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Correlative Satellite Measurements of Atmospheric Mass Density by Accelerometers, Mass Spectrometers and Ionization Gauges

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Abstract. A complement of experiments to monitor atmospheric density was flown as part of the payload on an Air Force research satellite. This paper describes neutral gas mass densities as measured by the following instruments on this satellite: an electrostatic accelerometer, an RF quadrupole mass spectrometer and a cold-cathode ionization gauge. Mass densities are determined from aerodynamic drag as recorded by the accelerometer, from summation of the densities of atmospheric constituents directly sampled by the mass spectrometer and from ambient pressure measurements by the ionization gauge operated simultaneously. Results obtained during 1974 between 160 and 250 km altitude were studied to compare the absolute densities obtained by the different methods. The results agree within experimental error, although there is some evidence that a systematic height dependence exists.

1. INTRODUCTION

One of the more important problems of aeronomy continues to be the uncertainty about the density and composition of the lower thermosphere. Early measurements by satellite-borne ionization gauges [1] and by rocket-borne mass spectrometers yielded lower mass densities than those predicted by atmospheric models based on orbital drag data. In a review of available data, von Zahn [2] compared several rocket mass-spectrometer-deduced total densities with satellite accelerometer data at 150 km. Von Zahn concluded that the mass spectrometer densities were too low, mainly due to difficulties in measuring atomic oxygen rather than to the model values being too high. Ionization gauge data were not included in this study because calibration in terms of absolute mass density was considered limited by complete or partial loss of atomic oxygen inside the gauge.

Recent satellite results indicate that after continuous exposure to atomic oxygen in orbit relatively stable surface conditions are established and atomic oxygen densities can be determined in closed source instruments [3]. Further, total mass densities from the AE-C Miniature ElectroStatic Accelerometer (MESA) [4] and the Open Source mass Spectrometer (OSS) [5] experiments have been found to be in very good agreement. Several hundred data points obtained during 1974 were compared in the altitude region 140–200 km. The average ratio of OSS mass density to MESA mass density varied from 0.89 at 140 km to 0.97 at 200 km [6].

In this paper mass densities derived from several instruments on an Air Force research satellite during 1974 are compared.

2. DESCRIPTION OF EXPERIMENTS AND DATA

The satellite had an elliptical orbit with perigee near 160 km and a near polar inclination. In addition to experiments to measure the neutral density and composition the spacecraft carried instruments to measure ion density and temperature, solar radiation and energetic electrons. Spin stabilization was maintained at 5 rev min^{-1}, with spin axis normal to the orbit plane, by magnetic torquing control. The density sensors were mounted perpendicular to the spin axis and sampled along the satellite velocity vector. In this paper comparison is made between measurements made by the electrostatic accelerometer (MESA) of air drag, by the Mass Spectrometer (MS) of the number density of different neutral constituents, and by the cold-cathode Ionization Gauge (IG) supplied by the Aerospace Corporation.

2.1. Electrostatic Accelerometer

The electrostatic accelerometer (MESA) consists of an electrostatically suspended mass whose position is electrostatically restored along a preferred or sensitive axis by a force proportional to the applied acceleration. A complete description of this instrument and its operating principles is given in [4]. Atmospheric densities are determined from direct measurements of the satellite deceleration induced by aerodynamic drag.

The data reduction techniques are described in [7]. The statistical error is estimated to be ±3% at perigee and ±5% at 250 km. The sources and magnitudes of these errors are estimated as follows: extraction of drag acceleration by numerical filtering varies from negligible at perigee to ±2% at 250 km, attitude ±2%, satellite area ±1%. In addition, a systematic error of about ±10% in the assumed value of 2.2 for C_D may exist [8].

This instrument has been flown successfully on many satellites, see, e.g., [9] and has proven to be a highly reliable and extremely accurate sensor.

2.2. Ionization Gauge

Earlier attempts to use hot- or warm-filament gauges on low altitude satellites resulted in difficulty in interpreting the results, possibly because of an interaction between the ambient atomic oxygen and the filament [10]. A general description of cold-cathode ionization gauge operation and data analysis is given in [11]. Density values were derived from the pressure measurements using a single point normalization to the accelerometer data. This was required since the complicated input geometry of the instrument precluded exact calculation of the sampling function. The relative accuracy of the density data is within ±10%.

2.3. Mass Spectrometer

The mass spectrometer uses an enclosed ion source of the type previously used on the Air Force OV3-6 and OV1-15 satellites [12]. The atmosphere is sampled through a thin orifice into a spherical thermal accommodation chamber before entering the ion source. The incoming gas is ionized by 40 eV electrons and detected by a secondary emission multiplier after passing through the RF quadrupole field. The source density is monitored by a hot filament density gauge technique to correct any change in multiplier gain. The configuration and calibration of this instrument allow high accuracy measurements to be made. The stability and linearity over the range of operating conditions is within ±5% for densities $>10^6\ \mathrm{cm}^{-3}$ and the number densities should be accurate to within ±15%. Mass densities are determined by summing the densities of molecular nitrogen, argon, molecular oxygen and atomic oxygen.

3. RESULTS

Measurements obtained in the altitude region 160–250 km were analyzed. Two groups of orbits were selected for study: orbits 100–156 and orbits 290–322. Perigee moved from 60°N to 72°N from orbit 100 to 156. Downleg data were acquired poleward of perigee. Upleg data were acquired equatorward of perigee with 250 km data occurring at about 40°N. From orbit 290 to 322 perigee moved southward from 81°N to 78°N. Downleg data occurred between 55°N and perigee; upleg data occurred between 76°N and 83°N.

An indication of the response of the instruments to local density variations is given in Fig. 1 for orbit 137. Some density enhancements relative to the solid line representing the Jacchia 1971 [13] (hereafter J71) model are recorded by all three instruments. In Fig. 2 the MS-measured N_2 densities (circled points) for orbit 113 are seen to follow the total densities obtained from the MESA observations (crosses). The summed MS mass density for this orbit is 0.94 of that obtained from the accelerometer at perigee.

Relative mass densities from the three sensors at 160, 190, 220 and 250 km have been studied. At 160 km the absolute values of the three measured densities are in good agreement. The average value for MESA, MS and IG derived densities in units of $10^{-12}\ \mathrm{g\ cm}^{-3}$ are 1.365(32), 1.380(32) and 1.427(26) respectively, where the numbers in parentheses indicate the number of data points.

The density ratios MS to MESA and IG to MESA are given in Table 1; in addition to 160 km results, the average upleg (U) and downleg (D) results at 190, 220 and 250 km are given. Also shown is the standard deviation and number of data points used.

It is concluded that the MS, MESA and IG derived densities agree within experimental error except at 220 km on the downleg. There is some evidence of an altitude dependence: the MS to MESA density ratio increases by an average of 17% from 250 to 160 km while the IG to MESA density ratio increases by an

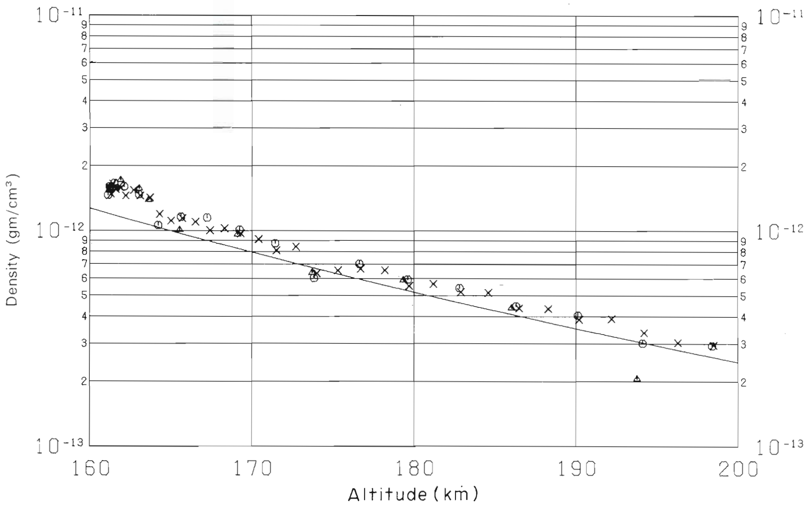

Fig. 1. Comparison of neutral density structure measured on orbit 137 by the accelerometer (×), mass spectrometer (△) and ionization gauge (○) with the J71 model.

average of 13% over this altitude region. Use of a satellite drag coefficient (according to free-molecular-flow theory) varying with height would reduce the observed altitude dependence of the density ratios by the order of only 1%. Some of the observed differences may also be due to uncertainties in the knowledge of the composition required to calculate the density from ionization gauge and mass spectrometer observations. A comparison of mass densities from the accelerometer

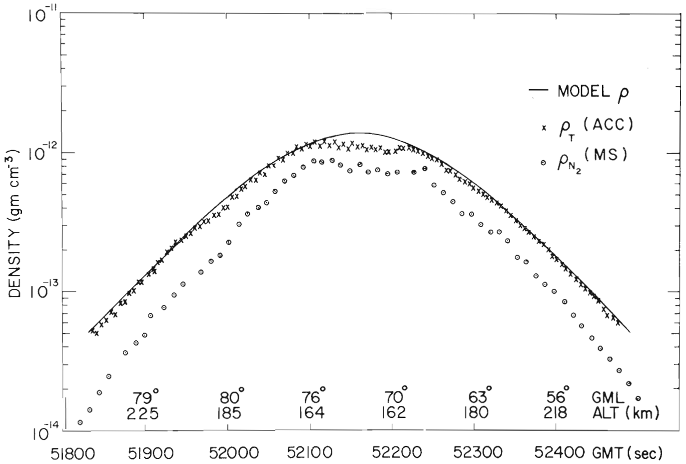

Fig. 2. Comparison of neutral density structure measured by the accelerometer on orbit 113 with the molecular nitrogen mass density measured by the mass spectrometer and the J71 model density value.

Table 1. Ratio of Density Measurements at different Altitudes

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	0.04 ± 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

and open source neutral-mass spectrometer (OSS) on the Atmosphere Explorer C (AE-C) spacecraft also showed excellent agreement, but with a 10% altitude dependence in the opposite sense; relatively higher accelerometer densities were found at lower altitudes [14]. The mass spectrometer used in the present study was a closed source instrument whereas the OSS was a semi-open source instrument. A difference in the spacecraft was that the cross-sectional area of AE-C was about three times larger than that of the Air Force satellite.

4. CONCLUSIONS

Atmospheric density measurements aboard an Air Force satellite made by an accelerometer, a mass spectrometer and an ionization gauge have been compared in the altitude region 160–250 km. The results agree within the experimental errors of the instruments. The ratio of density measured by either the mass spectrometer or the ionization gauge to that measured by the accelerometer increases by about 15% from 250 km to 160 km. Further investigations with these sensors and with the complement of instruments on the AE-C satellite should provide improved insight into the relative accuracy of various density measurement techniques.

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