

# Recommended Drag Coefficients for Aeronomic Satellites

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Densities derived from accelerometer measurements depend on the drag coefficient assigned to the satellite. Although laboratory measurements increase our understanding of gas-surface interactions, they are not adequate to determine the appropriate drag coefficient because it is not known how the surface conditions at any particular altitude relate to the heterogeneous chemisorption and physisorption revealed by measurements in the laboratory. Therefore it is necessary to rely on drag and accommodation coefficients which have been measured in orbit. We use knowledge of these coefficients from our recent review of satellite measurements, and insights gained from laboratory measurements, to construct a table showing how the accommodation coefficient of compact satellites varies with altitude and solar activity. We then insert the accommodation coefficients in theoretical calculations to provide recommended drag coefficients for a variety of satellite shapes in low earth orbit. By using all of the information on aerodynamic coefficients measured by previous satellites, we can minimize errors in density measurements made by future satellites. Soon a new aeronomic satellite, STEP-1, will be flown. If its large flat plates sometimes are oriented at several different angles to the airstream, our knowledge regarding the dependence of drag coefficients on altitude and angle of incidence can be improved.

## 1. INTRODUCTION

In order to derive atmospheric densities from accelerometer measurements, it is necessary to assume a drag coefficient,  $C_d$ , because aeronomic satellites do not incorporate a method of measuring it. Consequently, the accuracy of the inferred densities can be no better than the

accuracy of the assumed value of  $C_d$ . Its numerical value depends on the reference area, which often is chosen to be the cross sectional area of the satellite normal to the airstream. With that choice, the value of  $C_d$  which is customarily used for convex satellites of compact shapes is 2.2 [Cook, 1965, 1966]. By "compact shape" we mean that the ratio of the satellite's maximum to minimum diameter is less than 1.5, and the satellite does not have large external structures like solar paddles. A  $C_d$  in the neighborhood of 3.0 to 3.5 is used for long cylindrical satellites that fly like an arrow, depending on the length-to-diameter ratio of the satellite and the air temperature [Sentman, 1961; DeVries, 1972; Moe, et al., 1993].

The fundamental processes which determine the drag coefficient are momentum exchange and chemical reactions at the satellite surface, so we discuss laboratory studies of these processes in the following section. Then we summarize what has been learned about momentum transfer from orbital measurements, which we recently reviewed [Moe, et al., 1993]. From the orbital measurements of surface-particle interaction, we infer the appropriate parameters to use in calculating  $C_d$  at various altitudes for satellites in low-earth orbit. By low-earth orbit we mean an orbit with a perigee altitude below 1000 km and an eccentricity value less than 0.3. Because satellite measurements of the appropriate parameters have not been made above 325 km, we mention some theoretical studies which may be useful in extrapolating the parameters to higher altitudes. We use the measured parameters to calculate  $C_d$  for satellites of several simple shapes. Finally, we suggest some theoretical and experimental efforts that could improve our knowledge of satellite drag coefficients.

## 2. LABORATORY MEASUREMENTS

The exchange of momentum and energy when gases strike solid surfaces has been studied in the laboratory for eight decades. This research has shown that the exchange depends on many factors: the mass of the substrate atoms; the particular crystal face; the mass, fractional coverage, and binding energy of adsorbed molecules; and the mass, energy, and angle of incidence of the incoming molecules [Saltsburg, et al., 1967; Thomas, 1980; Boffi and Cercignani, 1986]. It would be almost impossible to measure all of these factors in orbit, then reproduce them in laboratory experiments. This is the reason we believe that in-orbit measurements of gas-surface interactions are essential.

On the other hand, laboratory measurements have yielded much information on the interaction of gases with surfaces, and have provided models which can be fitted to the satellite measurements of gas-surface interactions. An example is the laboratory data from O'Keefe and French [1969], which is copied in Figure 1a. It shows that when Argon (mass 40) with a kinetic energy of 1.35 eV strikes a surface covered with adsorbed Hydrogen (mass 2), much of the Argon is reemitted in the quasi-specular direction; but when the surface is covered with adsorbed gases which are heavier or bind more strongly to the surface, the quasi-specular peak is reduced, indicating a stronger interaction with the surface. Figure 1b shows the data from Gregory and Peters' [1987] experiment on the Space Shuttle Flight STS-8. Here atomic oxygen is reflecting from a surface which probably is coated with atomic oxygen chemisorbed

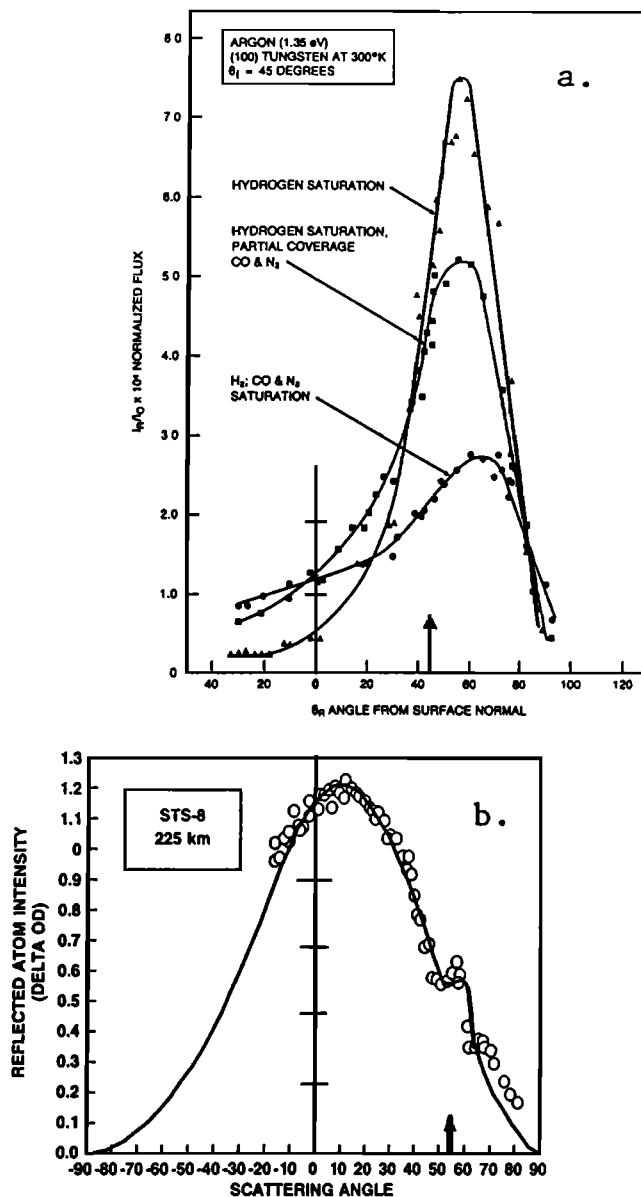


Fig. 1. This composite figure shows how the relative mass, binding energy, and fractional coverage of adsorbed molecules affect the angular distribution of reflected molecules: (a) The laboratory measurement of O'Keefe and French shows argon with a kinetic energy of 1.35 e.v. reflecting from the 100 crystal face of tungsten which is partly coated with weakly bound, lighter molecules. As the fractional coverage and mass of the physisorbed molecules increase, the high quasispecular peak is gradually reduced. In contrast, (b), from the satellite experiment of Gregory and Peters, shows that when atomic oxygen strikes a carbon surface coated with chemisorbed oxygen, which has a binding energy comparable with the incident kinetic energy of 5 e.v., the quasispecular component has been reduced to 2%. (see text).

with a binding energy comparable with the incident kinetic energy. In this case, the quasi-specular component is only 2% of the reflected beam. (The vertical arrows indicate the specular angle of reflection, i.e. the angle at which all the molecules would be reemitted if the reflection were 100% specular.) This figure illustrates the controlling influence of adsorption on the interaction of gases with surfaces.

Our understanding of adsorption has increased greatly since World War II because of the application of new analytic techniques, such as low-energy electron diffraction (LEED), Auger electron spectroscopy (AES), field ion microscopy, flash desorption, and many others. Knowledge obtained by these techniques can be applied to satellite problems, even though the techniques are too complicated to be employed in space. By using some of these techniques, Gomer [1967] showed that carbon monoxide adsorbs on tungsten in several different states. Farnsworth [1970] investigated the complicated chemical reactions of carbon monoxide and molecular oxygen on a nickel surface. Czanderna [1970] showed that molecular oxygen adsorbs on silver in several states, some atomic and some molecular. At the present time, an enormous body of knowledge has accumulated regarding the chemisorption and the physisorption of oxygen on the transition metals [Brundle and Broughton, 1990]. This experimental knowledge of surface chemical reactions can be combined with theoretical models of adsorption [Honig, 1967; Steele, 1967; Newns, 1969; Sparnaay, 1970; Ross, 1967; Roberts and McKee, 1978; Davenport and Estrup, 1990] to organize and rationalize the data obtained on gas-surface interactions from satellite experiments. Such studies could improve greatly the interpretation of future measurements of density and composition in the thermosphere.

### 3. ORBITAL MEASUREMENTS

The analysis of both satellite drag and mass spectrometric measurements requires understanding the surface reactions of atomic oxygen and carbon. The universal contaminant, carbon, interacts with the principal thermospheric constituent, atomic oxygen, to produce new species, some of which stick to the surface and modify the energy relationships when the airstream strikes a satellite surface. Evidence of these reactions was unmistakable in the Ogo 6 satellite measurements [Hedin, et al., 1973], in the comparison of rocket measurements by cooled and uncooled mass spectrometers [Offermann and Grossmann, 1972], and in the Long Duration Exposure Facility (LDEF) experiments [Levine, 1991]. A laboratory calibration by Offermann and Trinks [1971] also showed that carbon monoxide and carbon dioxide were produced within the mass spectrometer when molecular oxygen flowed in. Laboratory

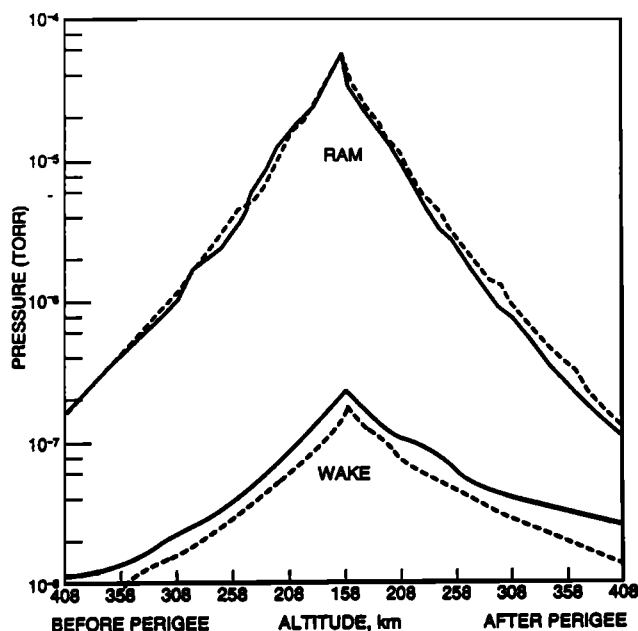


Fig. 2. History of the pressure in a gage aboard the Spades Satellite [after Carter, et al, 1969]. The loci of the maximum (ram) and minimum (wake) pressures during each spin cycle are shown for orbital revolutions 25 (solid lines) and 109 (dashed lines). These curves show that net adsorption occurs whenever the satellite descends toward perigee. Because adsorbed molecules increase energy accommodation, this figure suggests that  $C_d$  also changes as the satellite descends and ascends.

simulations in which atomic oxygen flowed into a mass spectrometer resulted in the formation of molecular oxygen, carbon monoxide, and carbon dioxide [Lake and Nier, 1973; Lake and Mauersberger, 1974].

Efforts to model adsorption at satellite surfaces [Moe and Moe, 1967, 1969; Hedin, et al., 1973] have utilized the Langmuir isotherm [Brunauer, et al., 1967] because of its simplicity and its ability to fit the data. Heterogeneous adsorption has been represented by a Langmuir "patch model" [Moe, et al., 1972]. Despite these modest successes, it should be realized that the commonly used isotherms (including Langmuir's) are models of physical adsorption. A more penetrating analysis of the combination of chemical and physical adsorption which occurs at satellite surfaces might require the application of the Hamiltonian representation of the energy relationships [Goldstein, 1980] which can be solved in the Hartree-Fock approximation [Newns, 1969; Einstein, et al., 1980]. Nevertheless, it is clear from the satellite data and the analyses which have been performed that the surface coverage of adsorbed molecules varies continuously as the satellite moves up and down in its orbit. This can be seen in Figure 2, which shows the

TABLE 1. Accommodation Coefficients (A diffuse angular distribution is assumed.)

F <sub>10.7</sub>	75	75	75	150	150	150	225	225	225
Altitude (km)	$\alpha$	M	Temp (K)	$\alpha$	M	Temp (K)	$\alpha$	M	Temp (K)
150	1.00	22	526	1.00	23	618	1.00	24	710
175	1.00	21	629	1.00	22	760	1.00	23	900
200	0.99	20	693	0.99	22	842	0.99	23	1027
225	0.98	19	728	0.98	21	887	0.99	22	1105
250	0.96	18	745	0.97	20	920	0.98	22	1156
275	0.94	17	757	0.95	19	938	0.96	21	1190
300	0.92	16	763	0.93	18	949	0.94	20	1213
325	0.89	15	766	0.92	17	955	0.93	19	1230
$\infty$			779			973			1270

maximum (RAM) and minimum (WAKE) pressure in the spinning pressure gage on the Spades satellite [Carter, et al., 1969]. The minimum pressure is supplied by desorption from the walls of the gage, so we deduce from this and similar data from other satellite instruments that the surface coverage varies continuously. Because energy exchange at surfaces depends strongly on surface coverage, we infer that drag coefficients also vary as the satellite moves up and down. We also deduce from Figure 2 that the surface coverage varies much more slowly with altitude than the ambient atmospheric density.

#### 4. RECOMMENDED PARAMETERS

Until a detailed Hamiltonian analysis can be performed for some representative satellite surfaces and compared with the satellite measurements, we suggest the use of a simplified empirical description utilizing the energy accommodation coefficient  $\alpha$  [Wachman, 1962] defined by

$$\alpha = \left( E_i - E_r \right) + \left( E_i - E_w \right) \quad (1)$$

where  $E_i$  is the kinetic energy carried to a unit area of the surface by the incident molecules,  $E_r$  the kinetic energy carried away from the unit area by the reflected molecules, and  $E_w$  the kinetic energy the reflected molecules would carry away from the surface if they were reemitted at the temperature of the surface (or wall). This coefficient has been measured in orbit by three paddlewheel satellites [Moe et al., 1993], and by the ratio of lift to drag on the S3-1 satellite [Ching, et al., 1977]. The angular distribution of reemitted molecules has been measured only on the STS-8 at 225 km, suggesting that only 2% of the oxygen atoms were reflected quasi-specularly at that altitude [Gregory and Peters, 1987]. Because we lack sufficient information on angular

distributions, and because high accommodation coefficients are associated with nearly diffuse angular distributions in laboratory experiments [Saltsburg, et al., 1967], we have used values of  $\alpha$  which were derived from satellite data by assuming a diffuse distribution. Using data from the three satellites (S3-1, Proton 2, Ariel 2) in low-earth orbit, we show in Table 1 as a function of altitude our estimate of the accommodation coefficient,  $\alpha$ , mean molecular mass,  $M$ , and atmospheric temperature for three levels of solar activity, as represented by the 10.7 solar radio emissions,  $F_{10.7}$ . Since none of the three satellites carried an accelerometer, the drag forces and torques represented an integration over the region around perigee. Therefore we assigned the measured values of  $\alpha$  to an altitude 2/3 of a scale height above the perigee altitude [King-Hele, 1966]. The values of  $\alpha$  for  $F_{10.7} = 75$  are based on the data in Figure 3 of Moe et al. [1993]; the values for higher solar activity are based on the assumption that the accommodation coefficient is determined by the amount of atomic oxygen adsorbed on the surface of the satellite. The relationship is highly nonlinear: Large changes in surface coverage have only a small effect on  $\alpha$  when it approaches 1.00. For this reason, this coefficient changes more slowly with altitude when high solar activity has caused the atmosphere to expand upward. The values we give in the tables are for use in calculating drag coefficients for satellites of compact shapes in low-earth orbit. There is insufficient evidence in the open literature to make such an estimate for the sides of a long cylindrical satellite, or for a satellite in a highly eccentric orbit [Moe, et al., 1993].

We have terminated Table 1 at 325 km because we do not have measurements of  $\alpha$  above that altitude. We expect that at higher altitudes, where  $\alpha$  is likely to be lower, a quasi-specular component of reemitted molecules should be included in calculations of drag coefficients. Methods of

TABLE 2. Drag Coefficient of a Satellite with  $L/D = 1$ 

The cumulative effect of the terms in equation (2) is shown for a cylindrical satellite capped by a flat plate which faces the airstream. The parameters are:  $\alpha = 0.95$ ,  $M = 19$ , satellite velocity,  $V_i = 7600$  m/s, local atmospheric temperature  $T = 938$  K, and satellite wall temperature  $T_w = 300$  K. A completely diffuse angular distribution of reemission is assumed.

TERM 1	TERMS 1 & 2	TERMS 1 & 2 & 3
2.000	2.317	2.627

incorporating a quasi-specular component have been developed by Schamberg [1959], Nocilla [1963], Boring and Humphris [1970], Fredo and Kaplan [1981], and Herrero [1983].

### 5. DRAG COEFFICIENTS

The measurement of atmospheric drag on a satellite leads to a determination of atmospheric density through the well-known relation

$$F_d = \frac{1}{2} \rho C_d A V^2$$

which also defines the drag coefficient. Here  $F_d$  is the drag force,  $\rho$  is the atmospheric density,  $A$  is a suitable reference area of the satellite, and  $V$  is the velocity of the airstream relative to the satellite.  $A$  is usually taken to be the projected area of the satellite normal to the velocity vector. Under most circumstances, the values of  $A$  and  $V$  are precisely known, so the measurement of  $F_d$  by an accelerometer determines the product  $\rho C_d$ . Any uncertainty in  $C_d$  produces an uncertainty in the density  $\rho$ . Suppose that the air molecules had no thermal motion and all of the incident molecules stuck to the surface. (The thermal velocity is a small fraction of the satellite velocity at altitudes below 300 km.) Then, according to Newton's second law, the drag force would be  $\rho A V^2$ . Therefore  $C_d = 2$ . If now we compute the effect of the molecules reemitted from the satellite surface, but still ignore any random thermal velocities, we obtain a correction term  $K$  which depends on the accommodation coefficient, the angular distribution of reemitted molecules, and the satellite shape. Adding the contribution of the reemitted molecules to that of the incident molecules, we have  $C_d = 2 + K$ . If, in addition, we take account of the random thermal motions of the molecules, we obtain a different correction term  $G$  which depends, in addition to the other parameters, on another parameter, the speed ratio,  $S$ , which is the ratio of the satellite orbital speed to the most probable speed of air

molecules. Now we can write  $C_d = 2 + G$ . For satellites of compact shapes, thermal motions typically increase  $C_d$  by 5% to 15%, but thermal motions can increase the  $C_d$  of long cylinders by 30% to 50% [Sentman, 1961; Mazzella, et al., 1983; Moe, et al., 1993].

We rewrite the expression for  $C_d = 2 + G$  as

$$C_d = 2 + K + H \quad (2)$$

where  $H = G - K$ . This is done to show why drag measurements of density are capable of higher accuracy than other thermospheric measurements: The expression for  $C_d$  begins with the constant, 2. For compact satellites in the lower thermosphere, this constant term is an order of magnitude larger than the other terms. An example of the size of the correction terms in Equation (2) is given in Table 2. It shows  $C_d$  for a short cylindrical satellite capped by a flat plate which faces the airstream. Its length-to-diameter ratio ( $L/D$ ) is 1.00. The parameters, which correspond to conditions at an altitude of 275 km, are given in Table 2. In the second column one sees the effect of the molecules reemitted from the front plate of the satellite when random motions are ignored (hyperthermal approximation). This quantity was calculated using Schamberg's [1959] model. The third column includes the effect of random thermal motions of the air [Sentman, 1961]. (This table is based on the assumption that molecules are reemitted diffusely.) By contrast with drag measurements of density, other thermospheric measurements of density (mass spectrometric, extinction) require calibration factors, knowledge of chemisorption, and photoabsorption cross sections which are not dominated by a large constant term which is known a priori.

Drag coefficient calculations which assume a completely diffuse angular distribution of reemitted molecules are computationally simple but not entirely satisfying, because of the laboratory measurements discussed earlier, which are illustrated by Figure 1. Imbro et al. [1975] explored several combinations of diffuse and quasi-specular distributions, but could not reach a definite

TABLE 3. Drag Coefficients for the Case  $\alpha = 1.00$ 


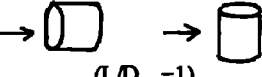
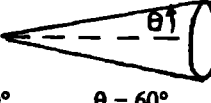
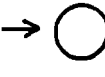
Temp.	M	Flat Plate 	Cylinder + Flat Plates (L/D = 1) 	Cone $\theta = 30^\circ$ 	Sphere 		
500 K	18	2.131	2.332	2.187	2.069	2.114	2.094
500 K	22	2.117	2.300	2.169	2.062	2.103	2.084
1000 K	18	2.139	2.424	2.232	2.077	2.122	2.106
1000 K	22	2.124	2.382	2.208	2.069	2.109	2.094
1500 K	18	2.147	2.496	2.269	2.085	2.130	2.118
1500 K	22	2.131	2.447	2.241	2.075	2.116	2.103

TABLE 4. Drag Coefficients for the Case  $\alpha = 0.95$ 


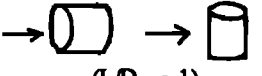
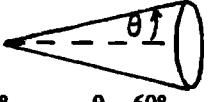
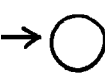

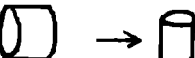
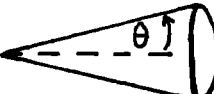
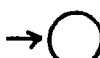
Temp.	M	Flat Plate 	Cylinder + Flat Plates (L/D = 1) 	Cone $\theta = 30^\circ$ 	Sphere 		
500 K	18	2.353	2.555	2.362	2.180	2.307	2.242
500 K	22	2.347	2.530	2.349	2.177	2.302	2.237
1000 K	18	2.361	2.646	2.407	2.188	2.315	2.254
1000 K	22	2.354	2.612	2.388	2.184	2.308	2.247
1500 K	18	2.369	2.718	2.444	2.196	2.323	2.266
1500 K	22	2.361	2.677	2.421	2.190	2.315	2.257

TABLE 5. Drag Coefficients for the Case  $\alpha = 0.90$ 

Temp.	M	Flat Plate 	Cylinder + Flat Plates (L/D = 1) 	Cone $\theta = 30^\circ$ 	Sphere 		
500 K	18	2.480	2.682	2.462	2.244	2.417	2.327
500 K	22	2.476	2.658	2.450	2.241	2.413	2.323
1000 K	18	2.488	2.773	2.506	2.252	2.425	2.338
1000 K	22	2.482	2.740	2.489	2.248	2.420	2.332
1500 K	18	2.496	2.845	2.544	2.260	2.433	2.351
1500 K	22	2.489	2.805	2.522	2.254	2.426	2.342

conclusion because of the limitations of previous satellite data. We have explored likely errors caused by these uncertainties for the satellite shape and parameters of Table 2. If the value of  $\alpha$  were 0.97 instead of 0.95, and the angular distribution remained diffuse, the value of  $C_d$  would be 2.560. If 90% of the molecules were diffusely reemitted with  $\alpha = 1.00$  and 10% were quasi-specularly reemitted with  $\alpha = 0.50$ , then  $C_d$  would be 2.513. If the molecules

striking the front plate were all diffusely reemitted with  $\alpha = 0.95$ , while 10% of the molecules which struck the cylindrical sides were quasi-specularly reemitted, then  $C_d$  would be 2.608. These exploratory calculations suggest that near 275 km, uncertainties in the accommodation coefficient and angular distribution could cause the calculated drag coefficient of compact satellites to be uncertain by about 4%. The uncertainties will increase rapidly with altitude.

On the other hand, at altitudes near 200 km, similar calculations suggest an uncertainty of about 1% in the drag coefficient.

As an example to assist experimenters who want to use more realistic drag coefficients in reducing density measurements, we have constructed Tables 3, 4, and 5 for a range of parameters, using Sentman's [1961] equations, which assume a completely diffuse angular distribution for the reemitted molecules. Despite the uncertainties discussed above, the tables are given to 3 decimal places to prevent rounding errors when they are interpolated.  $C_d$  is given for several simple shapes, using accommodation coefficients of 1.00, 0.95, and 0.90, respectively for three ambient temperatures and two values of the mean molecular mass. An orbital velocity,  $V_i$ , of 7,600 m/s and a satellite surface (wall) temperature,  $T_w$ , of 300 K are assumed. (The airstream, indicated by the arrow, is perpendicular to the surface of the flat plate.) The accommodation coefficient can be chosen from Table 1. An experimenter can use Table 1 and the exact shape of his satellite to calculate  $C_d$  at a range of altitudes, using Sentman's [1961] equations, as we have done.

## 6. DISCUSSION

We have presented tables which illustrate a method for estimating  $C_d$  for compact satellites in low-earth orbit. The tables are based on satellite measurements of accommodation coefficient and the theoretical model of Sentman [1961]. From laboratory measurements, we expect that the assumption of a completely diffuse angular distribution will cause errors of only a few percent at altitudes below 300 km, where the accommodation coefficient is above 0.90. Many of the remaining uncertainties could be resolved by the STEP-1 aeronomic satellite which will provide (in 1994) the rare opportunity to measure  $C_d$  in orbit. Its flat plates (solar panels) facilitate the measurement of lift and drag by its three-axis accelerometer. If the STEP-1 is flown with its flat plates in a number of different orientations during geomagnetically quiet times, it will provide a large body of information to resolve uncertainties regarding accommodation coefficients and angular distributions of reemitted molecules.

It may be that Hamiltonian methods will be used in the future to analyze the gas-surface interactions encountered in past and future laboratory and satellite experiments. Combining a realistic theory of chemisorption with the experimental data could lead to better measurements by accelerometers and mass spectrometers.

## 7. CONCLUSIONS

By combining satellite measurements of accom-

modation coefficient with Sentman's [1961] equations, we have constructed tables of recommended drag coefficients for several simple compact satellite shapes in low-earth orbit. By using this method with the exact shape to calculate  $C_d$ , experimenters can improve the accuracy of density measurements by accelerometers. The method of calculation itself can be improved by careful measurements with future aeronomic satellites, and by future developments in which the theory of chemisorption is combined with experimental data.

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