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Simultaneous Analysis of Multi-Instrument Satellite Measurements of Atmospheric Density

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When several different instruments have been used on the same satellite to measure the thermospheric density, significantly different results have been obtained. For 40 years there have been efforts to resolve these disagreements. Recent improvements in the analysis of drag coefficients and in-track winds have led us to reexamine the measurements of density made by an accelerometer, a mass spectrometer, and a density gauge deployed together on the S3-1 satellite. A simultaneous solution using data from the mass spectrometer and accelerometer significantly reduces the error caused by winds in the auroral zone during geomagnetic storms. A dramatic improvement is obtained among the three instruments by calculating the drag coefficients appropriate to the shape and altitude of the satellite instead of using the previously assumed value of 2.2 at all altitudes. A comparison of several recent studies in which 2.2 was replaced by corrected drag coefficients shows that much of the reported statistical discrepancy of 15% between density measurements and models could be removed by using appropriate drag coefficients in constructing models and in analyzing data.

Nomenclature

A	=	area of a flat plate
A_{ref}	=	reference area, $A\gamma$ for a flat plate and $\Sigma A\gamma$ for the S3-1 satellite
a	=	acceleration
C_d	=	drag coefficient
M	=	mass of a satellite
M_a	=	mean molecular mass of the atmosphere
S	=	ratio of satellite speed to most probable speed of ambient air molecules
T	=	absolute temperature, K
T_a	=	temperature of the ambient atmosphere
T_i	=	apparent kinetic temperature of the incident molecules
T_w	=	kinetic temperature of fully accommodated molecules, that is, wall temperature
V_i	=	velocity of the incident molecules
V_r	=	most probable velocity of reemitted molecules
α	=	energy accommodation coefficient
γ	=	cosine of angle between satellite velocity vector and normal to flat plate
ρ	=	air density

Introduction

ACCURATE measurements and predictions of thermospheric density are important for constructing satellite orbits and for predicting their lifetimes and reentry points. The Bell-MESA Accelerometer has been the preferred instrument for making local measurements of satellite drag,[1–7] which are used to infer atmospheric density. The Bell-MESA directly measures the air drag at altitudes between about 130 and 250 km. Density gauges[8,9] and mass spectrometers,[10–13] on the other hand, attempt to determine density by collecting an air sample, ionizing it, and measuring the resulting currents. The mass spectrometer measures the individual constituents and adds them to get the density. The density gauge uses modeled ion composition to evaluate its sensitivity. Each of these instruments has its advantages and its limitations. By simultaneously analyzing coincident data from several different instruments flown on the same satellite or on different satellites, one can sometimes reduce the uncertainties in the measurements as a whole. In this paper we apply this process to data from the accelerometer, mass spectrometer, and density gauge flown on the S3-1 satellite.

Accelerometer Measurements

The direct measurement of acceleration a by an accelerometer is converted to a measurement of the density ρ through the fundamental relation

$$a = \frac{\rho V_i^2 C_d A_{\text{ref}}}{2M} \tag{1}$$

The mass and area often are better known than 1%, but the velocity and drag coefficient are more uncertain. V_i is usually taken to be the orbital velocity. This generally causes negligible error, except at high latitudes during geomagnetic storms, where, for example, Feess[14] has measured winds that exceeded 1 km/s. If the satellite carries an accelerometer and a mass spectrometer or density gauge, one can solve simultaneously for the in-track wind and density, thereby eliminating this source of error.[15] The drag coefficient, on the other hand, is important at all latitudes and altitudes at which density is to be measured. For satellites of compact shapes, C_d is usually assumed to be 2.2, regardless of the detailed shape or altitude of the satellite. However, recent improvements in our knowledge of gas-surface interactions in orbit enable us to calculate the drag coefficient appropriate to the particular satellite shape and altitude. Recent success in resolving discrepancies between density measurements by compact and long cylindrical satellites[16] has encouraged us to apply the same method to the S3-1 satellite. In the following sections we shall show how the uncertainties regarding the velocity and drag coefficient can be removed when the satellite carries several different kinds of density measuring instruments.

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S3-1 Satellite and Its Orbit

S3-1 (1974-85C), a research satellite developed under the U.S. Air Force Space Test Program, was placed into near-sun-synchronous orbit in late 1974. The payload consisted of a number of instruments designed to measure thermospheric density and composition. On 4 November 1974 characteristics of the orbit were as follows[17]: apogee height, 3767 km; perigee height, 159 km; eccentricity e, 0.217; inclination i, 96.98 deg; right ascension of ascending node Ω, 29.04 deg; argument of perigee ω, 125.43 deg; and period T, 126.1 min.

Precise monitoring of the orbit and orientation of the S3-1 satellite has made possible several important studies. Ching et al.[17] analyzed the effects of aerodynamic lift and drag on the satellite's orbital inclination. They inferred the energy accommodation coefficient of air molecules that struck the satellite's planar surfaces then were reemitted. Philbrick et al.[18] published and compared the density measurements that were made by the accelerometer and mass spectrometer during two quiet periods and several geomagnetic storms. Marcos et al.[19] compared measurements of density made by a Bell-MESA Accelerometer, a closed-source mass spectrometer, and a magnetron density gauge carried on the satellite. This extensive documentation facilitates reanalysis of S3-1 data using more recent information about drag coefficients and in-track winds.

Simultaneous Solution for the In-Track Wind

Figure 1a shows the densities individually measured by the S3-1 accelerometer (Acc) and mass spectrometer (MS) under the assumption that the in-track wind was zero.[18] Notice that the densities reported by the two instruments often cross each other. These crossings occurred during geomagnetic storms when the winds were high. The accelerometer measurement is proportional to the square of the velocity, whereas the mass spectrometric measurement is linearly related to the velocity. By solving the appropriate equations simultaneously, the in-track wind can be calculated.[15] That calculation also makes it possible to compute the corrected densities[20] shown in Fig. 1b. The corrected densities move more nearly parallel without the crossings that occur in Fig. 1a. The remaining differences between the two instruments in Fig. 1b are caused by possible residual errors in calibration and drag coefficient as well as random errors of measurement. The S3-1 mass spectrometric measurements of the argon/molecular nitrogen ratio also make it possible to estimate the depth of the atmospheric circulation pattern that develops at high latitudes during geomagnetic storms.[20]

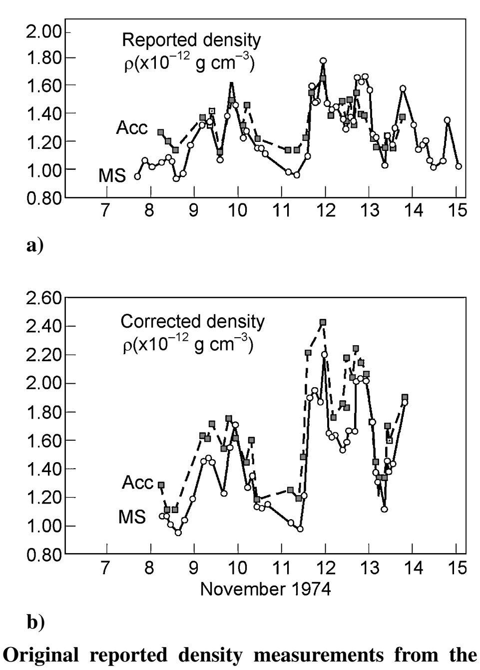

Fig. 1 Original reported density measurements from the S3-1 accelerometer (Acc) and mass spectrometer (MS) are shown in panel a; panel b shows the same measurements corrected according to the technique described in the text.

Improvement of the Drag Coefficient

During the past several decades, there have been only a few satellite measurements of the parameters needed to calculate drag coefficients, namely, the energy accommodation coefficient α and the angular distribution of reemitted molecules. These measurements have been reviewed in two papers.[16,21] Some of these measurements[17,22–24] were used in the calculation[25] of C_d for a sphere and cylinder, which are reproduced in Fig. 2. This figure shows how C_d varies with satellite shape and with altitude at a time of average solar activity. It also shows how much C_d deviates from the commonly used value of 2.2. (The shaded areas reflect uncertainty concerning the fraction of incident molecules that are quasi-specularly reflected.) Drag coefficients for several other simple shapes were calculated in an earlier paper.[21]

Before calculating the drag coefficient, it is necessary to calculate the velocity of reemission of molecules, using the energy accommodation coefficient α. The actual value of α depends on the amount of atomic oxygen already adsorbed on the surface and thus on the overall state of the atmosphere; values appropriate to many solar and geomagnetic conditions have been provided elsewhere.[16,21] Values appropriate to the S3-1 satellite are given in Table 1. The most probable velocity of reemission of molecules V_r is

$$V_r = (2/3)^{\frac{1}{2}} V_i[1 + \alpha(T_w/T_i - 1)]^{\frac{1}{2}} \quad (2)$$

where V_i is the incident velocity (customarily approximated by the satellite speed) and T_w is the temperature of the satellite surface (or wall), which is assumed to be 300 K. T_i is determined from the kinetic theory relation

$$\tfrac{1}{2} M_a V_i^2 = \tfrac{3}{2} R T_i$$

where R is the universal gas constant.[25]

Table 1 Average C_d of spinning S3-1 satellite

Altitude, km	α	C_d
160	1.00	2.24
200	0.99	2.32
250	0.96	2.43

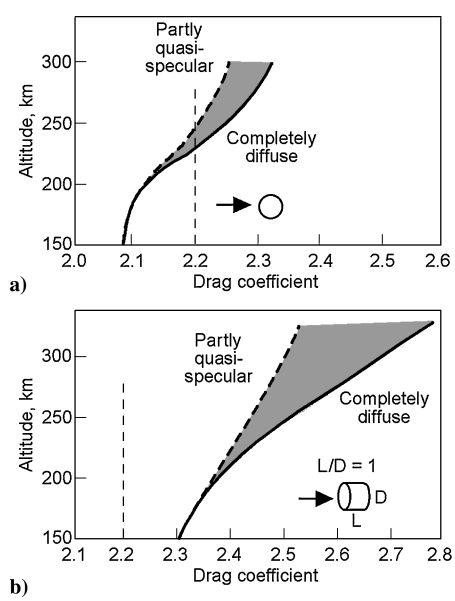

Fig. 2 Improved drag coefficients for spheres and short cylinders.

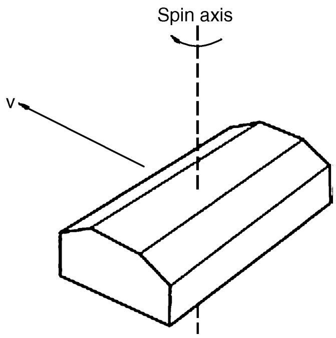

Fig. 3 S3-1 satellite shape and the position of its axis of rotation. (Reproduced with permission of Ching et al., Ref. 17.)

The shape of the S3-1 satellite, which was spin stabilized at 5 rpm, can be closely approximated by eight variously oriented flat plates. A sketch of the satellite's appearance, given in Ching et al.,[17] is reproduced in Fig. 3. We calculated the average C_d for the spinning satellite at several altitudes by using Sentman's drag-coefficient model,[26] which assumes free molecular flow, diffuse reemission, and a Maxwellian distribution of the random motion of air molecules. Through Eq. (2) we have introduced into Sentman's model the accommodation coefficients that have been measured in orbit since his work was published. These accommodation coefficients have been determined by a simultaneous analysis of two kinds of aerodynamic data collected by satellites of special design.[16,17,22–25] The resulting expression for the C_d of one side of a flat plate, appropriate to the S3-1 satellite, is

$$C_d = \frac{A}{A_{\text{ref}}}\left[\frac{P}{\sqrt{\pi}} + \gamma Q Z + \frac{\gamma V_r}{2V_i}(\gamma\sqrt{\pi}Z + P)\right] \tag{3}$$

where

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

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

Here A_{ref} is the reference area, which we have chosen to be the projected area $A\gamma$:

$$S = V_i/(2RT_a/M_a)^{\frac{1}{2}} \tag{4}$$

After averaging the calculations over various flat plates seen in Fig. 3 and over every 5 deg of satellite spin, we obtained the average drag coefficients in Table 1.

Density Ratios

Marcos et al.[19] compared density measurements of the three instruments by computing ratios.[19] To reduce the random errors of measurement, they averaged a large number of measurements at perigee and at several points on the downlegs D and uplegs U. Their average density ratios are reproduced in Table 2. In this table MS, MESA, and IG stand for the mass spectrometer, the Bell-MESA accelerometer, and the ionization gauge, respectively.

To reduce the random errors further, we averaged the upleg and downleg data and graphed the four remaining averages. We read from the graph values at 160, 200, and 250 km. We then corrected these ratios by multiplying them by the ratio of the calculated C_d in Table 1 to the assumed C_d of 2.2. The results are displayed in Table 3. The gauge data (IG) had originally been normalized to the accelerometer data at 210 km because the complicated input geometry of the gauge precluded calculating the sampling function. We therefore also renormalized the ionization gauge-to-MESA ratio as shown in the right column of Table 3. This renormalization had the effect of removing most of the systematic difference between the gauge and accelerometer data. After this renormalization the ionization gauge agreed with the accelerometer within 3% from 160 to 250 km, whereas they had previously disagreed by up to 10% even after the original normalization.

Table 2 Ratio of density measurements at different altitudes (from Ref. 19)

Altitude, km	MS/MESA	Number of points	IG/MESA	Number of points
250(D)	0.86 ± 0.12	17	0.98 ± 0.12	22
220(D)	0.79 ± 0.09	16	0.97 ± 0.13	22
190(D)	0.84 ± 0.07	18	1.04 ± 0.08	22
160	1.00 ± 0.10	31	1.09 ± 0.09	22
190(U)	0.91 ± 0.11	31	1.03 ± 0.11	22
220(U)	0.88 ± 0.08	31	0.95 ± 0.07	22
250(U)	0.84 ± 0.11	30	0.94 ± 0.14	22

Table 3 Smoothed and corrected density ratios

Altitude, km	MS/MESA		IG/MESA		IG/MESA
	Smooth	Corrected	Smooth	Corrected	Renormalized
160	1.00	1.02	1.08	1.10	1.03
200	0.87	0.92	1.10	1.07	1.00
250	0.83	0.92	0.96	1.06	0.99

The discrepancy between the accelerometer and mass-spectrometer measurements has also been reduced from a maximum of 17% to a maximum of 8%. Aeronomers have been trying to get measurements by different instruments to agree this closely for decades. This is also near the 5% accuracy that the U.S. Joint Chiefs of Staff[27] were seeking in 1986 and within the 10% accuracy being sought by the National Polar-Orbiting Environmental Satellite System.[28] Having accurate drag coefficients for S3-1 will make it worthwhile to analyze cooperatively the large collection of accelerometer and mass spectrometer data that C. R. Philbrick has archived. Many of these data are in the auroral zone, where high winds present during geomagnetic storms previously prevented accurate measurements from either instrument.

Consequences for Thermospheric Modeling

The cooperative analysis of satellite data has consequences that extend far beyond the measurement of density by a single satellite. For nearly two decades it has been reported that there is an irreducible statistical discrepancy of 15% between thermospheric measurements and models.[6,29] The densities in thermospheric models were derived from measurements of the orbital decay of compactly shaped satellites under the assumption that C_d is everywhere 2.2. As Fig. 2 demonstrates, C_d is rarely 2.2. The orbital decay of NASA's Orbital Debris Radar Calibration Spheres (ODERACS) was recently used[30] to test two thermospheric models, Jacchia 71 and MSIS 90. This was accomplished by adjusting the drag coefficient to force the model to fit the tracking data. The actual drag coefficients and their standard deviations were calculated by inserting into Sentman's theory[26] the accommodation coefficients measured in orbit by cooperative analysis of data from previous satellites of special design.[16,17,22,23]

The ratios of the modeled density to the actual density deduced from four of the ODERACS spheres are plotted in Fig. 4 and 5. By comparing the models with the orbital decay of spheres averaged over two-to-three-month periods, the day-to-day variations can be smoothed out, allowing the long-term modeling biases to stand out more clearly. This provides a lower bound on the modeling errors. The range of values derived from the four spheres is shown by a vertical bar for each of four altitude ranges during their orbital decay. The dashed line near the bottom of the figures represents the amount by which an error in our drag-coefficient analysis alone could bias the plotted ratios. This amounts to a possible bias error of $\pm 2\%$ at 250 km and $\pm 3\%$ at 350 km. Figures 4 and 5 show that at altitudes

Table 4 Drag coefficients at 200 km

Shape	Length/width	C_d
Sphere	1.00	2.12
AE	1.41	2.30
S3-1	0.81–1.24	2.32
Long cylinder	5.0	3.25

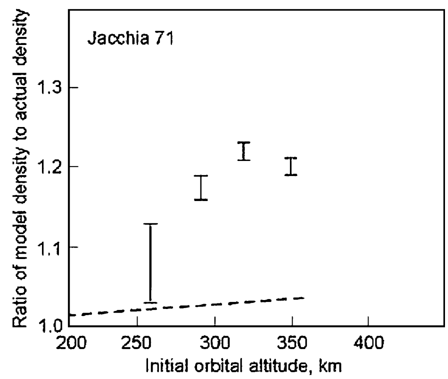

Fig. 4 Test of Jacchia model using ODERACS data. Each vertical bar represents the range of the deviation between the modeled density averaged over a period of several months and the average density measured by four ODERACS spheres during the same period.

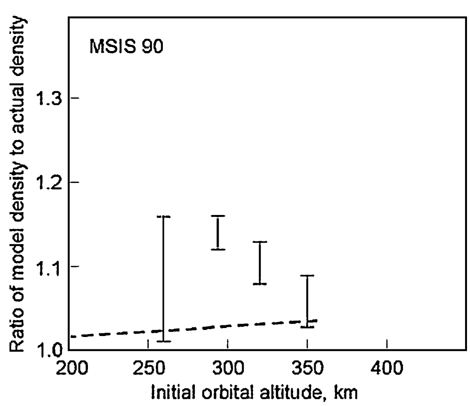

Fig. 5 Test of MSIS model using ODERACS data. As with Fig. 4, each vertical bar represents the range of the deviation between the modeled density averaged over a period of several months and the average density measured by four ODERACS spheres during the same period.

above 250 km, by assuming that C_d was 2.2 when it actually was higher, the Jacchia model overestimates the air densities by up to 23%, and the mass spectrometer-incoherent scatter (MSIS) model overestimates by up to 15%. On the other hand, the models should be better at altitudes near 200 km, where the average C_d of compact satellites is closer to 2.2, an effect that can be seen in Fig. 2 and Table 4. In Table 4 AE refers to the Atmosphere Explorer satellites, flat cylinders that rolled like a wheel through the orbit with minimal change in the drag cross section. The rectangular shape of S3-1 (see Fig. 3) causes the ratio of satellite length (characteristic in-track dimension) to width (characteristic cross-track dimension) to vary over the range 0.81–1.24 as the satellite spins; we took this systematic variation into account by averaging the drag over every 5 deg of satellite spin, as noted earlier.

When accelerometer measurements were compared with many density models at altitudes around 200 km, there was a systematic difference in the ratio of measured density to model density that depended on satellite shape.[6] The density ratios for compact satellites were about 10% above those for long cylindrical satellites that flew like an arrow. In Ref. 16 we calculated the average ratios of accelerometer measurements to the 11 most recent density models for the four compact satellites and three long cylindrical satellites from data presented in Ref. 6. Three of the compact satellites were Atmosphere Explorers, and the fourth was the S3-1. Correcting the drag coefficients brought the average density ratio for the Atmosphere Explorers to 0.98 ± 0.03 and for the long cylinders to 1.00 ± 0.03. Now that we have a drag coefficient for S3-1, we find that its corrected density ratio at 200 km is 0.97. This comparison shows that near 200 km, where the average drag coefficients of compact satellites are close to 2.2, the average density in the models is, in fact, close to being correct. The comparisons discussed in this section demonstrate that much of the widely reported statistical discrepancy between density models and accelerometer measurements is caused by using inappropriate drag coefficients both in constructing the models and in comparing the models with later measurements.

Conclusions

The simultaneous analysis of data from the S3-1 satellite has led to the resolution of some puzzling disagreements that existed in the past and has brought the density measurements into closer agreement. In general, a large fraction of the reported statistical discrepancy between densities measured by different instruments and by differently shaped satellites can be removed by using appropriate drag coefficients. The use of inappropriate drag coefficients has introduced errors into thermospheric density models because these models are based on the orbital decay of compactly shaped satellites, for which the drag coefficient has previously been assumed to be 2.2 regardless of satellite shape and altitude. The assumption that the in-track wind is zero introduces even larger errors into instrumental measurements at high latitudes during geomagnetic storms. These errors can be reduced by simultaneously analyzing data from two instruments that interact differently with the airstream, for example, an accelerometer and a mass spectrometer or density gauge. In summary, we point out that cooperative analysis of multiinstrument satellite data, coupled with the use of correct drag coefficients, can result in greatly improved density measurements and models.

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