JOURNAL OF SPACECRAFT AND ROCKETS
Vol. 46, No. 1, January–February 2009

Normalized Force Coefficients for Satellites with Elongated Shapes

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DOI: 10.2514/1.40940

The coefficient of drag is one of the largest sources of error when retrieving neutral density and winds from satellite accelerometer measurements. As the use of highly accurate accelerometers increases, so does our need for the improved modeling of surface forces. This paper discusses two analytical methods for calculating the coefficients of drag and lift in the context of long satellites with substantial surface areas parallel to the flow. The density data from one such satellite, the challenging minisatellite payload, is compared to the high accuracy satellite drag model of thermospheric density using each of the two methods for calculating the coefficients of drag and lift. When the random thermal motions of the ambient atmosphere are taken into account, the increase in agreement is found to be over 35%. These results show that the coefficient of drag for the challenging minisatellite payload satellite cannot be adequately represented under hyperthermal assumptions.

Nomenclature

A = surface area, m^2
$\vec{a}$ = acceleration, m/s^2
C = normalized force coefficient, unitless
Kn = Knudsen number, unitless
L = appropriate length of satellite, m
l = $\sin(\theta)$, unitless
m = satellite mass, kg
$\hat{n}$ = surface normal, unitless
R = specific gas constant, $J/kg \cdot K$
s = molecular speed ratio, $s = V_{\mathrm{inc}}/\sqrt{2RT_a}$, unitless
T = temperature, K
v, V = velocity, m/s
α = accommodation coefficient, unitless
γ = $\cos(\theta)$, unitless
θ = angle between the satellite velocity with respect to the atmosphere and the surface normal, rad
λ = mean free path, m
ν = parameter that defines the distribution of reemitted neutral particles, unitless
ρ = neutral density, kg/m^3
ϕ = angle from the central axis of a conical beam, rad

Subscripts

a = ambient atmosphere
D = drag (i.e., in the direction parallel to atmospheric flow)
i = satellite macromodel flat plate index
inc = incident neutral particles
L = lift (i.e., in the direction perpendicular to atmospheric flow)
re = reemitted neutral particles
ref = cross section normal to atmospheric flow

I. Introduction

IN-DEPTH knowledge of gas–surface interactions, usually represented by the normalized force coefficients of drag and lift, is often required at satellite altitudes. The operation of low-Earth orbiting satellites requires the estimation of such force coefficients, along with many other parameters, in order to precisely determine and predict a satellite's location. In addition to this macroscopic view of gas–surface interactions, the analytical and experimental derivation of force coefficients allows many satellite missions the opportunity to produce extra information related to upper atmospheric processes. Even in the early days of the space age, the orbital decay rates of artificial satellites were combined with a rudimentary knowledge of normalized force coefficients to produce estimates of upper atmospheric neutral density [1–3]. More recently, an increasing number of satellite missions have made use of high-precision accelerometers to estimate density and wind speeds at higher spatial and temporal resolutions [4–7]. To improve and validate techniques pertaining to the latter, this paper compares the statistical performance of two analytical formulations of the coefficient of drag. This study specifically uses neutral density data from the challenging minisatellite payload (CHAMP) mission [8] as processed by Sutton [9]. However, the techniques presented here are applicable to several other accelerometer missions with similar satellite geometries, that is, the gravity recovery and climate experiment (GRACE) [10] and the future Swarm satellites [11]. Recently there has been some controversy regarding the methods used to estimate the normalized force coefficients for such satellite missions (see Koppenwallner [12]). This paper seeks to resolve these issues and to report the most current procedures that are being used to calculate neutral density and winds from the CHAMP satellite.

II. Normalized Force Coefficients

With the knowledge or assumption of the normalized force coefficients, the parameters of neutral density and winds can be estimated using in situ satellite accelerometer measurements (see Sutton et al. [13]). This is done by solving the following equations which relate the acceleration in the directions parallel [Eq. (1)] and perpendicular [Eq. (2)] to the satellite velocity vector to the parameters of neutral density, satellite velocity with respect to the neutral atmosphere, satellite mass and reference area through the normalized force coefficients, C_D and C_L:

$$\vec{a}_D = -\frac{\rho}{2m} C_D A_{\mathrm{ref}} |\vec{V}| \vec{V} \tag{1}$$

$$\vec{a}_L = -\frac{\rho}{2m} C_L A_{\mathrm{ref}} |\vec{V}|^2 \hat{v}_L \tag{2}$$

where $\hat{v}_L$ is a unit vector to be determined by the satellite geometry and the calculation of C_L, in the plane perpendicular to the satellite velocity relative to the neutral atmosphere. In this study, we seek to compare two different methods for calculating drag and lift under the

Received 12 September 2008; revision received 10 November 2008; accepted for publication 12 November 2008.

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conditions of free molecule flow. This will be done by comparing density values computed from CHAMP accelerometer data using both methods with an empirical model of the thermosphere over the entire span of the data set (2001–2007).

At satellite altitudes, it is customary to assume that the body of the satellite does not disturb the atmospheric flow; this is termed free molecule flow. In the case of free molecule flow, the Knudsen number defined as the mean free path of molecules divided by an appropriate length of the satellite body, that is, $Kn = \lambda/L$, must be sufficiently large. However, the exact definition of the Knudsen number should be considered. There are several definitions of the mean free path that can be used, the most common of which is the mean free path in the freestream, λ_0. Here we will use the mean free path of the neutral particles incident on the satellite surface with respect to those reflected by the satellite surface, λ_{ir}, which is a conservative estimate more appropriate for use in the context of near-Earth satellite force coefficients. From Sentman [14], λ_{ir} can be related to λ_0 by the following equation:

$$\lambda_{ir} = \sqrt{\frac{\pi}{2}} \frac{V_{\mathrm{re}}}{V_{\mathrm{inc}}} \lambda_0 \tag{3}$$

When the Knudsen number based on the mean free path of the incident particles with respect to the reflected particles is much larger than unity, that is, $\lambda_{ir}/L \gg 1$, the assumption of free molecule flow is valid. Using this definition, a large Knudsen number, usually $Kn > 10$, implies that molecules reflected by the satellite surface will not interact with incident molecules over the length of the satellite body. Figure 1 shows the distribution of a conservative estimate of λ_{ir} for the CHAMP satellite using the full length of the satellite, including the boom, and assuming complete accommodation. The y axis is arbitrarily scaled so that the area of the histogram is unity. From 2001 through 2007, the CHAMP satellite is clearly in the free molecule flow regime.

The two methods for calculating normalized force coefficients used here are attributed to Schamberg [15] and Sentman [14]. Schamberg's assumptions state that the incident neutral particles all have the same speed and direction (i.e., hyperthermal flow), which can be approximated by the satellite velocity relative to the neutral atmosphere. After collision with the surface, particles are assumed to be readmitted in a conical beam of half-width ϕ_0. The velocity of the readmitted particles is constant whereas the number of particles varies with the angle ϕ from the central axis of the beam. The number of particles readmitted in the direction lying between ϕ and $\phi + d\phi$ is proportional to $\cos(\pi/2(\phi/\phi_0))$. The angle θ_{re} that the central axis of the beam of readmitted particles makes with the surface normal depends on the angle θ_{inc} that the incident particles make with the surface normal according to the following equation:

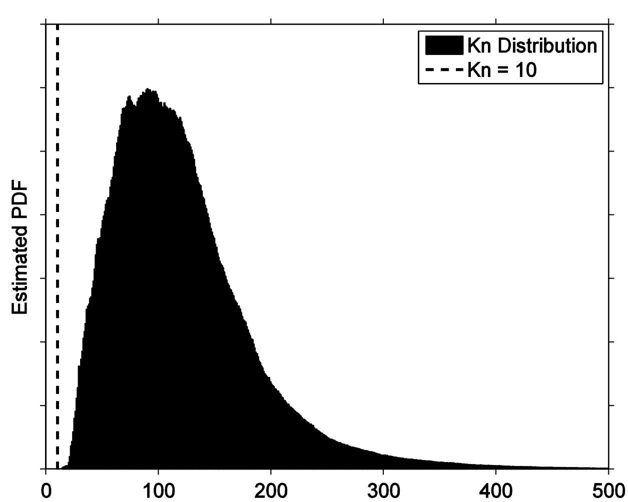

Fig. 1 Probability distribution of the Knudsen number *Kn* for the CHAMP satellite with *Kn* = 10 indicated by the dotted line. PDF = probability distribution function.

$$\sin\theta_{\mathrm{inc}} = \sin^{\nu}\theta_{\mathrm{re}} \tag{4}$$

Cook [16] imposed several additional simplifying assumptions to Schamberg's formulas to give the limiting cases of accommodated diffuse reemission ($\nu \to \infty$ and $\phi_0 = \pi/2$) and accommodated specular reflection ($\nu = 1$ and $\phi_0 \to 0$). The true case for satellite surface reflection, when assuming hyperthermal flow, is likely to exist somewhere between these two extremes; however, laboratory experiments of gas–surface interactions cannot adequately reproduce in-orbit satellite surface conditions [17]. In light of this constraint, we will limit ourselves to the case of diffuse reemission. Under these assumptions, the normalized coefficients of drag and lift for a flat plate of subscript i can be represented by Eqs. (5) and (6), respectively:

$$C_{Di}A_{\mathrm{ref},i} = A_i\left[2\gamma_i + \frac{4}{3}\gamma_i^2\sqrt{1+\alpha\left(\frac{3RT_w}{V_{\mathrm{inc}}}-1\right)}\right] \tag{5}$$

$$C_{Li}A_{\mathrm{ref},i} = \frac{4}{3}A_i\gamma_i l_i\sqrt{1+\alpha\left(\frac{3RT_w}{V_{\mathrm{inc}}}-1\right)} \tag{6}$$

The second method, attributed to Sentman [14], is similar to the above normalized force coefficients for many satellite geometries under the assumption of diffuse reemission. However, one major difference is that the random thermal motion of the neutral atmosphere is taken into account (i.e., the assumption of hyperthermal flow is rejected). The incident neutral flow at every point on the satellite's surface is a superposition of the bulk velocity, which can be estimated by the satellite velocity with respect to the neutral atmosphere, and a Maxwell–Boltzmann velocity distribution, which corresponds to the ambient temperature and composition of the atmosphere. The effect of this addition is quite small for the case of a flat plate oriented normal to the flow. However, for plates oriented such that the bulk velocity is near grazing incidence, the random thermal motion tends to dramatically increase the coefficient of drag. A second difference is that diffuse reemission, as defined by Sentman, implies that neutral particles leave the surface with a Maxwell–Boltzmann distribution of velocities whereas diffuse reemission, as defined by Schamberg and Cook, implies that the distribution of neutral particles decreases with increasing angle from the surface normal according to the cosine function given above. This difference causes a slight deviation in the two models, even when neglecting the random thermal motion of the neutral particles in Sentman's method.

According to Sentman [14] and adopting the notation of Moe and Moe [17], the drag and lift coefficients of a single flat plate of subscript i are given by the following formulas:

$$C_{Di}A_{\mathrm{ref},i} = A_i\left[\frac{P_i}{\sqrt{\pi}} + \gamma_i Q Z_i + \frac{\gamma_i V_{\mathrm{re}}}{2V_{\mathrm{inc}}}(\gamma_i\sqrt{\pi}Z_i + P_i)\right] \tag{7}$$

$$C_{Li}A_{\mathrm{ref},i} = A_i\left[l_i G Z_i + \frac{l_i V_{\mathrm{re}}}{2V_{\mathrm{inc}}}(\gamma_i\sqrt{\pi}Z_i + P_i)\right] \tag{8}$$

where

$$\frac{V_{\mathrm{re}}}{V_{\mathrm{inc}}} = \sqrt{\frac{2}{3}\left[1+\alpha\left(\frac{3RT_w}{V_{\mathrm{inc}}^2}-1\right)\right]}$$

$$P_i = \frac{e^{-\gamma_i^2 s^2}}{s} \qquad Q = 1 + \frac{1}{2s^2} \qquad G = \frac{1}{2s^2} \qquad Z_i = 1 + \mathrm{erf}(\gamma_i s)$$

and

$$\mathrm{erf}\,(x) = \frac{2}{\sqrt{\pi}}\int_0^x e^{-y^2}\,\mathrm{d}y$$

The molecular speed ratio s is the ratio of the incident bulk velocity to the most probable molecular speed of the ambient atmosphere, which is calculated using temperature estimates from the mass spectrometer and incoherent scatter (MSIS) [18] empirical model. Note that when s is large, Sentman's method is approximately equivalent to Cook's method, and thus has no dependency on the ambient atmospheric temperature.

In this study, the coefficients of drag and lift for the CHAMP satellite are calculated using a macromodel of flat plates (see Sutton et al. [13]). To calculate the total normalized force coefficients, C_D and C_L, the summation of the contribution of drag and lift acceleration from each plate is required. For the coefficient of drag, the contribution from each flat panel is always in the direction of the satellite velocity with respect to the neutral atmosphere. Because of the singularities of the coefficients of drag for a single flat plate that are encountered at an angle of $\theta_i = 90$, the term $C_{Di} A_{\text{ref},i}$ is summed over all plates and then divided by the entire reference area of the satellite to calculate the total normalized drag force coefficient:

$$C_D = \frac{\sum_i \{C_{Di} A_{\text{ref},i}\}}{A_{\text{ref}}} \tag{9}$$

where

$$A_{\text{ref}} = \sum_i A_{\text{ref},i}$$

for $\gamma_i \geq 0$.

For the coefficient of lift, the contribution from each flat plate will be in a direction dependent on the reflection of molecules, but always in the plane perpendicular to the satellite velocity with respect to the neutral atmosphere. Therefore, the calculation of the total normalized lift force coefficient requires a vector summation to resolve both the magnitude and direction of the lift force:

$$C_L \hat{v}_\perp = \frac{\sum_i \{C_{Li} A_{\text{ref},i} \hat{v}_{\perp,i}\}}{A_{\text{ref}}} \tag{10}$$

where $\hat{v}_{L,i}$ is the unit vector perpendicular to the mass flow in the direction of $(\vec{v} \times \hat{n}_i) \times \vec{v}$.

Figure 2 shows the distribution of the normalized drag force coefficients calculated using Cook's method and Sentman's method. The y axis is arbitrarily scaled so that the area of the histogram is unity; note the difference in the x scale between the top and bottom panels. The hyperthermal assumption of Cook's method ensures that the distribution deviates only slightly from the mean value as the satellite attitude changes with respect to the atmospheric flow. Here we have used a constant value for the accommodation coefficient of $\alpha = 0.93$, after Bowman et al. [19]. With this additional assumption, Cook's method has absolutely no dependence on the phase of the solar cycle, atmospheric temperature, or composition. In addition, panels which are oriented nearly parallel to the flow contribute very little to the overall coefficients. On the other hand, Sentman's method exhibits a large range of values. The inclusion of the random thermal motion of the atmosphere has increased the standard deviation by more than an order of magnitude while shifting the distribution toward higher values, with the mean increasing from 2.12 to 2.77. The large impact of the random thermal motion on the variation of the coefficient of drag is mainly caused by a combination of the elongated shape (see Fig. 3) and the typical variations in attitude of

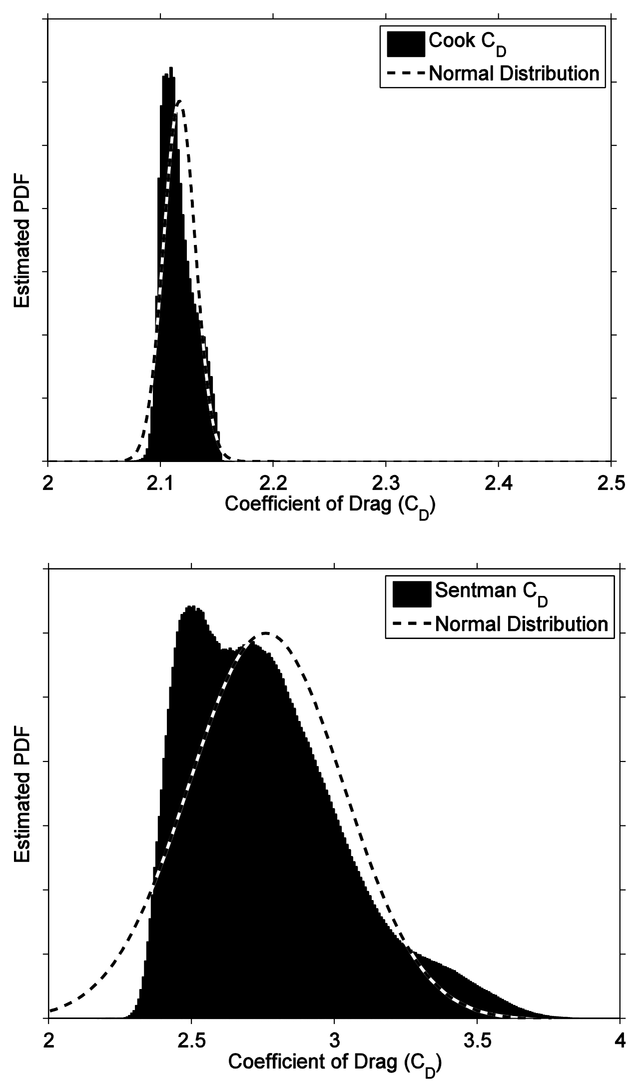

Fig. 2 Probability distribution of the coefficient of drag C_D for the CHAMP satellite using Cook's model (top) and Sentman's model (bottom). Equivalent normal distributions are indicated with dotted lines.

Fig. 3 Schematic of the CHAMP satellite.

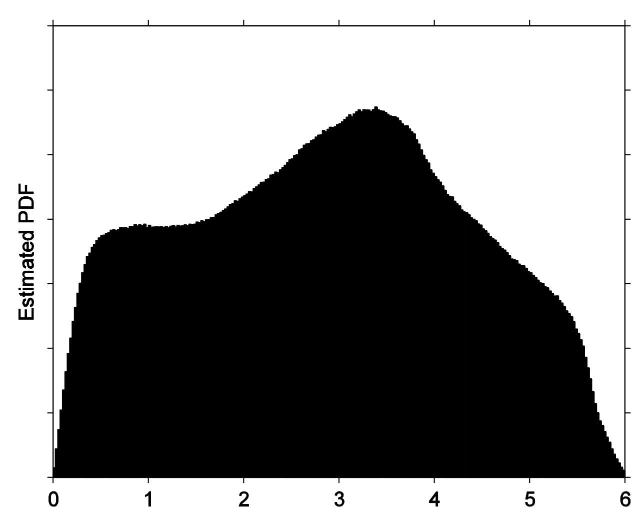

Fig. 4 Probability distribution of the angle of attack for the CHAMP satellite.

the CHAMP satellite. Figure 4 shows the distribution of the angle of attack of the CHAMP satellite, where the y axis is arbitrarily scaled so that the area of the histogram is unity. Comparison of Fig. 4 with the bottom panel of Fig. 2 illustrates the strong correlation between the angle of attack and Sentman's drag coefficient. When the satellite is nearly aligned with the neutral flow (i.e., angle of attack of 2 deg or less), the large side panels are affected by the random thermal motion of the atmosphere while contributing very little to the overall reference area, which causes the coefficient of drag to become larger than 2.7. At an angle of attack larger than 3 deg, the coefficient of drag is usually less than 2.7. For the CHAMP satellite, the angle between the x axis and the orbital plane is nominally less than 2.5 deg; however, the latitudinal variation of the corotating component of the atmosphere causes the angle of attack to fluctuate between 0 and 6 deg (see Fig. 4) over the course of half of a typical orbit.

III. Model Comparison Results and Discussion

In this section, density data from the CHAMP satellite are compared with the high accuracy satellite drag model (HASDM) [20] of thermospheric density. In doing this, we hope to gain a statistical sense of the errors associated with the two models of force coefficients that have been chosen. The ratios of CHAMP density to HASDM density have been computed using both Cook's and Sentman's methods. The resulting statistical distributions of this ratio are shown in Fig. 5, where the y axis is arbitrarily scaled so that the area of the histogram is equal to unity, for data spanning from 2001 through 2007. Figure 5 shows that Cook's method overestimates the HASDM density by 56.4–61.3% on average. Using Sentman's method, this reduces to 21.2–23.3% on average. In addition, the standard deviation of the ratio between the measured density and the empirical density decreases by 36.0%.

As described in previous sections, the MSIS model is used to drive the calculation of C_D and C_L when using Sentman's method, through the parameter T_a. Thus one might expect to see an artificial increase in agreement between the measured density values and those from HASDM. However, in general, changes in temperature that lead to an increase in density within the MSIS model also cause an increase in Sentman's normalized force coefficients, C_D and C_L. This in turn serves to decrease the density values measured by the CHAMP satellite causing a slight anticorrelation between measured density values and those produced by HASDM. Furthermore, when using Sentman's method the normalized force coefficients are much more sensitive to the typical changes in attack angle than to the typical changes in temperature. Therefore, the increased agreement is not caused by our previous use of an empirical model in the derivation of the normalized force coefficients, but rather by a more realistic understanding of gas–surface interactions.

The increase in agreement is not only evident in long-term statistical analyses; it is observed over the course of half of an orbit as variations occur in the angle of attack. If Cook's method is used to characterize the normalized force coefficients, Fig. 2 shows that variations will be very small. The error in density measurements when using Cook's method (or by choosing a constant value for C_D) is significant at low latitudes and increases near the poles. This causes the latitudinal structure of the measured density to be misleading, even when normalization techniques are employed in an attempt to offset the apparent error between measurements and empirical models or other density data sets. Although normalizing a data set can easily change the mean value of density, the standard deviation will remain large.

There are several issues that have not been addressed by the current state of research in the field of gas–surface interactions. Many of the assumptions used in this study have never been directly tested under the realistic conditions of a satellite orbit due to laboratory constraints. For instance, the accommodation coefficient is only vaguely known at satellite altitudes. Our understanding of this parameter is further complicated by its sensitivity to changing satellite surface properties. Both the accommodation coefficient and the distribution of the scattering angle are sensitive to the amount of surface adsorption of atomic oxygen. In addition, the degree of

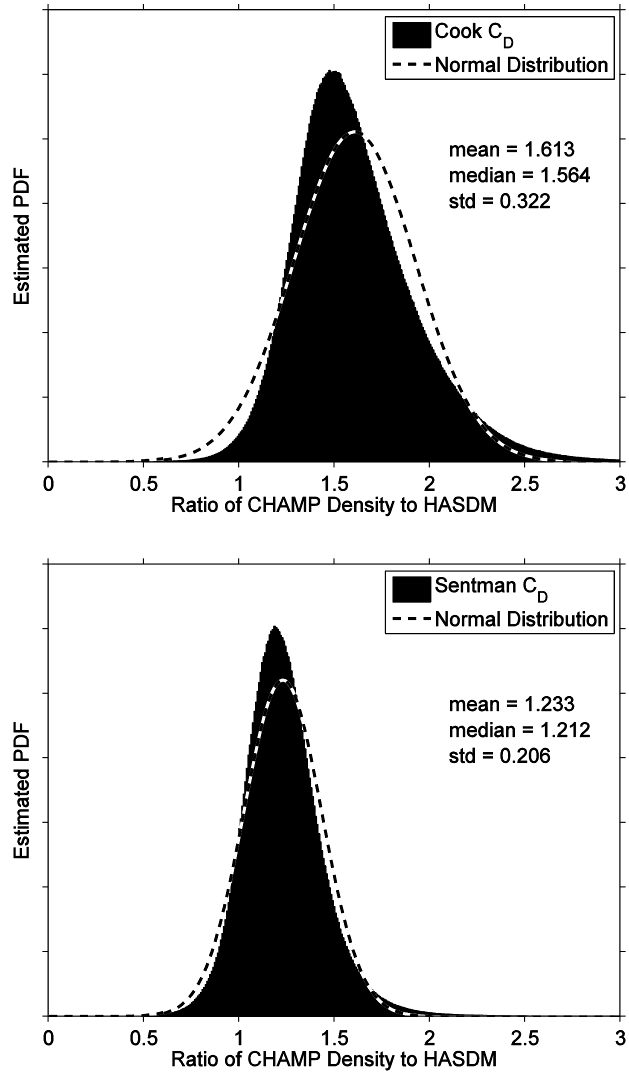

Fig. 5 Probability distribution of the ratio of measured density to HASDM modeled density using Cook's model (top) and Sentman's model (bottom). Equivalent normal distributions are indicated with dotted lines.

adsorption depends on atmospheric composition and density and cannot currently be quantified with any degree of accuracy. For these reasons, further "tuning" of Sentman's formulas can often result in the increased agreement between measured and modeled density. For example, choosing an accommodation coefficient of 0.80 reduces the median and mean of the ratio to 18.0 and 19.8%, respectively, while the standard deviation is reduced to 0.200. Aside from the uncertainty of the accommodation coefficient and scattering angle distribution, this increased agreement could arise from several simplifying assumptions used in this study. For instance, shadowing of the plates, which occurs when one satellite component disturbs the atmospheric flow incident to another component, cannot be treated analytically. One such case occurs when plates facing away from the atmospheric flow are near grazing incidence. In reality, the random thermal motion will cause an interaction between the atmosphere and these plates. However, Sentman's equations do not correctly represent this case as the assumptions related to the undisturbed atmospheric flow are violated. Therefore we choose to set the forces on plates of this configuration to zero. Ignoring this effect causes a slight overestimation of density. Multiple scattering of neutral particles and the oversimplification of satellite plates within the macromodel could also account for the increased agreement when a lower accommodation coefficient is used. These problems, which are related mostly to the complex shape of the CHAMP satellite, can only be resolved by using computationally expensive numerical techniques.

IV. Conclusions

In several recent studies using accelerometer data from the CHAMP and GRACE satellites, hyperthermal assumptions have been routinely used. This paper has shown that the normalized force coefficients, C_D and C_L, cannot be adequately represented by a constant value or by Cook's method (i.e., assuming hyperthermal flow) when dealing with long satellites oriented along the velocity vector. In addition, we have shown that the error associated with these assumptions cannot be mitigated simply by normalizing large amounts of data due to its systematic reliance on spacecraft attitude and latitude. The results presented here have implications for current and future satellite missions involving accelerometers in the areas of neutral density data processing, mission planning, and precision orbit determination.

For the CHAMP satellite, density values are overestimated by approximately 56.4–61.3% when employing hyperthermal assumptions. This is reduced to 21.2–23.3% by adopting Sentman's method whereas the standard deviation of the ratio between measured and empirical density is reduced by 36.0%. While further tuning of Sentman's formulas can yield an increased accuracy, this is most likely just masking several issues related to the complex shape of the satellite. Numerical direct simulation techniques are required to overcome such issues; however, the uncertainties related to the accommodation coefficient and the scattering angle distribution remain unresolved.

Acknowledgments

This work was supported by the National Science Foundation (NSF) Space Weather Program under Grant ATM-0719480 to the University of Colorado at Boulder. The author thanks Jeffrey M. Forbes and R. Steven Nerem for their valuable comments and suggestions.

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