# Refinements in the Determination of Satellite Drag Coefficients: Method for Resolving Density Discrepancies

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#### **Abstract**

The discrepancies in atmospheric densities deduced from satellites of compact and long cylindrical shapes are used to improve our knowledge of drag coefficients. Constraints on the accommodation coefficient imposed by experiments in space and in the laboratory make it possible to resolve the discrepancies and gain information on the angular distribution of molecules reemitted from satellite surfaces. On the basis of the published data, we have deduced that the assumption of a diffuse angular distribution of reemitted molecules is adequate (at least in the altitude range 150-240 kilometers), even for the long cylindrical sides where a significant fraction of the molecules strike at grazing incidence. A sequel to this paper will give recommended drag coefficients for a variety of satellite shapes and orbital conditions.

### I. Introduction

The drag coefficients of satellites in the free molecular flow regime (approximately in the altitude range 150 to 500 km) usually are calculated from two assumptions: 1) The molecules that strike the surfaces of the satellite lose nearly all of their incident energy, and 2) these molecules subsequently are reemitted with a diffuse angular distribution (1-5). For satellites of compact shapes at altitudes between 168 and 290 km, these assumptions have been largely substantiated by the analyses of data from three paddlewheel satellites (6-10) and from the flat plate carried on the Space Shuttle Flight STS-8 (11). There has always been the question of whether the above assumptions are appropriate for long attitude-controlled satellites that fly like an arrow. For these satellites, a significant portion of the drag is produced by molecules that strike the long sides at grazing incidence: In this case the reemission could be quasi-specular. The opportunity to answer this question has

presented itself as a byproduct of the detailed comparison of atmospheric density measurements and models by Marcos (12). He discovered that densities deduced from three long cylindrical satellites were consistently 10% to 15% below those derived from four satellites of compact shapes. He attributed this discrepancy to systematic errors in drag coefficient estimation. The present work investigates whether assumptions 1) and 2) should be changed to improve the drag coefficient calculations and thereby reconcile the densities deduced from the two types of satellites.

# II. Drag and Accommodation Coefficients of Satellites in Free-Molecular Flow

The drag coefficient is defined by relating the atmospheric density  $\rho$  to that part of a satellite's acceleration, **a**, which is caused by drag:

$$a = (1/2) \rho C_d A_n V_i V_i / m$$

Here  $V_i$  is the velocity of the air stream relative to the satellite,  $\mathbf{A_n}$  is the projected area of the satellite normal to the air stream,  $\mathbf{m}$  is the mass of the satellite, and  $\mathbf{C_d}$  is its drag coefficient. Under most circumstances, the values of  $\mathbf{V_i}$ ,  $\mathbf{A_n}$ , and  $\mathbf{m}$  are well known, so the measurement of  $\mathbf{a}$  by an accelerometer provides knowledge of the product of  $\rho$  and  $\mathbf{C_d}$ .

It is convenient to calculate  $\mathbf{C_d}$  by expressing the drag force as the sum of two contributions. The first contribution is produced by the air molecules when they strike the surface. The second contribution (positive or negative) is produced as they leave the surface. This second contribution depends on the angular distribution of the reemitted molecules and on the degree to which they are accommodated to the temperature of the satellite surface. The energy accommodation coefficient (13),  $\alpha$ , is defined by

$$\alpha = (E_i - E_r) \div (E_i - E_w),$$

where  $E_i$  and  $E_r$  are, respectively, the average kinetic energies of the incident molecules and the reemitted molecules, and  $E_w$  is the average kinetic energy that molecules would have if they left the satellite surface at the temperature of the wall.

The value of the accommodation coefficient appropriate to a particular satellite will depend on the stream velocity, the kind of incident molecule, and on the surface conditions. The surface conditions are influenced by many parameters. The most inportant is the altitude, which largely determines the number of oxygen atoms striking and adsorbing on the surface. Atomic oxygen binds strongly to many surfaces and changes the surface properties (14-15). An adsorbed surface layer increases the accommodation coefficient (16). It also broadens the angular distribution of the reemitted beam until, in many cases, the reemitted beam approaches the Lambert cosine law (completely diffuse reemission) (17).

The accommodation coefficient is a well-defined quantity when a particular gas, moving at a known velocity, strikes a particular clean crystal face of a substance (e.g., helium striking the epitaxially deposited (111) plane of gold before background gases have adsorbed on the fresh surface (17)). When the surface becomes contaminated with adsorbed gases, the accommodation coefficient becomes strongly dependent on the amount and nature of the adsorbed gases and no longer is characteristic of the substrate (16). These effects were known twenty-five years ago for gases having energies ranging from thermal energies to about 1 eV.

In recent years, atomic oxygen beams have been generated with energies up to 5 eV (18, 19). This is the energy with which atomic oxygen strikes satellites in low earth orbit. Time-of-flight measurements with one of these beams confirmed what had often been seen with various gases in molecular beams at lower energies: Quasi-specular reemission exhibits incomplete accommodation (about 0.5 in Reference 18), whereas diffuse (cosine) scattering exhibits complete accommodation. In an experiment aboard the Space Shuttle STS-8 with a perigee altitude of 225 km, a silver ring measured the scattering of oxygen atoms from a carbon surface (11). The scattered atoms were in the broad lobular pattern in Figure 1. (The back-scattered portion of the reemitted beam was masked by the holder.) The experimenters estimated that only 2% of the scattered oxygen atoms were in a narrow lobe, while the rest were diffusely reemitted.

These recent results place close bounds on the accommodation coefficients which were previously deduced from three paddlewheel satellites by assuming five angular distributions measured in the laboratory at lower energies (7). Polar plots of the five angular distributions are shown in Figure 2. The arrows represent the incoming particles. The recent observations eliminate all but the Schamberg diffuse model and the Alcalay and Knuth (20) case of a broad lobular distribution seen on an old glass surface. This lobular distribution can be represented as the sum of a diffuse distribution (a sphere in three dimensions) and a cigar-shaped quasi-specular component which contained about 10% of the molecules. In the Space Shuttle experiment, only 2% of the reemitted molecules were in the quasi-specular lobe.

The accommodation coefficients deduced from paddlewheel satellite data by assuming the five angular distributions are shown in Figure 3, in which we shall limit our attention to the two angular distributions just described. We observe that Explorer VI in a highly eccentric orbit had considerably lower values of  $\alpha$  than Ariel II, even though the perigee altitude of Ariel II was higher. We note that oxygen atoms struck Explorer VI with a kinetic energy of about 6.5 eV, compared with 5 eV for the other two satellites. Since these are of the order of chemical binding energies, we believe that oxygen atoms striking

Explorer VI had a lower probability of being trapped in the potential well corresponding to chemisorption (21). This is a plausible physical explanation of the lower accommodation coefficients observed for the highly eccentric orbit of Explorer VI.

The values of  $\alpha$  calculated by assuming the diffuse and broad lobular distributions in the case of Ariel II at 290 km were 0.89 and 0.90, respectively. In the case of Proton 2 at 168 km, Beletsky (9) calculated only the Maxwellian reflection coefficient, which represents the fraction of molecules diffusely reflected. Since it was 0.999, almost all of the energy was diffusely reflected, so we are safe in assuming that the accommodation coefficient was 1.00.

The satellites studied by Marcos (12) were in orbits of low and moderate eccentricity. They collected drag data at an average altitude of about 200 km. By interpolating between the values for Proton 2 and Ariel II, we estimate the accommodation coefficient appropriate to this altitude to be approximately  $\alpha = 0.975$ . For the calculations in the following sections, we use this value of  $\alpha$ , a diffuse angular distribution, a satellite speed of 7600 m/s, a wall temperature of 300 K, a mean molecular mass of 22, and an atmospheric temperature of 920 K (an average at 200 km for the time period over which the satellites of Reference 12 returned data).

# III. Drag Coefficients for Satellites of Compact Shapes

It has been customary to use a drag coefficient of 2.2 for satellites of compact shapes in free molecular flow. This value of  $C_d$  is based on studies by Cook (4), who derived an average value which took into account the fact that satellites have many different shapes, and may be tumbling in unknown ways. However, if one knows the accommodation coefficient, the angular distribution of reemitted molecules, and the detailed shape and orientation of the satellite, one can calculate  $C_d$  with greater precision (1-3, 22-24). Three of the four compact satellites studied by Marcos were Atmosphere Explorers, for which the shape and orientation are known (25). We therefore proceed to calculate  $C_d$  for Atmosphere Explorers at 200 km, which was near the average altitude of Marcos' data.

The Atmosphere Explorer (AE) satellites had the shape of a drum-like cylinder of diameter D=1.4 meter and length L=1 meter . The spin axis, which coincided with the symmetry axis of the cylinder, was oriented normal to the air stream (orbital velocity vector). The projected area of the satellite normal to the airstream was simply the product of length and diameter, LD. We calculate the drag coefficient for the cylindrical surface from three models of gas-surface interaction: the hyperthermal approximation according to Schamberg (22), the Joule Gas approximation (23), and the Maxwellian velocity

distribution of gas molecules superposed on the stream velocity (1, 2). In all three models, we assume a completely diffuse angular distribution of reemitted molecules. An examination of the numerical results in Table 1 confirms that, for the cylindrical surface, there is little difference in the drag coefficients calculated from the hyperthermal model (which ignores the random thermal motion of the gas molecules compared to the stream velocity), the Joule gas model (which approximates the thermal motion by three pairs of orthogonal velocities superimposed on the stream velocity), and the free stream plus Maxwellian velocity distribution. The last model is the most realistic for the contribution of the incident molecules to the drag force.

We calculate the contribution of the circular flat plates (at the two ends of the cylinder) to the drag coefficient only from the free stream plus Maxwellian velocity distribution, because the other two models are inadequate for molecules striking a surface near grazing incidence, as was pointed out by Sentman (3). The result is an additional term 0.136 which must be added to the drag coefficient of the cylindrical surface to obtain a total drag coefficient for the AE satellites. The result is  $\mathbf{C_d} = 2.35$  at 200 km altitude.

As noted in Section II, the value of the accommodation coefficient ( $\alpha = 0.975$ ) used in these calculations was obtained by interpolating between the Proton 2 and Ariel II measurements. However, we can not be certain that a linear interpolation is justified. To show the uncertainty in the drag coefficient caused by the uncertainty in  $\alpha$ , we present in Table 2 additional drag coefficients calculated from the free stream plus Maxwellian velocity distribution, assuming wide bounding values,  $\alpha = 0.950$  and  $\alpha = 1.00$ .

We conclude that the drag coefficient of the AE satellites at 200 km altitude is Cd = 2.35 + 0.07 or - 0.11.

### IV. Drag Coefficients of Long Cylindrical Satellites

Long cylindrical satellites which fly like an arrow differ from compact satellites in that a significant fraction of the drag can be caused by the random thermal motion of the ambient air: For example, the area of the cylindrical sides of such a satellite with a length to diameter ratio of 5 is 20 times the projected area of the front of the satellite. Even though the satellite speed can be 10 times the root mean square molecular speed, the area ratio magnifies the effect of molecules which strike (by virtue of their thermal motion) the long sides of the cylinder at grazing incidence.

As mentioned in Section III, the hyperthermal and Joule gas approximations are inappropriate for molecules which strike the surface near grazing incidence. For this reason, we omit the hyperthermal and Joule gas cases from the calculations of this Section.

Our knowledge of gas-surface interactions at grazing incidence is limited: Paddlewheel satellites have so far been unable to make measurements at grazing incidence, and laboratory measurements are also difficult at such angles. The satellite study of Marcos (12) provides for the first time the opportunity to determine the character of gas-surface interactions in orbit at grazing incidence. The three long cylindrical satellites used in that study had a length to diameter ratio (L/D) of approximately 5. However, the exact shapes of these satellites have not been published. We therefore assume three frontal shapes for the cylinders and take the average value of the drag coefficients calculated as representative of the cylindrical satellites. Two of the shapes (A and B) are cylinders terminated by the frustrum of a cone, with the ratio of the larger diameter, D, to the smaller diameter, d, being 3. The cone angle for frustrum A is 30 degrees and that for the frustrum B is 45 degrees. The third shape (C) is a cylinder terminated by a hemisphere. coefficients are again calculated with the same values of orbital velocity, wall temperature, mean molecular mass, and atmospheric temperature as given in Section III. If we assume a completely diffuse angular distribution for the reemitted molecules and assume the accommodation coefficient to be 0.975, we obtain the drag coefficients shown in Table 3. We notice that the result for shape C is close to the average for the three shapes. Therefore, we use shape C in calculating the effect of various accommodation coefficients on  $C_d$ . The results are given in Table 4.

We conclude that the average  $\mathbf{C_d}$  for cylindrical satellites at 200 km altitude with L/D approximately 5 is about 3.30 if the angular distribution of molecules reemitted from the long sides of the cylinder is diffuse. In the case that this value of the drag coefficient fails to resolve the discrepancies in the measured atmospheric densities, then a different model of reemission from the cylindrical sides could be used. For example, one might employ Sentman's formulas (2) for the momentum transfer by the incident molecules and the diffuse fraction of the reemitted molecules. For the remaining fraction of reemitted molecules one might use Schamberg's model (22) with a quasi-specular angular distribution and a smaller accommodation coefficient, e.g.,  $\alpha = 0.5$  from the laboratory experiments of Cross and Blais (18). Such options are included in our computer program for calculating drag coefficients.

# V. The Resolution of Densities Deduced from the Two Types of Satellites

The ratio of the densities deduced from the compact satellites to those deduced from the cylindrical satellites in Reference 12 is  $1.12 \pm 0.02$ . This mean ratio and its standard deviation were calculated from the data in Table 2 of that reference. We shall now use this experimental ratio together with the calculations of Sections III and IV to determine whether assumptions 1 and 2 need to be modified for molecules striking at grazing incidence.

The drag data determine only the product of density and drag coefficient. The densities determined by the two types of satellites would agree if the ratio of the  $C_d$  used for the cylindrical satellites to that used for the compact shapes in Reference 12 were reduced by 12%. In other words, if the  $C_d$  for the compact shape is correct, then the  $C_d$  for the cylindrical shape should be reduced by 12%. There is a possible physical reason why  $C_d$  for the cylindrical satellite might have to be reduced: If a significant portion of the molecules which strike the long cylindrical sides at grazing incidence are then reemitted in a quasi-specular lobe rather than in a diffuse pattern, the momentum transfer to the satellite, and hence, the drag would be reduced. A provision for such a distribution of reemitted molecules was made in our computer program.

The values of the drag coefficients used in the analysis quoted in Reference 12 were the customary  $\mathbf{C_d} = 2.2$  for the AE satellites and  $\mathbf{C_d}$  "near 3.5" for the long cylindrical satellites. The assumed ratio of cylindrical to compact drag coefficients is then  $\mathbf{R_a} = 3.5/2.2 = 1.59$ . A reduction of 12% would give 1.40 for the correct drag coefficient ratio,  $\mathbf{R}$ . Referring back to Sections III and IV, we find that the assumption of diffuse reemission of molecules with an accommodation coefficient of 0.975 gives  $\mathbf{C_d} = 2.35$  for the AE satellites, and  $\mathbf{C_d} = 3.30$  for the cylindrical satellites. The calculated ratio,  $\mathbf{R_C}$ , of cylindrical to compact drag coefficients is then  $\mathbf{R_C} = 3.30/2.35 = 1.40$ , in agreement with  $\mathbf{R}$  for these particular satellites. Thus the density discrepancy is resolved without the necessity of introducing different angular distributions and accommodation coefficients near grazing incidence at 200 km.

The effect of the accommodation coefficient on the calculated ratio,  $\mathbf{R_c}$ , is displayed in Table 5. The uncertainty caused by  $\alpha$  is about 2%. The lack of knowledge of the frontal shape of the cylinder was shown in Table III to yield a drag coefficient of 3.30  $\pm$  0.05. This produces an uncertainty of 1.5% in  $\mathbf{R_c}$ . Assuming the effects of  $\alpha$  and the frontal shape to be independent, we obtain an uncertainty of 2.5% in  $\mathbf{R_c}$ . The small uncertainty in the calculated ratio,  $\mathbf{R_c}$ , and its close agreement with the corrected ratio,  $\mathbf{R}$ , support the

conclusion that there is no significant departure from assumptions 1 and 2 of Section I at 200 km.

We caution that these results are based on average values from the published data (12) which involve different satellites having different orbital conditions and collecting data at different times. What we can say with confidence is the following: On the basis of the limited data available to us and the interpolated values of accommodation coefficients measured in orbit, we see no need to change the usual assumptions concerning the diffuse angular distribution of reemitted molecules (even at grazing incidence) at altitudes near 200 km. However, under other conditions, such as higher perigee altitudes or more eccentric orbits (for which we expect less accommodation), the assumption of diffuse reemission should be reexamined. To explore these conditions, it would be desirable to fly a dedicated paddlewheel satellite experiment (26-29) to measure the actual drag and accommodation coefficients.

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Table 1

Drag coefficients for the AE Satellites at 200 km according to three models of gas-surface interactions, assuming  $\alpha = 0.975$  and diffuse angular reemission.

Surface \ Model	Hyperthermal	Joule Gas	Free stream plus
			MaxwellianVelocity
			Distribution
Cylinder	2.184	2.209	2.217
Two Flat Plates	-	-	0.136
Total <b>C</b> d	-	-	2.353

### Table 2

Drag coefficients for the AE Satellites at 200 km for three values of the accommodation coefficient, assuming diffuse angular reemission and the model of free-stream plus Maxwellian velocity distribution.

Surface \ α	0.950	0.975	1.000
Cylinder	2.286	2.217	2.105
Two Flat Plates	0.136	0.136	0.136
Total <b>C</b> d	2.422	2.353	2.241

Table 3

Drag coefficients of cylindrical satellites at 200 km assuming diffuse angular reemission,  $\alpha$  = 0.975, and L/D = 5.

Shape	Front	Sides	Total <b>C</b> d
A	2.153	1.095	3.248
В	2.199	1.155	3.354
С	2.187	1.114	3.301

Table 4

Drag coefficients of cylindrical satellites (Shape C) at 200 km for different values of the accommodation coefficient (assuming diffuse angular reemission and L/D = 5).

α	Frontal Hemisphere	CylindricalSides	Total <b>C</b> d
0.950	2.246	1.114	3.360
0.975	2.187	1.114	3.301
1.00	2.092	1.114	3.206

# Table 5

Calculated ratio  $(\mathbf{R_c})$  of drag coefficients of the cylindrical to the compact satellites for different values of the accommodation coefficient.

α	0.950	0.975	1.00
R <sub>c</sub>	1.39	1.40	1.43

# **Figures**

- 1. Polar diagram of angular distribution of the 5 eV oxygen atoms scattered from polished vitreous carbon plate exposed to the airstream on the Space Shuttle. A pure Cosine law reemission is shown for comparison. The cut-off in the backward hemisphere was caused by the detector film holder. (after Gregory and Peters)
- 2. Models of angular distribution of reemitted molecules which were used to calculate accommodation coefficients from paddlewheel satellite measurements. The figures are polar plots in the plane of incidence. The arrows represent the incident airstream.
- 3. Accommodation coefficients calculated from paddlewheel satellite data corresponding to the five angular distributions in Figure 2. The perigee heights, velocities at perigee, and orbital eccentricities of the three satellites are shown in the box.