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Atmospheric Drag Analysis with the AEROS Satellite

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Abstract. Atmospheric Drag Analysis (ADA) is a passive experiment in the complement of experiments in the AEROS mission. The decay of the satellite's orbit is analyzed to determine the total gas density at perigee. The prime scientific objective is the comparison of orbital drag-derived densities with *in situ* measurements of neutral atmospheric parameters.

Key words: Orbital Drag — Thermosphere — Atmospheric Density — Intercomparison — Measuring Technique.

1. Introduction

Comparisons of atmospheric density data derived from various techniques have been relatively scarce. Orbital drag-derived densities were compared with *in situ* measurements by accelerometers and pressure gauges on the same satellite for altitudes below 160 km and yielded very good agreement (Carter *et al.*, 1969; Champion *et al.*, 1970; Champion and Marcos, 1973). In the upper thermosphere where density variations reach larger amplitudes, density data from orbital drag were compared to pressure gauge measurements aboard satellite EXPLORER 32 by Schäfer and Wulf-Mathies (1969). Near 275 km altitude the *in situ* density data with much higher time resolution scattered about the drag-derived densities by some 25%. A common problem connected with retrospective comparisons is the random coincidence in the epochs of the different measurements. The AEROS satellite with its complement of neutral atmosphere experiments offered one of the first opportunities to plan comparisons of the total gas density as determined from mass-spectrometer measurements and from orbital drag in a regime of the thermosphere which is characterized by lively medium scale variations in gas density.

2. Orbital Drag Technique

The basic equation for orbital drag measurements is

$$D = \frac{1}{2} \varrho v^2 C_D A \tag{1}$$

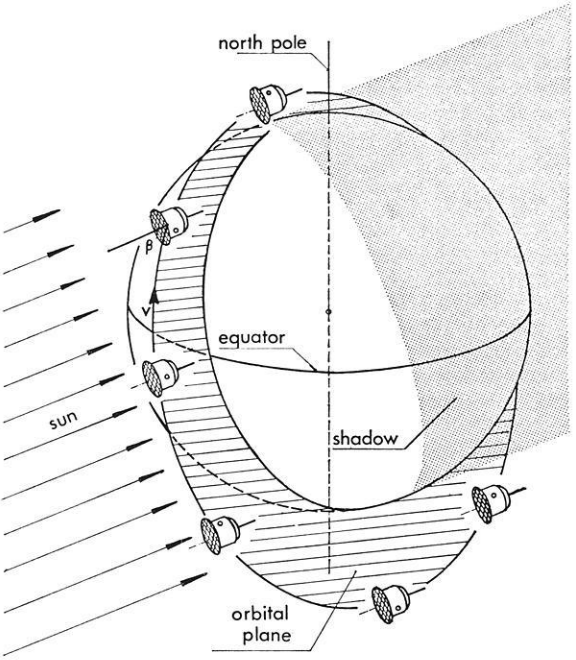

Fig. 1. Schematic orbit of the AEROS satellite. Angle β between orbital velocity vector v and the spin axis varies from 0° to 360° during one revolution

where D is the drag force antiparallel to the velocity v relative to the ambient gas, whose density is ϱ, acting on a body with cross-sectional area A and drag coefficient C_D. Knowledge of the product of effective cross-sectional area A times drag coefficient C_D is crucial in deducing atmospheric density ϱ. Along its orbit the AEROS satellite moves in a free molecular flow regime where the drag coefficient depends on the shape and orientation with respect to the orbital velocity vector, the angular distribution of re-emitted molecules, the energy accommodation coefficient, and the molecular speed ratio between free stream velocity and most probable thermal velocity. Recently some progress has been made in one aspect of supporting laboratory measurements, the generation of molecular nitrogen and atomic oxygen beams at satellite orbital speed (e.g., Boring and Humphris, 1973). As Moe (1973) has pointed out, it has so far not been possible to reproduce in the laboratory the conditions of surface contamination encountered by satellites. *In situ* determinations of the drag coefficients with the help of paddlewheel satellites yield values of 2.1 to 2.4 for spherical satellites at perigee heights between 190 and 300 km for various eccentricities (Moe, 1973). It is safe to conclude that the drag

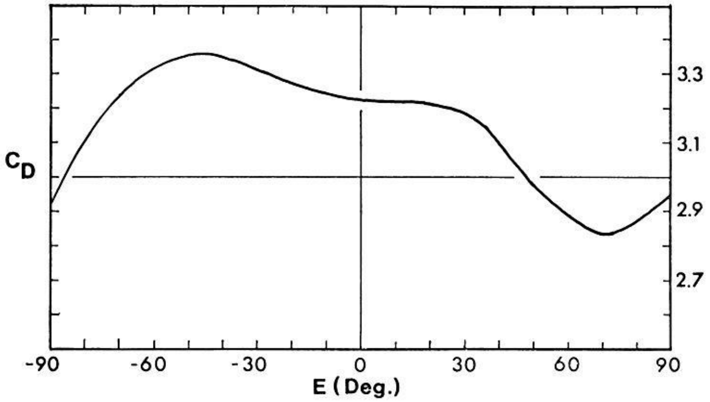

Fig. 2. Drag coefficient based on the shank projection of the cylinder. The drag coefficient C_D along the orbit of AEROS for February 27, 1973 varies between 3.35 at —45° eccentric anomaly E and 2.85 for $E=70°$. The position of the extrema depends on the location of perigee in latitude and local solar time

coefficient in the molecular nitrogen and atomic oxygen dominated regime of the thermosphere, i.e. near the perigee of the AEROS satellite, is known within an error of $\pm 10\%$.

Based on this experimental evidence we are able to adopt Cook's (1966) conclusions on the variation of the accommodation coefficient for the computation of the drag coefficient of the AEROS satellite. We can treat the spacecraft as an effective cylinder with a diameter-to-length ratio of 1.32 whose spin axis is directed towards the sun within 3°. As can be seen in the schematic view of the satellite's orbit in Fig. 1 the angle β between the velocity vector $\boldsymbol{v}$ and the spin axis varies from 0° to 360° during one revolution. Thus the aerodynamic angle of attack $\alpha = 90° - \beta$ changes slowly from 90° via —90° to 90° in the course of one orbit. If the reference area A in the product $C_D \cdot A$ is kept constant and set equal to the shank projection of the cylinder, the drag coefficient C_D is of the order 3.1 with a significant variation of $\pm 10\%$ along the orbit. In Fig. 2 an example of the variation of the drag coefficient within $\pm 90°$ eccentric anomaly around perigee is given for February 26, 1973 when perigee was at latitude —78°, local solar time 17h and at 239 km altitude. This example shows that the variation of the drag coefficient which is primarily due to the changing angle of attack has to be taken into account in the derivation of atmospheric density from orbital drag.

In the orbital drag technique Eq. (1) cannot be used directly since the instantaneous drag D is not monitored. Instead we analyse the loss of orbital energy during a complete revolution which is given by the integral over (1) along the orbit:

$$\Delta E = -\frac{A}{2} \oint\limits_{\text{orbit}} C_D\, \varrho\, v^2\, ds \tag{2}$$

where ΔE is the loss in orbital energy during one orbit and ds is an element of the orbital path. Making use of the relation between anomalistic period P and orbital energy E in a Keplerian orbit, we have

$$\frac{\Delta P}{P} = \frac{dP}{dt} = -\frac{3}{2}\,\frac{Aa}{m\mu}\,\varrho_\pi \oint C_D \left(\frac{\varrho}{\varrho_\pi}\right)_{\text{model}} v^2\, ds \tag{3}$$

where m is the mass of the satellite, ϱ_π the atmospheric density at perigee to be determined, a the semimajor axis, and μ the constant of the earth's gravitational field. We solve Eq. (3) for the density at perigee ϱ_π by using the orbital elements and the observed rate of change of period dP/dt and by a numerical solution of the integral in an iterative process where the relative variation of density along the orbit $(\varrho/\varrho_\pi)_{\text{model}}$ is taken from an appropriate atmospheric model like CIRA 1972. Details of the numerical integration of the drag force acting on the satellite along the actual orbit have been given by Jacchia and Slowey (1962) and Roemer (1963).

3. Analysis of Tracking Data

Interferometer observations by the NASA STADAN network known as Minitrack observations and range and position observations by four selected radar stations are the input for the derivation of the observed rate of change of period. The analysis of tracking data is broken down into several steps:

1. Observations for arcs of 2—4 days are used in a differential orbit improvement program to compute orbital elements argument of perigee ω, right ascension of the ascending node Ω, eccentricity e, inclination i and mean anomaly M at the center epoch.

2. Orbital elements $\bar{\omega}(t)$, $\bar{\Omega}(t)$, $\bar{e}(t)$, $\bar{i}(t)$ and $\bar{M}(t)$ for a 30 to 40 day period are expressed as functions of time using a least-squares process. No systematic residuals are permitted for elements $\bar{\omega}$, $\bar{\Omega}$, $\bar{e}$ and $\bar{i}$.

3. Residuals of the mean anomaly ΔM corresponding to the *individual* observations with respect to the least-squares fit are computed in a further differential orbit improvement process.

4. These residuals ΔM as a function of time are fitted by a cubic spline (Sauer and Szabo, 1968). The second derivative of this fit yields the correction to the rate of change of period based on individual observations.

5. The second time derivative of $\bar{M}(t)$ corrected for the apsidal motion by a term $(1+e^2/2+3e^4/8\cdot\dot{\omega}$ is combined with $d^2(\Delta M)/dt^2$ from step 4.

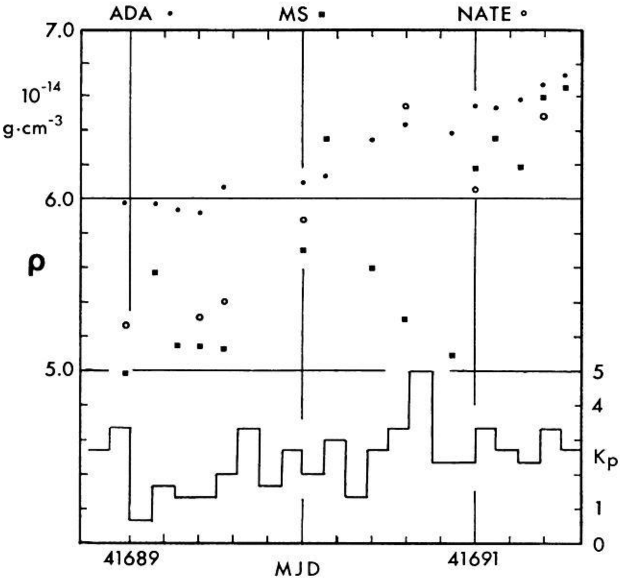

Fig. 3. Comparison of total gas density. For days January 7 through January 9, 1973, equivalent to modified Julian Date MJD 41689 through 41691, total gas density at perigee as derived from orbital drag (ADA), the Heidelberg mass-spectrometer (MS) and the Goddard mass-spectrometer (NATE) are compared. Atmospheric density is plotted in a linear scale in units of 10^{-14} g · cm^{-3}. The 3-hourly K_p-index is plotted at the bottom

Division by $d\overline{M}/dt$ yields the observed rate of change of period $\acute{P}$ which is the input of the numerical integration procedure.

On the average 10—20 independent observations of the Minitrack network and the selected RADAR stations are available per day. This allows a maximum time resolution of 2 orbits, i.e. the standard time interval between measuring orbits in the AEROS program.

4. *Scientific Goals*

The geophysical parameter determined by ADA is the total atmospheric density at perigee. Due to the smoothing inherent in the orbital drag technique each data point is effectively averaged over ±20° eccentric anomaly around perigee. For a near-polar satellite like AEROS this causes a smoothing in latitude of about ±15°. Maximum obtainable time resolution is 2 orbits for absolute values of density, possibly 1 orbit during disturbed periods for relative density variations.

Density data obtained from ADA are free from sensitivity changes during the mission and therefore will serve as a calibration procedure for the *in situ* mass-spectrometer measurements. First results taken from experimenters' data record EDR-6 for January 7 to January 9, 1973 are compared in Fig. 3. This example shows that the unedited total gas density data derived from the Heidelberg mass-spectrometer by summation of partial densities are on the average some 15% lower than the drag-derived densities and density data from the NATE experiment on the average some 10% lower. Corrections for gas-surface interaction in the Heidelberg ion source will raise the data obtained from the Heidelberg mass-spectrometer. This comparison of less than 3 days of measurements serves as an example only for the comparison and calibration program of the various neutral atmosphere experiments aboard satellite AEROS.

The objectives of experiment ADA are:

1. determine gas density at perigee by an independent method with the highest obtainable time resolution;
2. serve as a calibration technique for on-board mass spectrometers;
3. compare results with *in situ* measurements by mass-spectrometers and EUV-absorption technique to deduce consistent density data;
4. contribute to the determination of absolute number densities of atomic oxygen by the mass balance procedure;
5. calibrate the time resolution of the orbital drag technique during short time scale transient atmospheric density changes by using actual *in situ* mass-spectrometer measurements as input to the numerical integration process for a comparison with the observed orbital changes.

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