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The Space Analysis Division's Atmospheric Density Analysis Project has been used in the companion paper to derive fitted drag coefficients for several sets of spherical satellites having different surface materials and different surface treatments. Comparison of these drag coefficients reveals that, for spheres having uniform surface composition, the adsorption of atomic oxygen on the satellite surface masks the effect of different surface materials at altitudes around 200 km. However, at higher altitudes, where the amount of adsorbed atomic oxygen decreases, the characteristics of the surface materials slowly emerge. To interpret the observed changes with altitude, we have used a combination of Sentman's and Schamberg's models of physical drag coefficient along with parameters of gas-surface interactions measured in orbit. Tables of average values of physical drag coefficients of smooth spheres at sunspot maximum and minimum are provided in the Appendix. Those satellites which have had their spherical surfaces modified by the addition of numerous flat plates (such as mirrors or solar cells) are observed to have drag coefficients which depart significantly from the drag coefficient of a uniform sphere. We attribute most of this effect to reflection of incident molecules from the edges of the flat plates.

Introduction

The Orbital Debris Radar Calibration Spheres (ODERACS)[1] were cleverly designed by NASA to measure the effect of surface material and roughness on the drag coefficient, while satisfying their primary mission of radar calibration. Soon after the ODERACS I spheres were launched into circular orbits at altitudes near 350 km in February, 1994, Tan and Badhwar[2] used the orbital data to study surface effects. They reported that surface materials and surface treatment have a small but measurable effect on the drag coefficients of spheres. Then, in 1997, Chao, et al.[3] analyzed all of the ODERACS I and II tracking data. They were able to determine the biases in the Jacchia 71 and MSIS 90 atmospheric models. They found some evidence that supported Tan and Badhwar's discovery, but felt that the scattering of the models precluded arriving at definite conclusions regarding the effect of surface material on the drag coefficient. Since these early investigations, data from many more spherical satellites have become available for analysis. Furthermore, the Air Force Space Command[4,5] has recently refined the parameters of the Jacchia thermospheric density model, reducing the scatter in the derived ballistic coefficients by more than half. This has encouraged us to reexamine the data from ODERACS and other historical satellites. This is an opportunity to study the variation of drag coefficients with altitude, the density model biases caused by inappropriate drag coefficients, and the dependence of drag coefficients on surface composition and surface roughness. Surface effects are studied in the present paper. Altitude dependence and model bias are investigated in the companion paper[6] entitled "Drag Coefficient Variability at 175-500 km from the Orbit Decay Analysis of Spheres".

Physical Drag Coefficients

In astrodynamics, the term "drag coefficient", is used in two different senses: (1) as a fitting coefficient (C_D) which is used to force an atmospheric model to agree with the tracking data when constructing a satellite orbit, and (2) as a physical factor (C_{DP}) from which one can calculate the in-tract component of the force of the ambient air on the satellite. Early in the space age, most orbit analysts decided to use 2.2 as the physical drag coefficient of compactly shaped satellites when deducing atmospheric density from satellite drag measurements[7-9]. This was an intelligent choice before there were any measurements of gas-surface interactions in orbit. For long cylindrical satellites that fly like an arrow, a higher drag coefficient was used because of the air drag on the long sides[10].

When energy exchange at satellite surfaces began to be measured in orbit, it became apparent that molecules colliding with satellite surfaces at altitudes near 200 km lose nearly all of their kinetic energy, and are reemitted in a diffuse angular distribution[11-13]. This puzzled some researchers, until analyses of data from orbiting pressure gauges and mass spectrometers revealed that atomic oxygen strongly adsorbs on satellite surfaces[14-16]. It has long been known from laboratory measurements that surface contamination increases energy loss when molecules strike surfaces[17, 18]. The collisionally excited molecules emit radiation, producing the "spacecraft glow"[19]. At higher altitudes, there is less adsorbed atomic oxygen[15], so some incident molecules strike a bare patch of surface, and are reemitted with a quasispecular angular distribution. By a quasispecular distribution we mean that the molecules are reemitted near the specular angle after losing a significant fraction of their incident energy.

Previous analyses[20-26] have shown that physical drag coefficients depend on many parameters: Satellite shape, orientation, and altitude; atmospheric composition and temperature; molecules adsorbed on satellite surfaces; the loss of energy of incident molecules (accommodation) before these molecules are reemitted; the angular distribution of the reemitted molecules; and even the orbital eccentricity. (Some of these parameters are correlated with each other, and some have an effect of less than 1 %.) In the present paper, we shall restrict our attention to spherical satellites and modified spherical satellites, so that the effects of surface composition and surface treatment can be distinguished from some of the other effects.

The degree to which molecules have lost their initial energy upon collision with the satellite surface is described by the energy accommodation coefficient, α:

$$\alpha = (E_i - E_r)/(E_i - E_w) \quad (1)$$

Here E_i is the kinetic energy of an incoming molecule, E_r is the kinetic energy of a reemitted molecule, and E_w is the kinetic energy of a reemitted molecule that has adjusted completely to the temperature of the surface (or wall) before reemission.

Measurements made in orbit[11-13] have shown that in the neighborhood of 200 km altitude, α is between 1.00 and 0.99, and that the angular distribution of reemitted molecules is diffuse. Sentman's model of drag coefficients[20] is appropriate for calculating the physical drag coefficients of satellites near 200 km, because it assumes diffuse reemission. However, at altitudes near 300 km, the accommodation coefficient has fallen by about 10 % to the vicinity of 0.9. This suggests that as the amount of oxygen adsorbed on the satellite surface decreases, some of the incident molecules are reemitted in a quasispecular distribution, since this is what happens in the laboratory as surface contamination is reduced[18]. In this connection, Schamberg's model of drag coefficients[21, 22, 24, 27] is appropriate for calculating the contribution of the quasispecular component to the drag coefficient. We use the satellite measurements of angular distribution by Beletsky[11] and Gregory and Peters[13], and the measurements of fitted drag coefficients from the companion paper[6] to estimate the fraction of molecules that are reemitted quasispecularly.

Most orbital measurements of energy accommodation were made near sunspot minimum, when the atmospheric concentration of atomic oxygen was low. To estimate the accommodation coefficients near sunspot maximum, when the concentration of atomic oxygen is high, we use orbital measurements of atomic oxygen concentration collected in the monograph on the US Standard Atmosphere, 1976[28], as well as satellite measurements of adsorption[14-16, 29]. The accommodation coefficients appropriate to sunspot maximum at various altitudes are then inserted in Sentman's and Schamberg's models to calculate physical drag coefficients at sunspot maximum.

Schamberg's Model of Physical Drag Coefficients

The physical drag coefficients appropriate to the case of completely diffuse reemission have been discussed in the companion paper[6]. Here we present Schamberg's more general model[21] for the physical drag coefficient, which we apply to the case of quasispecular reflection from a clean, spherical surface. Specializing Schamberg's Eqn. (53) for a sphere to the case of a 5° reemitted beam, the physical drag coefficient of a sphere becomes

$$C_{DP} = 4 \int_{o}^{\pi/2} \sin\theta \cos\theta \; [1 - (V_r / V_i) + 2 (V_r / V_i) \sin^2\theta)] \, d\theta , \quad (2)$$

where the angle of incidence, θ, is measured relative to the tangent to the surface, and the reemitted velocity, V_r, is the rms value, rather than the most probable value used by most other writers. To a very close approximation, $(V_r / V_i) = (1 - \alpha)^{1/2}$, regardless of the mean molecular mass of the air. (Alpha will be calculated from Goodman's equation which we discuss later.) Integration yields a complicated expression which gives a hyperthermal, quasispecular C_{DP} value of 1.82 for clean aluminum (atomic mass = 27), 1.88 for chromium (atomic mass 52), and 1.92 for thermal control paint (molecular mass = 85). These limiting values of C_{DP} will be approached near the top of the thermosphere, where a negligible amount of atomic oxygen is adsorbed on satellite surfaces. However, at altitudes near 300 km, where most incoming molecules strike near adsorbed atoms, the physical drag coefficient of a smooth sphere should be calculated from Sentman's analysis described in the companion paper. That analysis yields a value of C_{DP} around 2.3 at 300 km altitude. A small correction for the quasispecular component can then be calculated from Equation (2). (See Appendices A and B.)

Drag Coefficients Near Sunspot Minimum

The ODERACS spheres were launched into circular orbits near 350 km for radar calibration studies during the solar minimum period of 1994-1995. These spheres are excellent candidates for determining the drag coefficient variations resulting from different surface characteristics, because half a dozen satellites with different surfaces were simultaneously launched from the Shuttle into similar orbits on two occasions.

Figure 1 shows the ballistic coefficients, B, obtained by the AFSPC/XPY Atmospheric Density Analysis Project[5], using the daily temperature corrections for two four-inch ODERACS spheres with surfaces of smooth chrome and sandblasted aluminum. The variations of approximately +-6% are the result of the remaining unmodeled density variations. The important thing to notice is the almost constant difference between the two curves. The curves are almost identical because both spheres had the same mass, and were released at almost the same time into almost identical orbits. Therefore, any unmodeled density variations will affect both spheres in the same manner. The sandblasted aluminum surface has a slightly greater ballistic coefficient than the polished chrome surface. This is discussed later in the paper.

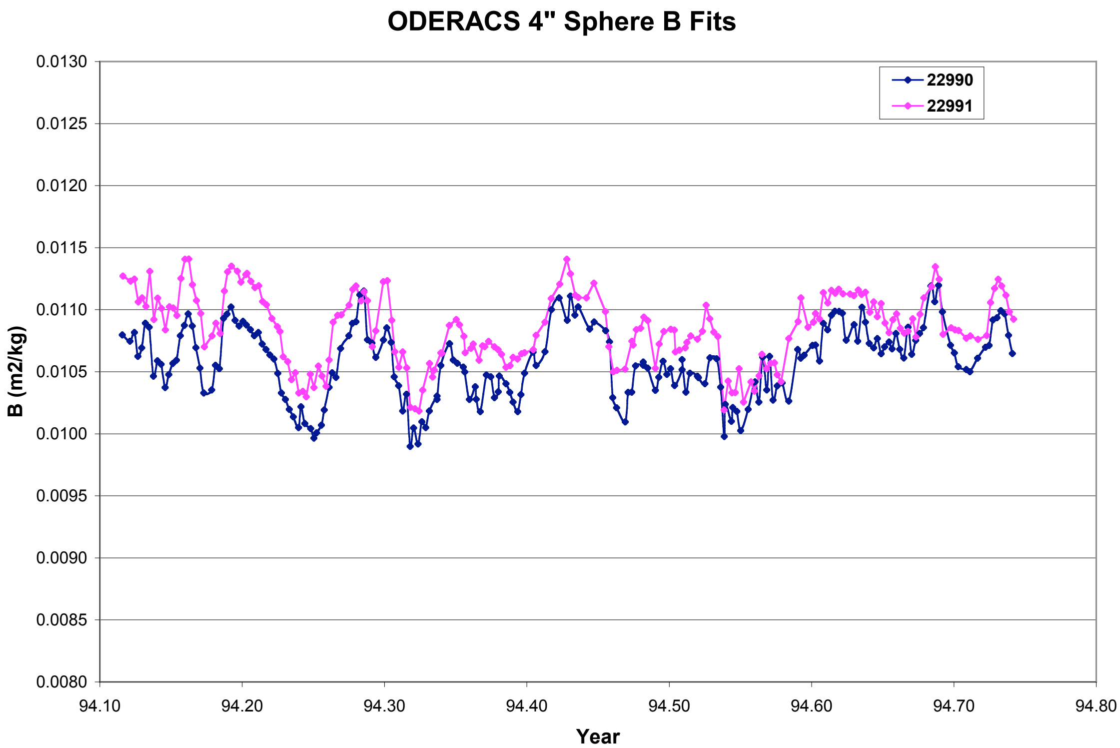

Figure 1. B values of two 4" ODERACS spheres during their lifetimes. Satellite 22990 had a polished chrome surface, while 22991 had a sandblasted aluminum surface. The B values were computed using the temperature corrections described in the companion paper[6].

In Figures 2 and 3 we show the differences between the fitted drag coefficients for two pairs of ODERACS I spheres that had the same size and mass, but different surface materials and treatments: The 6 inch spheres and the 4 inch spheres. These figures show that the effects of surface composition and treatment are obscured by adsorbed atomic oxygen near 200 km, but gradually reveal themselves as the altitude increases and the surface coverage of atomic oxygen is reduced by desorption.

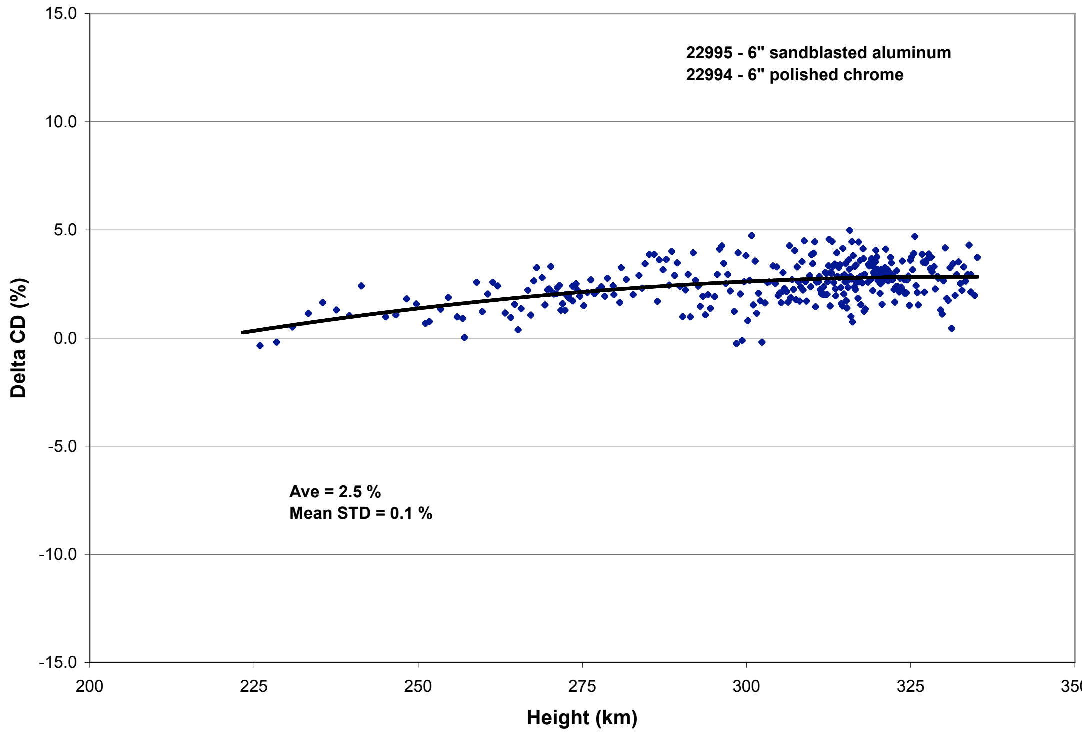

Figure 2. Difference as a % in C_D between the sandblasted 6” aluminum sphere 22995 and the polished 6” chrome-plated sphere 22994 for their entire lives. The roughened sphere shows a slightly greater C_D value, with the difference decreasing as the altitude decreases.

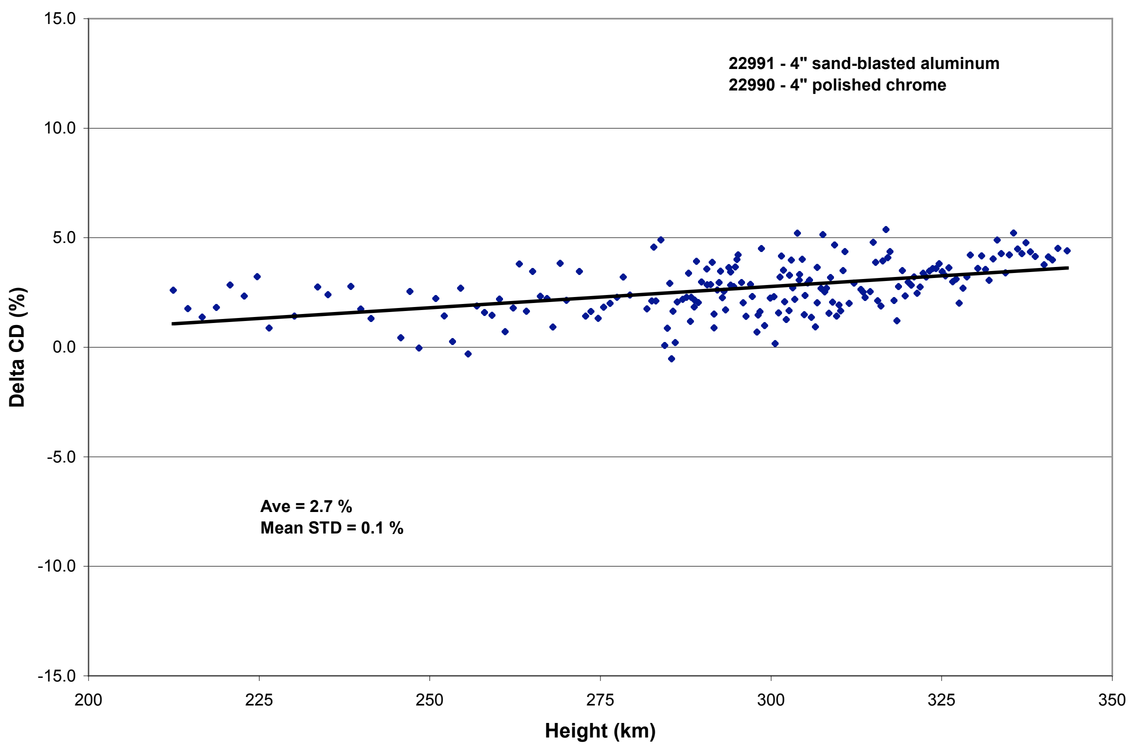

Figure 3. Difference as a % in C_D between the sandblasted 4” aluminum sphere 22991 and the polished chrome-plated 4” sphere 22990 for their entire lives. The roughened sphere shows a slightly greater C_D value, with the difference decreasing as the altitude decreases.

Figures 1, 2, and 3 are in agreement: Different surface materials and treatments cause small, but real differences in fitted drag coefficients, as was first reported by Tan and Badhwar[2]. More precise evidence is presented below in Table 3, which shows the mean fitted C_D value and the percent C_D differences among smooth chrome-plated spheres, roughened aluminum spheres, and painted spheres. The 2299x spheres were released into orbit in 1994, while the 2347x spheres were released a year later.

Satellite	Diameter	Surface	CD	Mean Sig %	Delta CD % (-aluminum)
22991	4"	sand-blasted aluminum	1.99	0.2	-----
22990	4"	polished chrome	1.93	0.2	-3.0
23472	4"	white chemglaze paint	1.96	0.2	-1.5
22995	6"	sand-blasted aluminum	2.01	0.2	-----
22994	6"	polished chrome	1.96	0.2	-2.5
23471	6"	black iridite	1.97	0.2	-2.0

Table 1. Mean and standard deviation C_D values, with differences from a roughened aluminum sphere, for the 4" and 6" ODERACS spheres at an average altitude of about 280 km.

The small differences among the fitted drag coefficients reported above for the different materials are surprising, if one believes that the accommodation coefficients that have been measured for decades on clean surfaces in the laboratory apply in space: Goodman[30] has established and Trilling[26] confirmed that the accommodation coefficients, α, measured in the laboratory are well represented by the equation,

$$\alpha \ = \ 3.6\, u \cos \varphi \,/\, (1 + u)^{\,2}, \qquad (3)$$

where u is the ratio of mass of the gas molecule to that of the surface atom, and φ is the angle of incidence measured from the normal to the surface. From Goodman's Equation (3), one can calculate that if the satellite surfaces had been clean, the accommodation coefficients of aluminum and chromium would have been in the ratio of 83 to 62. When we inserted Goodman's theoretical accommodation coefficients into Schamberg's equation (Equation 2) for the physical drag coefficient of a sphere, we found the drag coefficients of clean spheres of aluminum, chrome, and paint to be 1.82, 1.88, and 1.92, respectively. But from Sentman's model for contaminated spheres using orbital measurements of accommodation, we calculated physical drag coefficients near 2.3 at an altitude of 300 km (see Appendix A). We attribute most of this enormous difference to the fact that atomic oxygen is adsorbed on satellite surfaces at 160 to 700 km altitude, as satellite measurements by pressure gauges and mass spectrometers have shown[14-16, 29].

The fact that the fitted drag coefficient of sandblasted aluminum is slightly higher than that of chemglaze paint, which is higher than that of polished chrome, while the physical drag coefficient of aluminum calculated from Schamberg's model is slightly lower than both, is more difficult to explain. Healy[31] solved the differential equation for clean, roughened surfaces, showing that roughening the surface results in quasispecular reemission, rather than diffuse. The adsorbed atomic oxygen will cause the reemission to be more nearly diffuse, except possibly near the edge of the sphere. Healy's solution did not consider shadowing and backscattering near the edge of the sphere. Such backscattering could slightly increase the drag coefficient of roughened aluminum.

With regard to paint, the Long Duration Exposure Facility (LDEF)[32-33] showed that solar radiation, atomic oxygen, and micrometeoroids synergistically alter many spacecraft materials, especially paints and plastics. We therefore suspect that the painted surfaces were abraded in orbit much more than chrome, so that the painted surfaces had more backscatter around their edges than the chrome had. These effects might account for the slight increases in the drag coefficients of the sandblasted aluminum and the white chemglaze paint over those of smooth chrome.

We also have tracking data from one smooth Russian Taifun sphere at sunspot minimum, but we do not know its surface material. We plot in Figure 4 the fitted drag coefficients, C_D, of Taifun 21190 along with its physical drag coefficients, C_{DP}, from Appendix A. The % difference between the fitted drag coefficient near 2.0 and the partly quasi-specular physical drag coefficient measures the bias in the Jacchia density model.

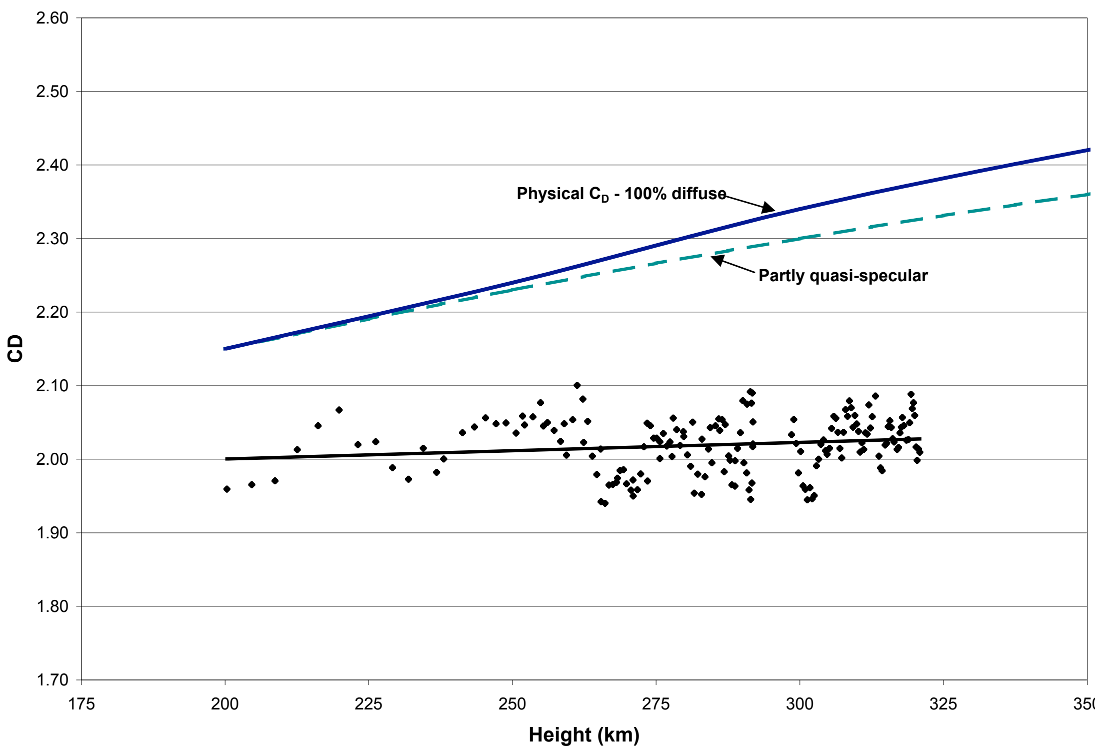

Figure 4. Drag coefficients of Taifun 21190 versus orbit height . C_D is near 2.0, while the values of C_{DP} for completely diffuse reemission and for partly quasispecular reemission are 8 to 15 % higher. (The percent difference between the partly quasispecular C_{DP} curve and the fitted C_D curve is the percent bias in the Jacchia 70 density model.)

Comparing C_D with C_{DP} for this and other satellites will also help us to separate the effect of adsorption from the effects of surface composition and surface treatment, as the following figures will show. Adsorbed atomic oxygen is responsible for increasing the physical drag coefficients of spheres at altitudes near 300 km from about 2.0 that they would have if their surfaces were clean to the actual value, about 2.3. This knowledge helps us to estimate the quasispecular fraction of reemitted molecules and consequently enables us to calculate the amount by which the physical drag coefficients from Sentman's diffuse model must be reduced. This fractional reduction becomes larger as the altitude increases. These results fit reasonably well with the error estimates previously calculated for spheres at sunspot minimum[24]. Those calculations used Sentman's and Schamberg's models for the diffuse and quasispecular fractions, respectively. The resulting values of the physical drag coefficient at solar minimum are collected in Appendix A. Physical drag coefficients are compared with the fitted drag coefficients in the companion paper[6] to determine the biases in the Jacchia density model.

Drag Coefficients near Sunspot Maximum

We now recognize that the properties of surface materials are partly masked by adsorbed atomic oxygen. Atomic oxygen is much more abundant in the thermosphere at sunspot maximum than at minimum, so accommodation coefficients are higher and less variable at maximum. Higher accommodation coefficients produce lower drag coefficients for spheres when reemission is diffuse, as can be seen in Appendix A; therefore, drag coefficients are lower at solar maximum. This knowledge helps us to extrapolate the measurements of accommodation coefficient made near sunspot minimum to conditions at sunspot maximum, by relating the accommodation measurements to the concentration of atomic oxygen at a particular altitude when the measurements were made. Inserting these accommodation coefficients into Sentman's and Schamberg's drag coefficient models has enabled us to derive the physical drag coefficients for sunspot maximum that are collected in Appendix B.

We now examine fitted drag coefficients measured at sunspot maximum. The Starshine satellites were launched into circular orbits in the 1999-2001 time period for optical tracking experiments. The first two had an orbital inclination of 53^o. Their surfaces were composed 68 % of small mirrors and 32% of spun aluminum. Starshine 3 had an orbital inclination of 67^o. Its surface was 30% mirrors and 70% black chemglaze polyurethane paint. (This plastic paint could have been deeply eroded and pitted by atomic oxygen in orbit[32, 33], thus possibly changing its accommodation coefficient and drag coefficient with time.) The mirrors on all three satellites were coated with silicon dioxide. The three Starshines decayed during solar maximum conditions. None of the Starshines was aerodynamically spherical, because of the flat plates (mirrors) which projected 3/8 inch above the spherical subsurface. The edges of the projecting mirrors could have increased the drag on the part of the satellite where the incident velocity vector was nearly tangent to the spherical subsurface. Finally, three Calspheres in circular orbits were also used in the analysis. Calspheres 3 and 4 were covered with smooth aluminum. Calsphere 5 was covered with smooth gold. All three decayed during the high solar activity of 1989 and 1990.

The three Starshine satellites were expected to have very similar fitted C_D values, even though Starshine 3 had a different surface material and was launched into a higher orbit. The number of observations was much greater for Starshine 1 than for Starshine 2, which meant that the orbit determinations were slightly lower in quality for Starshine 2 than for Starshine 1. Starshine 3 did have high tracking density, so its orbit fits were of high quality.

Figure 5 shows the plot of fitted C_D values for all three Starshine satellites during their last 100 days of life. We attribute the high fitted C_D of Starshine 1 and 2 to backscattering from the edges of the flat mirrors on their surfaces. Starshine 3 was more like a smooth sphere, because only 30 % of its surface was covered with mirrors. Physical drag coefficients of smooth spheres from Appendix B are also plotted. None of the Starshines is a smooth sphere, so the difference between the fitted and physical drag coefficients is caused by surface structure as well as by biases in the Jacchia density model.

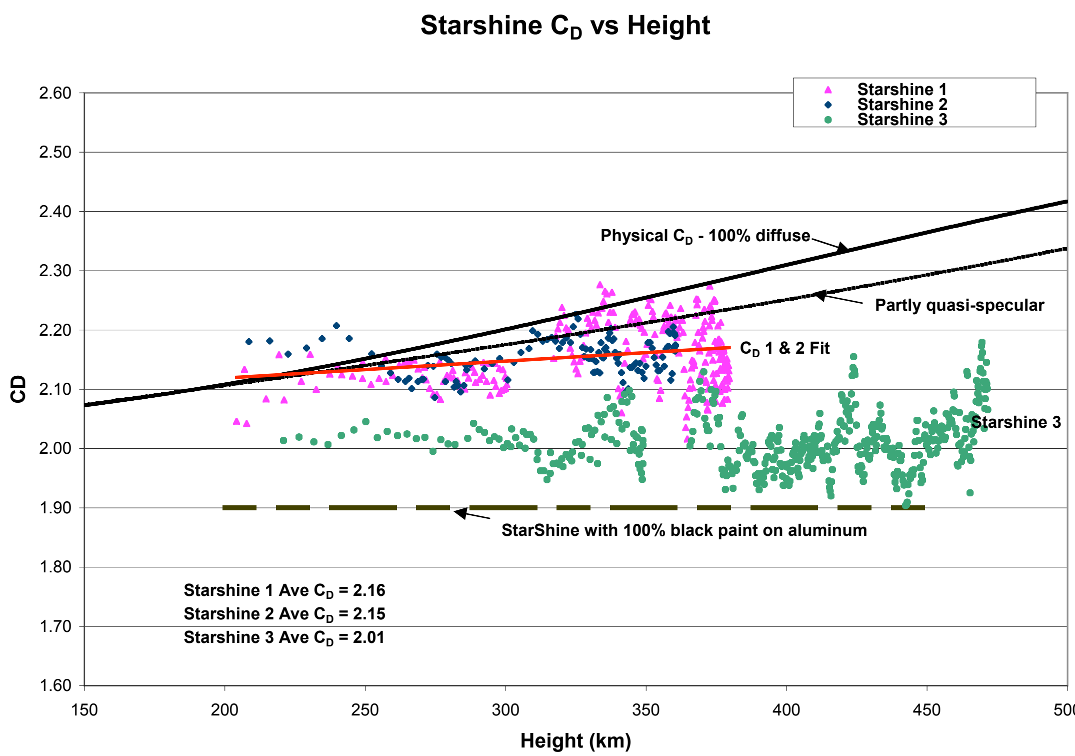

Figure 5. C_D values for the Starshine satellites, plotted as a function of orbit height. The physical drag coefficient calculated from Sentman's model is a solid line, and the physical drag coefficient corrected for quasispecular reflection is dashed. We attribute the high fitted drag coefficients of Starshine 1 and 2 to strong backscatter from the edges of those mirrors that are edge-on to the airstream. A hypothetical starshine without mirrors is also plotted dashed.

Although none of the Starshines is a true aerodynamic sphere, the drag coefficient of a smooth sphere having a surface of spun aluminum and black chemglaze polyurethane paint can be approximated by using the difference between Starshine 1 and Starshine 3**.** The difference can also be used to estimate the fitted drag coefficient of a hypothetical Starshine that was covered entirely with flat mirrors. When these calculations were performed the resulting fitted drag coefficient for a sphere of aluminum and paint resembled that of the ODERACS spheres, while that of the all-mirror Starshine was far above the values obtained for smooth spheres. Data from all of the non-spherical satellites will be plotted together later in Figure 7.

Calspheres 3, 4, and 5 were all launched together in early 1971 into a circular 775 km polar orbit. They all decayed in the late 1989 early 1990 time frame. The surfaces of Calspheres 3 and 4 were smooth aluminum, while the surface of Calsphere 5 was smooth gold. Almost all references to these spheres list the mass as 1 kg each. Only King-Hele[34] lists a different mass of 0.73 kg. The 1 kg listing is most likely an approximate value, so the 0.73 kg value was adopted for each sphere. The diameter is listed by King-Hele as 0.26 m, which is 10.2”. However, the diameters of other calibration spheres are normally even numbers of inches, so it was decided to use a 10.0” diameter for these spheres. Therefore, the C_D values were computed based on the above assumptions, which means that the absolute C_D values plotted below may not be accurate. However, the variation in the fitted C_D values should be accurately represented. Figure 6 is a plot of all three sphere’s C_D values as a function of orbit height. Because of the lightness of the spheres their decay was very rapid once the orbit height fell below 500 km. Figure 6 represents the decay during the last 100 days of lifetime. There are no data points below 300 km because it took less than 24 hours to decay from a circular orbit of 300 km.

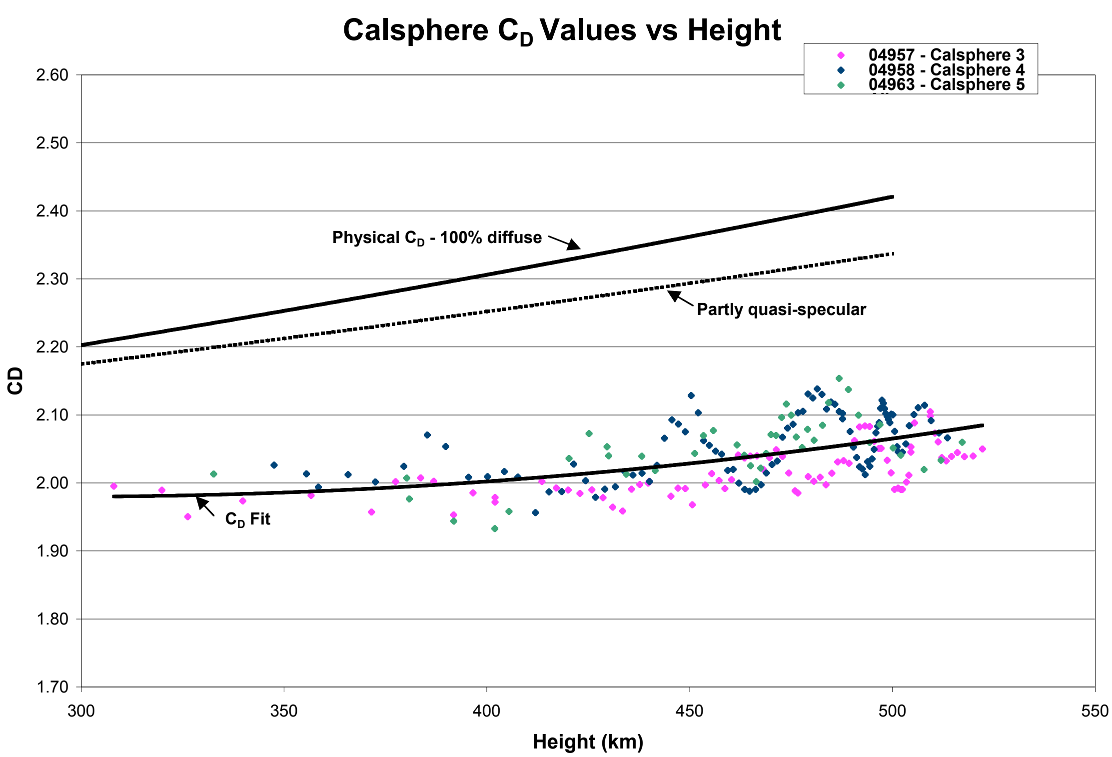

Figure 6. C_D values for Calspheres 3 through 5, plotted as a function of orbit height. The physical drag coefficient calculated from Sentman’s model is plotted as a solid line. The physical drag coefficient corrected for quasispecular reemission is dashed. (The difference between the partly quasispecular and fitted drag coefficients reflects the bias in the Jacchia density model at sunspot maximum.)

The fitted drag coefficients for the three Calspheres at 400 and 500 km are collected in Table 2. They still reflect the masking effect of adsorbed atomic oxygen, even at these high altitudes. Because of the small data sample, the fitted drag coefficients scatter too much to give a clear indication of the effect of the underlying surface material. We therefore have also tabulated the decay dates, which mainly reflect conditions near 700 km earlier in the flight. The decay dates suggest that near 700 km, a smooth aluminum sphere has a fitted drag coefficient about 1 % above that of a smooth gold sphere. If the surfaces had been perfectly clean, we could find the hyperthermal, quasispecular, physical drag coefficients by inserting Goodman's accommodation coefficients, Eqn. (3), in Schamberg's C_{DP} model, Eqn. (2). The result is 1.82 for aluminum, and 1.98 for gold. Comparing this difference of - 8 % with the + 1 % difference of the fitted C_D values suggests that the satellite surfaces were far from clean and the reemission was mostly diffuse, even at 700 km.

Surface material	**400**	**Altitude (km)**	**500**	**Decay Date**
Cal 3: Smooth Aluminum	1.99		2.04	Oct 17, 1989
Cal 4: Smooth Aluminum	2.02		2.08	Sep 20, 1989
Cal 5: Smooth Gold	2.01		2.08	Jan 7, 1990

Table 2. Fitted Drag Coefficients of Calspheres

Modified Spherical Satellites

Some satellites appear to be spherical, yet are not aerodynamically spherical. Such modifications as attaching flat mirrors or solar cells to the surface changed the aerodynamic properties of the Starshine and Taifun-Type 2 spheres (as well as slightly changing the dimensions). Holes drilled into the spherical surface of GFZ-1 greatly changed its drag coefficient. We show the fitted drag coefficients of these satellites in Figure 7. We also show what the C_D of Starshine would be if it were entirely covered with flat mirrors (except for the irregular holes between mirrors), and, alternatively, if its surface were only spun aluminum and black paint. Only the bottom curve, labeled "Starshine – all black paint on aluminum" approximates the C_D of a smooth sphere.

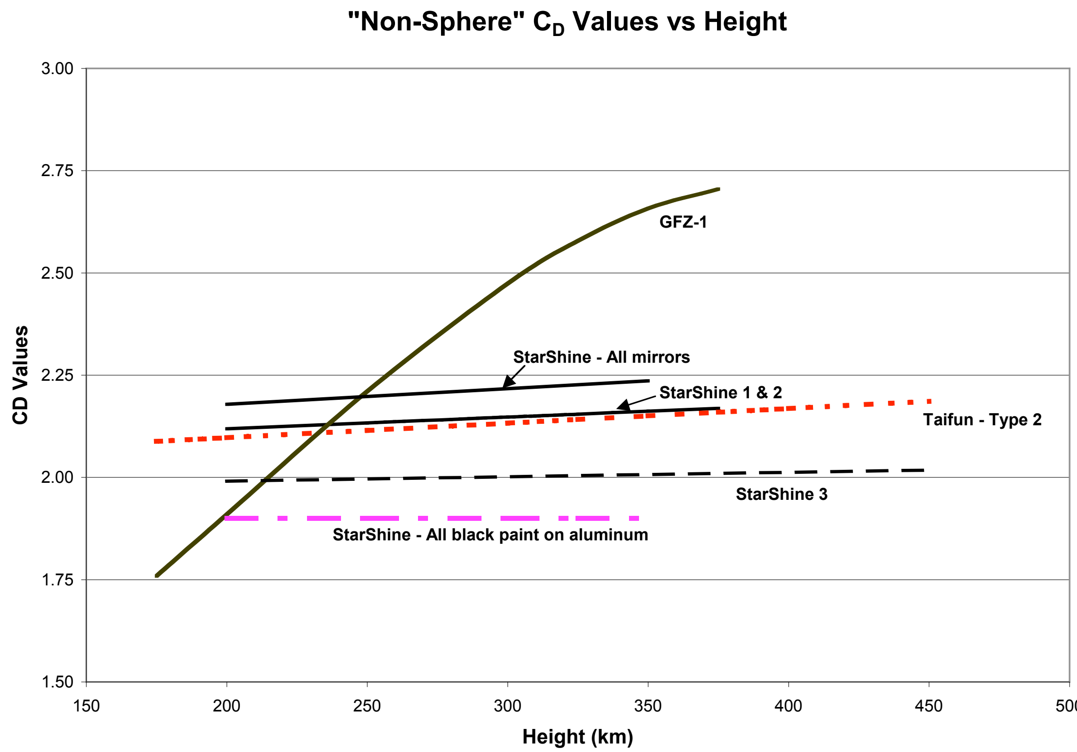

Figure 7. Fitted drag coefficients of modified spheres, plotted as a function of orbit height. The dashed curves, "Starshine – all mirrors" and "Starshine-all black paint on aluminum" approximate Starshines completely covered by mirrors and without any mirrors, respectively. Only the last approximates a smooth sphere.

Summary

Drag coefficients in the thermosphere are strongly influenced by atomic oxygen adsorbed on satellite surfaces. When an incident molecule strikes an adsorbed atom, both molecules are collisionally excited. The excited molecules lose most of their energy by radiation, producing the spacecraft glow. Near 200 km, the reemitted molecules have lost nearly all of their incident kinetic energy, regardless of the satellite surface material or treatment. At higher altitudes, where there is less atomic oxygen, the reemission is influenced by the surface characteristics more and more as the altitude increases. We have tabulated the influence of surface material and treatment on the measured drag coefficients: In our small sample, adsorption seems to limit surface effects to about 1 % at 200 km, and 3 % at 280 km. We have also investigated changes in the fitted drag coefficients caused by modifications to the spherical shape: The addition of flat plates or indentations can change the drag coefficient by 20 or 30 %. In the Appendices we have tabulated the physical drag coefficients of smooth spheres of typical composition, calculated by inserting satellite measurements of accommodation coefficients and angular distributions into the drag coefficient models of Sentman and Schamberg. These physical drag coefficients are compared with fitted drag coefficients in the companion paper[6] to remove biases from the Jacchia density model.

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Appendix A. Physical Drag Coefficients of Spheres Near Sunspot Minimum

The drag coefficients appropriate to diffuse reemission were calculated by inserting orbital measurements of energy accommodation into Sentman's drag coefficient model. The quasispecular contribution was calculated by using fitted drag coefficients and orbital measurements of angular distribution to choose a fraction from Schamberg's model of drag coefficients for the case of quasispecular reemission.

Altitude (km)	Alpha	Diffuse	Quasi-specular	C_{DP}
150	1.00	2.08	0.00	2.08
200	0.99	2.15	0.00	2.15
250	0.97	2.24	-0.01	2.23
300	0.93	2.34	-0.03	2.31
350	0.89	2.42	-0.05	2.37

Appendix B. Physical Drag Coefficients of Spheres Near Sunspot Maximum

Adsorbed atomic oxygen strongly influences energy accommodation, so atomic oxygen measurements at sunspot minimum and maximum were compared and used to modify the accommodation coefficients measured at sunspot minimum. These modified accommodation coefficients were used with Sentman's and Schamberg's models to calculate physical drag coefficients at sunspot maximum. In general, atomic oxygen is more abundant at sunspot maximum, so accommodation coefficients are higher, and the drag coefficients of spheres are lower at sunspot maximum.

Altitude (km)	Alpha	Diffuse	Quasi-specular	C_{DP}
150	1.00	2.08	0.00	2.08
200	1.00	2.09	0.00	2.09
250	0.99	2.16	-0.01	2.15
300	0.98	2.21	-0.03	2.18
350	0.97	2.25	-0.04	2.21
400	0.95	2.31	-0.05	2.26
450	0.93	2.36	-0.06	2.30
500	0.90	2.42	-0.08	2.34

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