ATMOSPHERIC STRUCTURE MEASUREMENTS FROM ACCELEROMETER INSTRUMENTED FALLING SPHERES

by

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Abstract:

A three-axis piezoelectric accelerometer, mounted in a 25 cm diameter sphere has been used to measure the atmospheric density and winds and obtain a temperature profile in the altitude range of 50 to 150 km. The sphere with its own telemetry system, beacon transponder and associated support electronics was released from a Nike-Orion boosted payload at an altitude of about 70 km on the up-leg of the flight. The drag acceleration measured by the accelerometer can be used to directly calculate the atmospheric density with a vertical resolution of about 100 meters. The wind field is calculated under the assumption of a uniform distribution in the horizontal plane between the up-leg and down-leg regions which are separated by about 30 km. The atmospheric temperature profile is determined by integrating along the density profile under the assumptions of the ideal gas law and hydrostatic equilibrium. The profiles obtained from the density, temperature and wind profiles can be used to describe those regions of the atmosphere which would be expected to be statically and dynamically unstable. A prototype of the high frequency accelerometer which should be able to measure the drag acceleration component associated with structure scales as small as 2 meters was also included in the payload. The purpose of this high frequency accelerometer is to measure the structure

associated with the inertial subrange of turbulence layers in the mesosphere. Data were obtained at 0447 UT on 16 November and 0009 UT on 1 December 1980. The measurements were made in conjunction with many other experiments during the two salvos for disturbed geomagnetic conditions as part of the Energy Budget Campaign.

Introduction:

Two accelerometer instrumented payloads to measure the atmospheric density, temperature and wind structure were prepared for the Energy Budget Campaign. These two payloads, identified as E6a, were combined with chemical release payloads from University College London and launched on Nike-Orion vehicles. Two flights were made from ESRANGE, Sweden, on 16 November 1980 at 0447 UT as part of Salvo B, moderate geomagnetic storm conditions, and on 1 December 1980 at 0009 UT as part of Salvo A, major geomagnetic storm conditions. A description of the launch conditions and overview of the campaign has been given by Offermann (1981).

The piezoelectric accelerometer instrumented sphere payload was developed to provide higher resolution measurements of atmospheric properties over a larger altitude range than had been previously available (Philbrick, Faire and Fryklund, 1978). Over the past few years the calibration techniques and data analysis procedures have been continually improved to provide a more useful instrument for accurate measurements of atmospheric properties.

Falling Sphere Experiment:

Measurements of the drag force on a freely falling body can be used to directly determine the atmospheric density and wind. The density is determined from the magnitude of the drag acceleration vector which is colinear and oppositely directed to the velocity vector. The magnitude and direction of the horizontal wind is determined by comparing acceleration component ratios between up-leg and down-leg while assuming that the wind is horizontal and uniform over the separation distance.

The accelerometer axes are orthogonal to each other with the z-axis aligned with the spin axis of the sphere. The z-axis moment of inertia of the sphere is adjusted to be about 15% larger than the uniform moment of inertia of any axis in the transverse plane. This arrangement provides a stable spin configuration for the flight of the sphere and separates the spin axis precession frequency sufficiently from the spin frequency so that electronic filtering of the precession acceleration can be used. The typical spin frequency is about 6 Hz and corresponds to a precession frequency of about 1 Hz.

The sphere payloads contain a three-axis accelerometer, a single axis precession accelerometer, a high frequency accelerometer, a telemetry encoder and transmitter, a tracking beacon and supporting equipment. The 25 cm diameter sphere was released from the rocket payload near 65 km altitude, following about 2 seconds after nose cone ejection. A few seconds after the sphere was separated from the rocket payload, caging jaws released the proof masses of the three-axis accelerometer. The sphere ejection mechanism is a spring loaded cradle which releases the sphere with a separation velocity of about 4 m/sec. The mechanism is designed to separate the sphere with the least possible torque to minimize the precession cone angle of the spin axis.

The spinning motion of the sphere provides a modulation of the acceleration measured by the x-axis and y-axis accelerometers as the sensitive direction of each sensor passes through the plane of the trajectory. In Figure 1 the relationship of the sensor axes relative to the drag acceleration vector is indicated on down leg of the flight. On up-leg the z-axis is very nearly aligned with the velocity vector, thus the x- and y-axis accelerometers experience only a very small component of atmospheric drag. The up-leg measurements provide data which are strongly influenced by the horizontal wind velocity. On down-leg the much larger velocity component of the vertical motion causes the x and y sensors to respond primarily to the atmospheric drag acceleration. The three drag acceleration components are used to determine the orientation of the spin axis in inertial space. The spin inertia and the careful balancing of the mass properties to place the center of gravity

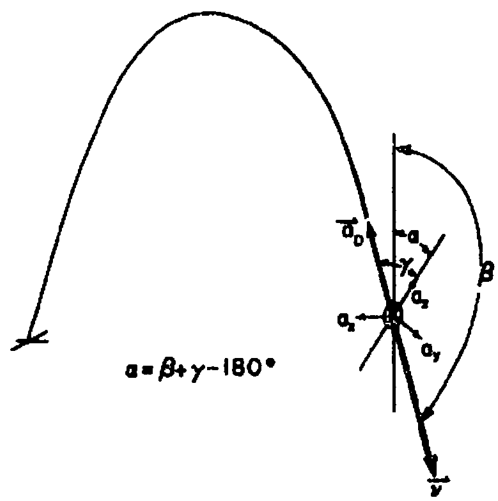


Figure 1. A representation of the sphere axes relative to the local vertical and the velocity and drag acceleration vectors on the down-leg of the flight.

coincident with the center of pressure results in an extremely small torque on the sphere during flight. The worst case cumulative effect is estimated to be less than 0.2 degrees over the flight to 50 km altitude.

To determine the wind profile the acceleration ratio of up-leg and down-leg data are used under the assumption that the wind field is uniform over the 20 to 50 km that separate the up-leg and down-leg data. The up-leg data provides most of the information on the wind velocity and the down-leg provides the density data.

The equation for the atmospheric drag force,

$$m\, a_D = \frac{1}{2}\, \rho\, v^2\, C_D\, A$$

$$\rho = \frac{2\, a_D\, m}{v^2\, C_D\, A}$$

is used to derive the atmospheric density from the measured drag acceleration, a_D, where v is the magnitude of the velocity, m and A are the mass and cross-sectional area of the sphere, and C_D is the drag coefficient. The drag coefficient for the conditions encountered in the continuum flow region between 50 and 90 km has been determined from wind tunnel tests, Bailey and Hiatt (1972). For altitudes above 110 km the free molecular flow drag coefficient is based on the studies of Schaaf and Chambre (1958). In the transitional flow region between 90 and 110 km, the model solution of Rose (1964) is used. The errors in the drag coefficients used are estimated to be ± 3% in the continuum flow region below 90 km and increasing to ± 5% in the free molecular low region. The errors in the mass, area and velocity are all less than 1%. The errors in a_D are due primarily to the determination of the pointing direction of the sphere spin axis in inertial space and to the separation of the wind component from the density component of acceleration. The errors in the density depend in general upon the analysis of a particular experiment but should be less than ± 10%. The spin modulated acceleration, which is measured by the x- and y-axis sensors, is fitted for each spin cycle at half spin period intervals. Unique measurements of the acceleration magnitude are thus determined 12 times per second for each sensor. The typical velocity in the mesosphere is about 1200 m/sec for trajectories with apogees between 150 and 180 km. The measurement resolution is approximately 100 meters in the mesosphere but depends on the altitude and the particular flight trajectory. The relative profile of the small scale structure in the measurements should be useful for values less than 1% except at the higher altitudes where the drag acceleration is very small and the precession acceleration disturbs the measurement.

The atmospheric temperature is determined by integrating down the density profile under the assumptions of hydrostatic equilibrium and the ideal gas law which can be combined into the form

$$T_{M2} = T_{M1} \frac{\rho_1}{\rho_2} - \frac{M\,g}{\rho_2\,R} \int_{z_1}^{z_2} \rho\, dz \,.$$

The acceleration of gravity, g, the mass density, ρ, and the mean molecular weight, M, are dependent upon altitude, R is the universal gas constant. The molecular scale temperature, T_M, is related to the gas kinetic temperature by $T = \frac{M}{M_o} T_M$, where M and M_o are the mean molecular weight at the altitude, z, and at ground level, respectively. The mean molecular weight in constant up to about 90 km altitude and values from the US Standard Atmosphere, 1976 are used at higher altitudes. The equation integrates downward from an initially assumed temperature at the top of the profile and the error in the initial assumption is removed within two density scale heights.

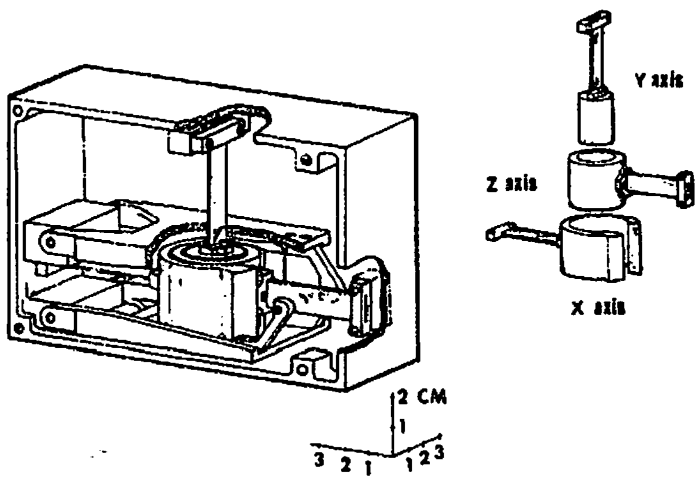
In addition to the primary three-axis accelerometer, a single axis accelerometer with lower sensitivity is used to measure the magnitude of the precession cone angle and the precession acceleration. This accelerometer is located near the periphery of the sphere and its sensitive axis is parallel to the z-axis. The measurements from this accelerometer also extend the range of measurements from approximately 60 km to near 40 km on down-leg portion of the flight.

A prototype of a high frequency response accelerometer was included in the two payloads launched in the Energy Budget Campaign. The high frequency accelerometer is intended to measure the small scale fluctuations in the atmospheric structure associated with turbulence layers in the mesosphere. The frequency response is 10 Hz to 2 kHz and corresponds to the expected scale size of the inertial subrange of mesospheric turbulent layers. The sensitive direction of the sensor is parallel to the z-axis. The measurement range of the instrument was from 2×10^{-5} m/sec^2 to 1×10^{-3} m/sec^2 which would correspond to fluctuations of the background density of approximately 0.5 to 20% near 100 km and 0.005 to 0.1% near 60 km.

The sphere contained a C-Band beacon transponder to provide accurate trajectory data from the DFVLR MPS 16 and ESRANGE tracking radars. An accurate trajectory of the sphere is important because the gradient of the atmospheric density would cause an apparent error of 1% in density for each 60 meters error in the assigned altitude. An S-Band telemetry system encoded and transmitted the PCM data from the three-axis accelerometer and the precession accelerometer. The high frequency accelerometer signal was transmitted on an FM carrier with a high frequency response. The PCM data provided 10 bit digital words at a rate of 120 words per second for each of four overlapping amplifier ranges for the three primary accelerometer axes.

Accelerometer Sensor:

The accelerometer configuration is shown in Figure 2. The three proof masses are made so that they have a common center of gravity which is aligned to be coincident with the geometric center and the center of gravity of the sphere. Each proof mass is suspended on a piezoelectric crystal bimorph which is secured to a stiff case that is machined from a solid block of metal. The caging jaws are used to clamp the proof masses until the sphere is separated from the rocket payload. This prevents crystal breakage during handling and launching operations.



Three Axis Piezoelectric Accelerometer

Figure 2. The arrangement of the three proof masses in the accelerometer case.

The piezoelectric accelerometer has the advantage of extremely linear response over a large dynamic range. The sensitivity of the piezoelectric sensor is typically 6 to 8 volts output for an acceleration of 1 m/sec^2. Figure 3 shows a schematic representation of the bimorph construction of the sensor. The typical natural frequency of the sensors used is about 12 Hz, or twice the forcing frequency of the atmospheric drag at the 6 Hz spin rate. Each sensor is calibrated using the configuration shown in Figure 4 by a forced simple harmonic oscillator. The magnitude of the input acceleration is known from the horizontal displacement of the mount and the forcing angular velocity, $\ddot{x} = \omega^2 x$. The natural frequency of the sensor is also measured on the calibration

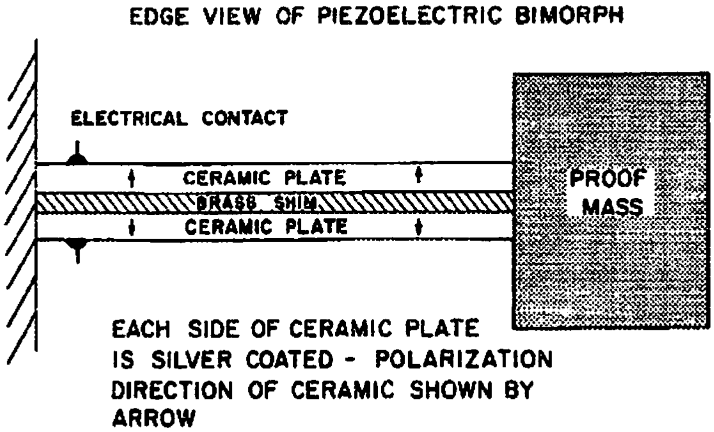


Figure 3. A schematic representation of the sensor construction indicating the orientation of the polarization field of the piezoelectric ceramic.

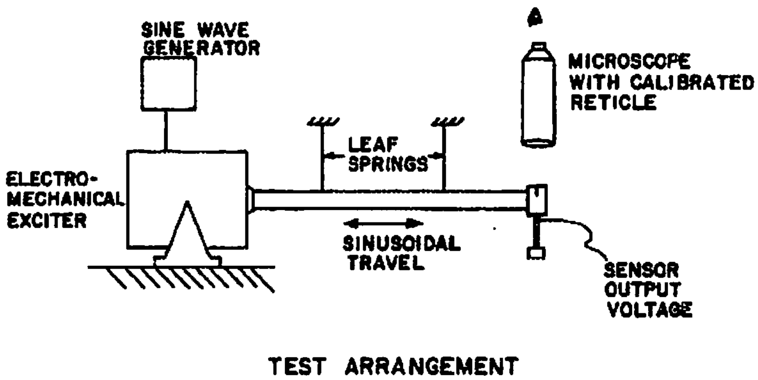


Figure 4. Schematic diagram of the calibration arrangement where the acceleration is determined from the horizontal displacement as measured by a microscope.

table, on a rigid mount and in the sensor case to assure that the natural frequency is known and is consistent from sensor to sensor. In the laboratory environment the stiffening due to the gravity must be considered and in the flight environment the stiffening due to the spin acceleration must be included in the analysis. The natural frequency under flight conditions can be measured during the first few seconds after uncaging of the proof masses. The voltage output of the piezoelectric accelerometer is given by the relationship,

$$V = \frac{K\,a}{\omega_N^{\,2}} \left\{ \left[1 - \left(\frac{\omega}{\omega_N}\right)^2 \right]^2 + \left(2\,\frac{\zeta\,\omega}{\omega_N}\right)^2 \right\}^{-\frac{1}{2}} ,$$

where K is the calibration constant, a is the acceleration, ω is the angular velocity of the forcing acceleration, and ω_N is the resonance angular velocity. The second term in the brackets is negligible because of the small damping factor, ζ, of these sensors.

Measurements in the Energy Budget Campaign:

The two falling sphere payloads, E6a, were launched at 0447 UT on 16 November 1980 and 0009 UT on 1 December 1980 as part of Salvo B and Salvo A, respectively. The final analysis of the results are expected to yield profiles of atmospheric parameters over the altitude regions listed below.

Salvo B - 16 November 1980

Density	40 to 150 km
Temperature	40 to 140 km
Wind	85 to 130 km

Salvo A - 1 December 1980

Density	60 to 150 km
Temperature	60 to 140 km
Wind	85 to 130 km

The static stability of the atmosphere can be determined from the density profile and the dynamic stability from the wind and temperature profiles. These studies will indicate those regions where turbulent layers may be expected. The lower altitude density measurements were not obtained in Salvo A because of a failure in the amplifier output of the precession accelerometer. The upper altitudes of the density and wind profiles were adversely effected by a large precession cone angle which will result in a larger than normal error assignment. Both of these flights exhibited significant cone angles near 45 km on up-leg of the flight which indicates that some degree of roll-pitch coupling took place. The precession cone angle of the sphere at the time of separation was approximately 12° whereas about 1° would normally be expected. In addition, the large precession acceleration adversely effected the high frequency accelerometer data. Only a small percentage of the high frequency accelerometer data is expected to be useful.

Both of these payloads have provided good quality data on the primary atmospheric properties of density, temperature and wind structure. The results of the analysis of the data will be reported in a future paper.

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