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Technical Comments

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Reply by the Authors to G. Koppenwallner

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Nomenclature

A	=	area of a flat plate
A_{ref}	=	reference area of a flat plate, $A_{\text{ref}} = A\gamma$
C_D, C_L	=	normalized drag and lift force coefficients
l	=	$\sin(\theta)$
R	=	specific gas constant
s	=	molecular speed ratio, $s = V_{\text{inc}}/\sqrt{2RT_a}$
T_a	=	temperature of the ambient atmosphere
T_w	=	temperature of the satellite wall
V_{inc}	=	velocity of incident particles
V_{re}	=	velocity of reemitted particles, assuming diffuse reemission
α	=	accommodation coefficient
γ	=	$\cos(\theta)$
θ	=	angle between plate inward normal vector and incident mass flow

THE authors thank G. Koppenwallner for his comments on the article by Sutton et al. [1]. The authors also thank the Associate Editor for the opportunity to respond to these comments. Although the oversights brought up by Koppenwallner are valid concerns, these issues have been addressed in the current version of our data set (version 2.0).‡ In the last year, our processing efforts have undergone several significant changes to be reported in a future article that will be submitted to the *Journal of Spacecraft and Rockets*. One of the largest changes involves the calculation of the normalized force coefficients (i.e., drag and lift). In brief, we acknowledge that the expression for T_i was not used in a manner consistent with that of Schamberg [2]. This misunderstanding stems from an insufficient explanation of the term T_i by Cook [3] and its subsequent perpetuation in several publications. This oversight was brought to our attention while conducting research leading up to the reprocessing of our density and wind databases. In addition, the effects of the random thermal motions of the atmosphere on the normalized force coefficients for long satellites (Sec. II.B in the comments by Koppenwallner) were brought to our attention by M. Moe and K. Moe.§ Our new formulation for the coefficient of drag is adopted from Sentman [4,5] with modifications that allow for inclusion of the accommodation coefficient. For a single flat plate, the normalized force coefficients take the following form:

$$C_D = \frac{A}{A_{\text{ref}}}\left[\frac{P}{\sqrt{\pi}} + \gamma Q Z + \frac{\gamma V_{\text{re}}}{2V_{\text{inc}}}(\gamma\sqrt{\pi}Z + P)\right] \tag{1}$$

$$C_L = \frac{A}{A_{\text{ref}}}\left[lGZ + \frac{lV_{\text{re}}}{2V_{\text{inc}}}(\gamma\sqrt{\pi}Z + P)\right] \tag{2}$$

where

$$\frac{V_{\text{re}}}{V_{\text{inc}}} = \sqrt{\frac{2}{3}\left[1 + \alpha\left(\frac{3RT_w}{V_{\text{inc}}^2} - 1\right)\right]}, \qquad P = \frac{e^{-\gamma^2 s^2}}{s}$$

$$Q = 1 + \frac{1}{2s^2}, \qquad G = \frac{1}{2s^2}, \qquad Z = 1 + \text{erf}(\gamma s)$$

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

It should be noted that for large speed ratios s, the preceding formulas are essentially equivalent to those given by Cook [3], and there is no dependence on the ambient atmospheric temperature. In the case of the Challenging Minisatellite Payload (CHAMP) and Gravity Recovery and Climate Experiment (GRACE) satellites, implementation of these formulas gives a more realistic account of the variations of the normalized force coefficients imposed by the changes in satellite orientation with respect to the incident atmospheric flow over the course of an orbit. For the CHAMP satellite, typical ranges of C_D are between 2.2–2.4 when using Cook's method, whereas this range increases to 2.3–3.7 when using Sentman's [4,5] method. The effect of this update on the density database is apparent in the increased agreement with empirical models. For instance, over the entire span of the data set (from 2001 through 2007), the standard deviation of the ratio of density calculations made from in situ CHAMP satellite measurements of acceleration to the Naval Research Laboratory's mass spectrometer and incoherent scatter empirical model of thermospheric temperature and density improved by 30% with the use of Eqs. (1) and (2).

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‡Available online at http://sisko.colorado.edu/sutton/data.html since December 2007.

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