cylinders were not available.

Many theoretical models of the accommodation coefficient approximate the interaction of inert gases with clean surfaces by letting a hard sphere collide with a lattice of hard spheres that are not coupled to each other (Ref. 2, pp. 406–414). Goodman[34] has one such model, which produces a quasispecular reflection with an accommodation coefficient that is large at normal incidence and approaches zero at grazing incidence. Figure 10 shows the result of using Goodman's static-lattice, hard-sphere model of accommodation instead of orbital measurements to calculate drag coefficients. For the AE satellites, we obtain $C_d = 2.40$ instead of 2.2 and for the long cylinders $C_d = 1.96$ instead of 3.5. This causes the density ratio for the AE satellites to fall to 0.935 and that for the long cylinders to rise to 1.66. Instead of reconciling the measurements by satellites of two different shapes at 200 km, hard-sphere models increase the discrepancy to more than 70%. Many static-lattice, hard-sphere models that make similar assumptions and arrive at similar results are cited in Refs. 2 and 7. Hard-sphere models may be appropriate for analyzing laboratory measurements of inert gases striking carefully cleaned surfaces or satellite drag data at much higher altitudes but not for measurements on satellite surfaces near 200 km that are coated with adsorbed atomic oxygen and other contaminants.[9,11] Hard spheres would not adsorb (Fig. 1) or react chemically on surfaces (Fig. 2), and hard spheres do not have quantum levels, and so they cannot contribute to spacecraft glow.[12–14]

Energy Accommodation in a Molniya Orbit

Explorer 6 (Ref. 35) flew in a molniya orbit with a perigee altitude of about 260 km and an apogee of 42,500 km. It measured an accommodation coefficient of about 0.7. In contrast, Ariel 2, which had a perigee height of 290 km in a low Earth orbit, measured an accommodation coefficient of about 0.9, whereas Proton 2 and S3-1, with perigee heights below 200 km in low Earth orbit, measured accommodation of 0.99–1.00. These satellite measurements are shown in Fig. 3, which is taken from Ref. 17. The reduced accommodation in a molniya orbit might be explained by the 30% higher kinetic energy of incident molecules, which would reduce the likelihood of trapping. (For example, an incident oxygen atom would have about 6.5 eV, vs 5 eV in low Earth orbit.) Laboratory measurements on contaminated surfaces reported by Kostoff et al.[36] reveal a similar result: In Fig. 11, Kostoff's accommodation coefficients have been smoothed and plotted as linear functions of kinetic energy. Although the absolute values are not of high accuracy, the trends are unmistakable. In all cases, as the kinetic energy rose, α fell. In these laboratory measurements, we believe that the contaminants were physisorbed with a binding energy of about 1 eV. In contrast, the binding energy of atomic oxygen to surfaces is 5–8 eV. Another interesting feature of Fig. 11 is that, when the incident kinetic energy is far below the binding energy, surface roughness does not affect α, but when the kinetic energy approaches the binding energy, roughness has a sizable effect. By analogy, we would also expect other surface properties to become increasingly important in the satellite case as the altitude increases and the amount of oxygen adsorbed on the surface falls.

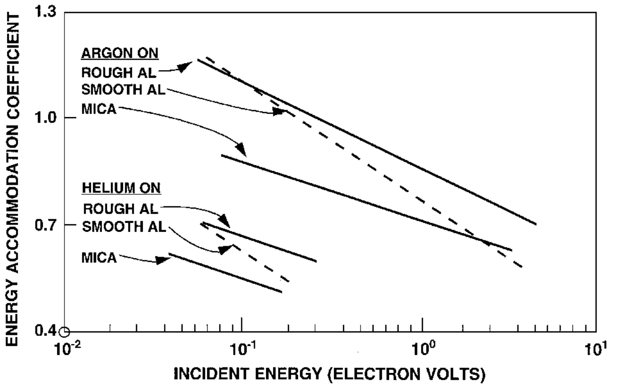


Fig. 11 Energy accommodation coefficients measured in the laboratory on contaminated surfaces (data from Ref. 36).

Gas–Surface Interactions at 800–1000 Kilometers

Although Fig. 10 demonstrates that static-lattice, hard-sphere models such as Goodman's[34] do not apply at 200 km, such models might apply at much higher altitudes, where the surface contamination is lower (see Fig. 1) and the light gas, helium, is a major constituent. In fact, the analysis of Harrison and Swinerd[21] at 800–1000 km reveals less diffuse reemission than at 200 km. As was demonstrated in Figs. 5–10, the drag coefficient depends on the shape and orientation of the satellite, as well as on the law governing energy accommodation. Harrison and Swinerd[21] used the effects of shape and orientation of three satellites that were simultaneously in orbit to study gas–surface interactions above 800 km. They found that the speed of reemission was about 2 km/s and the average angle of reemission was halfway between the normal and the specular directions.[21]

Shuttle Re-Entry

Because of its complicated shape and the changing flow regimes, the re-entering Shuttle presents a difficult computational problem: It is in free-molecular flow while in orbit and then passes through the transitional regime and into continuum flow as it descends toward the Earth. Blanchard[22] and Blanchard and Nicholson[37] have performed several important studies of the instrumental data collected during re-entry, using the High Resolution Accelerometer Package (HIRAP). Blanchard's HIRAP accelerometer measurements varied considerably from one flight to another. On average, he measured a lift-to-drag ratio of 0.13 at 160 km at an angle of attack of 40 deg (Ref. 22). This ratio is well above what would be expected for diffuse reflection with complete accommodation. Blanchard's analysis shows that his average data from six flights would agree with either a Maxwellian reflection coefficient of 0.91 or diffuse reflection with $\alpha = 0.93$. This contrasts with the accommodation coefficients in Fig. 3 of 0.99–1.0 measured by S3-1 and Proton 2 at similar altitudes. This discrepancy and the variability of the Shuttle measurements should be investigated further. The Shuttle is a complicated, concave, maneuvering structure that carries people, emits effluents, and carries many active systems. Perhaps some of these complications contribute to the discrepancy. At 160 km, the Shuttle is just entering transitional flow. The interaction between incoming and reflected molecules also could have an exaggerated influence on the HIRAP measurements because of the Shuttle's nonconvex shape.

On Shuttle flight STS-62, Blanchard and Nicholson[37] flew an improved accelerometer package, the Orbital Acceleration Research Experiments. With this improved instrumentation, they clearly recorded the beginning of the transition from free molecular flow at about 165 km. They observed the effects of gases emitted from the orbiter during re-entry, when significant effects could be expected, and possible effects of ejected gases under certain conditions above 230 km (Ref. 37). Because of its large size, the Shuttle entered the transitional regime at about 165 km. More information about the transitional regime could come from a comparative analysis of Blanchard and Nicholson's[37] Shuttle data with the data of King-Hele[38] and Bowman,[39] who analyzed the final decay of satellites of lengths 2 and 3.5 m. These satellites entered the transitional regime at altitudes of 120 to 130 km. By the time the Knudsen number reached $\frac{1}{2}$, when the mean free path was half the satellite length, C_d had fallen to about half of its value in free-molecular flow. An important question to investigate is how best to calculate the Knudsen number and how to treat transitional flow for satellites of different shapes and attitudes. A vast body of theoretical work on transitional flow was evaluated in impressive papers by Willis[40] and Cercignani,[41] but the internal excitations of molecules revealed by observations of spacecraft glow[12–14] have not yielded to such methods of treatment. On the other hand, advances in digital computation have made it possible to treat transitional flow by Monte Carlo methods[42] that can include energy levels of atoms and vibrational–rotational levels of molecules. The application of Monte Carlo methods could vastly improve our understanding of the Shuttle re-entry data.

Summary

As was shown in Figs. 1 and 2, incoming oxygen atoms adsorb on satellite surfaces and react strongly with other adsorbed molecules. These adsorbed molecules increase energy accommodation and broaden the angular distribution of reflected molecules, as has been demonstrated in many of the laboratory experiments cited in the references. For this reason, satellite drag coefficients should be calculated from accommodation coefficients and angular distributions measured in orbit, rather than from those calculated from theory or measured in the laboratory, which usually involve inert gases colliding with clean surfaces. We have described how orbital measurements of energy accommodation have been inserted in the drag coefficient models of Sentman[18] and Schamberg[19,20] to calculate realistic drag coefficients of various satellite shapes at altitudes near 200 km. Figures 8–10 demonstrate that such realistic drag coefficients produce more consistent atmospheric density measurements than do drag coefficients based on the hard-sphere models that were developed to explain laboratory measurements. As the altitude increases, the surface coverage decreases, so that the nature of the substrate begins to influence the accommodation coefficient and angular distribution of reflected molecules, causing the uncertainty in C_d to increase. We have suggested how future measurements can reduce this uncertainty. Then we turned to the use of several satellites in nearby orbits by Harrison and Swinerd[21] to improve our knowledge of the interaction at 800–1000 km. Finally, we discussed the Shuttle re-entry measurements of Blanchard[22] and Blanchard and Nicholson[37] that help us to understand the transition from free-molecular flow as reflected molecules begin to deflect incident molecules from striking the spacecraft. A comparative analysis of re-entry measurements from the Shuttle and unmanned satellites using Monte Carlo methods could improve our understanding of transitional flow.

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