THE DYNAMICS EXPLORER WIND AND TEMPERATURE SPECTROMETER

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Abstract. The Wind and Temperature Spectrometer (WATS) is designed to measure the concentration, kinetic temperature and motions (3 mutually perpendicular components of the wind) of the neutral particles. In addition, measurements of the concentration and velocity of the ambient thermal ions are possible. Two of the three wind components, the temperature and the concentration of the dominant constituent, can be measured to an altitude of about 650 km, the third wind component to about 375 km (estimated). Ion measurements can be made throughout the orbit.

A quadrupole mass spectrometer is the basic sensor for the instrument. Measurements of the zonal and vertical components of the wind are made through interpretation of the modulation of the particle stream entering the mass spectrometer, induced by baffles that scan slowly (one vertically and one horizontally) in front of the entrance port of the mass spectrometer. The third component, horizontal, in the orbit plane, is obtained by evaluating the potential required to decelerate ions entering the quadrupole analyzer.

The instrument affords measurement accuracies approximately as follows: concentration of neutral particles, 20%; their temperature, 5 K; and neutral winds by the baffle technique, 10–20 ms^{-1}; neutral wind component by RPA technique estimated about 50 ms^{-1}, with experimental confirmation of the latter to be obtained in orbit.

1. Introduction

The multi-purpose instrument described in this paper, using a mass spectrometer as the basic sensor, has evolved through the development and use of a series of similar rocket and satellite instruments. The basic objective of the instrument series has been to measure the ambient concentration of atmospheric neutral species, and more recently through local perturbation of the particle motions due to a special scanning baffle and the satellite motion, a variety of other media characteristics such as the temperature and velocity of the neutral, and for this instrument, the ionized particles. The series of instruments began with an omegatron (sensor) instrument designed to measure the concentration and temperature of molecular nitrogen using rockets [1], then progressed to similar omegatron instruments on San Marco 3 and 4, quadrupole instruments on Aeros A and B [2], Atmosphere Explorer C, D, and E [3] and the Pioneer Venus Orbiter [4], and to the Dynamics Explorer (DE) quadrupole instrument discussed here. The AE instruments have demonstrated the capability to obtain in situ measurements of the vertical and orbit-plane-normal components of the wind using the baffle technique, and the Pioneer Venus instrument has provided the first step in obtaining measurements of the velocity component aligned with the mass spectrometer orifice normal.

The instrument has been optimized for the DE mission to measure the three compo-

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nents of the wind noted above and the kinetic temperature of a single but selectable gas, usually molecular nitrogen (N_2), or atomic oxygen (O), depending upon the altitude at which the measurements are made. Measurement of the relative concentrations of these and the other neutral species comprise a secondary objective for this mission. A special experimental mode for measurement of the concentration of ions has also been included in the instrument design. The possible utility of the baffle technique when the instrument is in the ion mode will be explored in orbit.

2. Technique

The use of a mass spectrometer for the direct in situ measurement of kinetic temperature and wind has been described in detail in other papers [3, 5] and thus the technique will be discussed here only briefly. The temperature measurement involves determination of the velocity distribution of the particles of a single gas, usually N_2, from which the kinetic temperature is calculated. The thermal velocity distribution is obtained through observation of the modulation of the gas flow into the mass spectrometer due to a baffle which partially intercepts the flow as it is mechanically scanned in front of the mass spectrometer entrance port. Figure 1 illustrates the basic concept showing the essentials of the mass spectrometer inlet antechamber and baffle geometry.

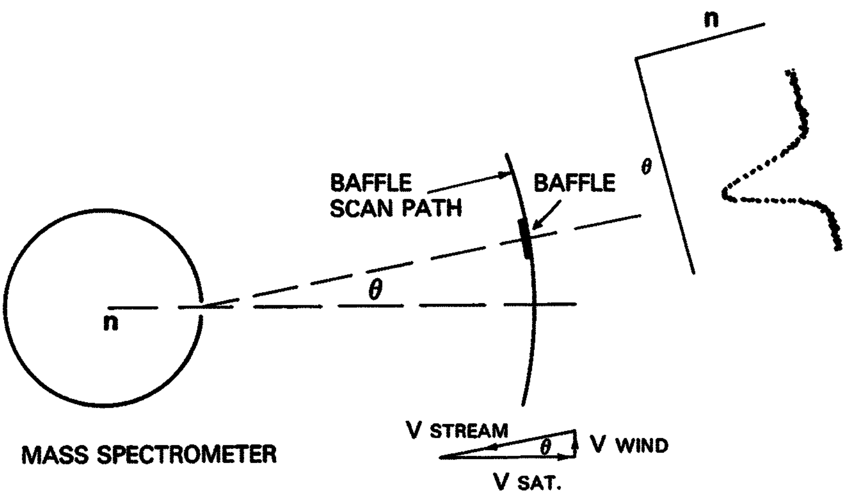

Fig. 1. Illustration of mass spectrometer inlet/baffle geometry. Baffle scans causing n to vary as shown, based on the particle velocity relationships depicted.

Shown at the right of the figure is a sample of the typical mass spectrometer antechamber N_2 density, n, (data taken from Atmosphere Explorer) whose magnitude varies with time due to baffle modulation of the entering stream. The signal minimum occurs at the point in the scan where the stream is maximally intercepted. Taking into account the velocity and orientation of the spacecraft, measurement of the angle θ between the orifice normal and the direction of the minimum permits calculation of the wind component lying in the plane defined by V_{sat} and the baffle scan path. The kinetic temperature of N_2 is computed from the variation of density in the curved regions defining each side of the density minimum, an independent temperature value resulting from each side. A complete baffle scan cycle period (four seconds) yields two interceptions and thus a temperature calculation can be made on the average of once per second, or about every 8 km along the satellite trajectory. A wind component measurement is also made at each interception, twice per scan cycle or about every 16 km.

For this instrument two baffles are employed, one which scans in the plane of the orbit (normal to the spacecraft z axis) [6] allowing computation of the vertical component of the wind, V_v, and one that scans normal to the orbit plane (normal to the spacecraft y axis) allowing computation of the wind component normal to the orbit plane (since DE-B is in a polar orbit this is the zonal component, V_z). The two baffles are scanned and the components measured sequentially. The two baffles are not arranged to modulate the neutral particle stream simultaneously because of complications in the data analysis procedures that would result.

The third component, also horizontal but in the orbit plane (meridional component, V_m, for DE-B), is determined by using the retarding potential analyzer (RPA) concept [7], but this technique is new for this instrument. The ion source of the quadrupole mass spectrometer, (Figure 2) which is very similar to that developed for the Pioneer Venus Orbiter neutral gas experiment, employs a retarding grid assembly following the ionization region. Neutral particles ionized in the ion source region by electron impact pass through the retarding grid assembly and are focused and directed into the quadrupole for mass separation. Varying the potentials applied to the retarding grid assembly permits retardation of the ion stream, allowing evaluation of the average ion velocity,

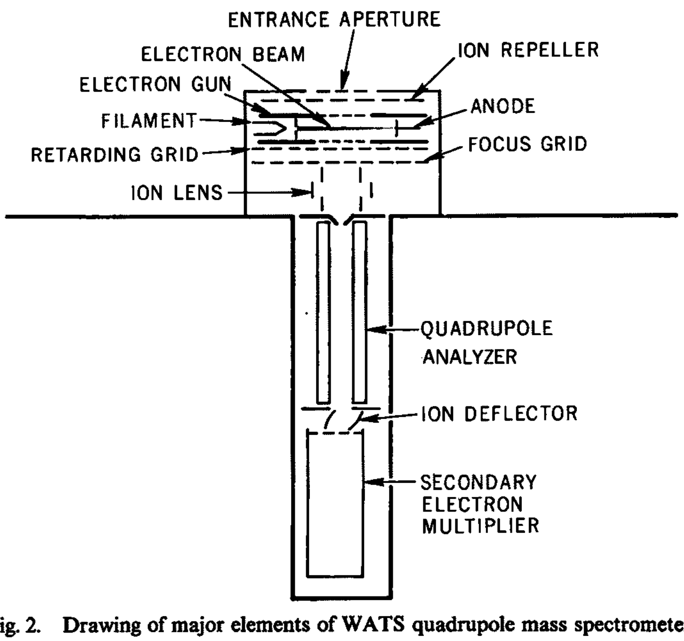

Fig. 2. Drawing of major elements of WATS quadrupole mass spectrometer.

which is equivalent to the neutral particle velocity along the ion source center-line. Inflight calibration for ambient ions will be obtained through comparisons with data from the RPA instrument. The sensitivity of the instrument in this mode is expected to be less than that experienced in the other modes because of the absence of the particle concentration enhancement due to the ram effect, as discussed immediately below.

The concentration, n, of the neutral particles selected for wind measurement is measured in a manner similar to a conventional mass spectrometer. Two modes are employed as in the Pioneer Venus instrument [4]: a closed source mode where particles are thermalized through contact with the antechamber and ion source surfaces, and an open source mode where particles entering at the stream velocity are measured directly before surface contact occurs. The latter is useful for (a) the measurement of reactive particles such as atomic oxygen which recombine to O_2 as a result of surface collisions and cannot be measured directly in the closed source mode, and (b) as an 'RPA' device, and (c) for the measurement of the wind velocity in oxygen dominant regions as described in the previous paragraph.

In the closed source mode, the density of the gas in the ionization region is increased many fold over the ambient concentration as defined by the following equation:

$$n = N_a(T_a/T_i)^{1/2} f(s),$$

where n is the instantaneous antechamber density for a particular gas, N_a is the ambient density of the gas, T_a is the ambient temperature of the gas, T_i is the temperature of the gas inside the chamber (equivalent to the antechamber walls), and $f(s) = \exp(-s^2) + \pi^{1/2} s [1 + \mathrm{erf}(s)]$, with $s = V/(2k\,T_a/m)^{1/2} \cos \alpha$, and α is the angle between the velocity vector and the orbit plane. The ratio of the spacecraft speed to the most probable velocity of the selected gas is $V/(2k\,T_a/m)^{1/2}$, m the mass of the gas and k is Boltzmann's constant. For DE-B, $\cos \alpha$ is unity, and the density (n) increases by approximately a factor of 68 for N_2 and 36 for O compared with ambient values. This effect improves the signal to noise ratio and greatly increases the altitudes where winds and temperature (by baffle) can be measured. The density enhancement effect is not realized in the open source mode as only free streaming entering particles are measured. For this reason, the wind component in the orbit plane cannot be measured at altitudes as great as the other components (see Table I).

An ion mode during which neutral particles are not ionized can be employed permitting measurement of the concentration of ambient ions allowed to enter the antechamber. This mode, including the possibility of baffle modulation and hence ion velocity measurements, is experimental for this instrument since the design has not been optimized in this regard.

3. Instrument Description

The instrument is assembled into two separate packages, a sensor unit and an electronics unit, as shown in the photograph (Figure 3) for ease of mounting in the spacecraft. The sensor assembly contains the quadrupole mass spectrometer (sensitivity about 10^{-7} amps

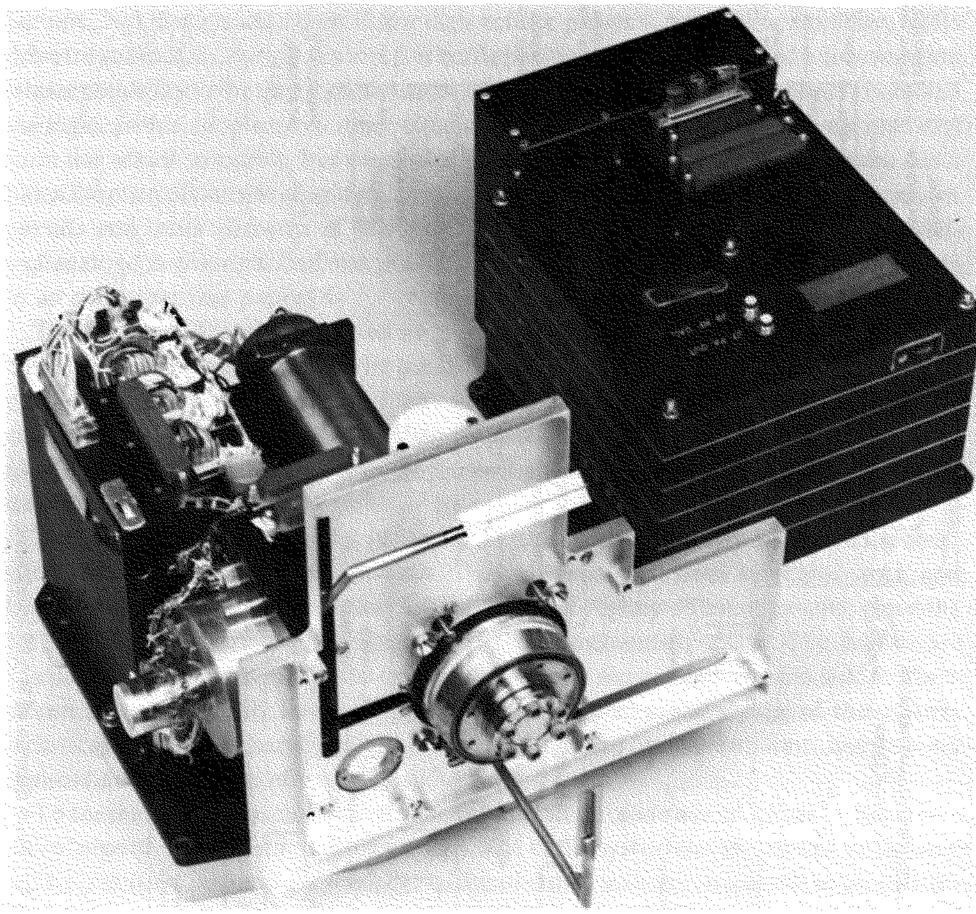

Fig. 3. Photograph of the wind and temperature spectrometer.

TABLE I

Values of estimated accuracy and maximum altitude based on MSIS model and solar flux of 175

Parameter	Est. accuracy	Maximum altitude[a] km	Resolution (max)
$n(0)$	20%	550	120 m
$n(N_2)$	20%	430	120 m
T_A	5 K	450	8 km
V_v	10–20 ms^{-1}	650	16 km
V_z	10–20 ms^{-1}	650	16 km
V_m	50 ms^{-1}	375	16 km
n_i	No calibration	apogee	16 km

[a] Values based on signal level of approximately 2000 counts/IP.

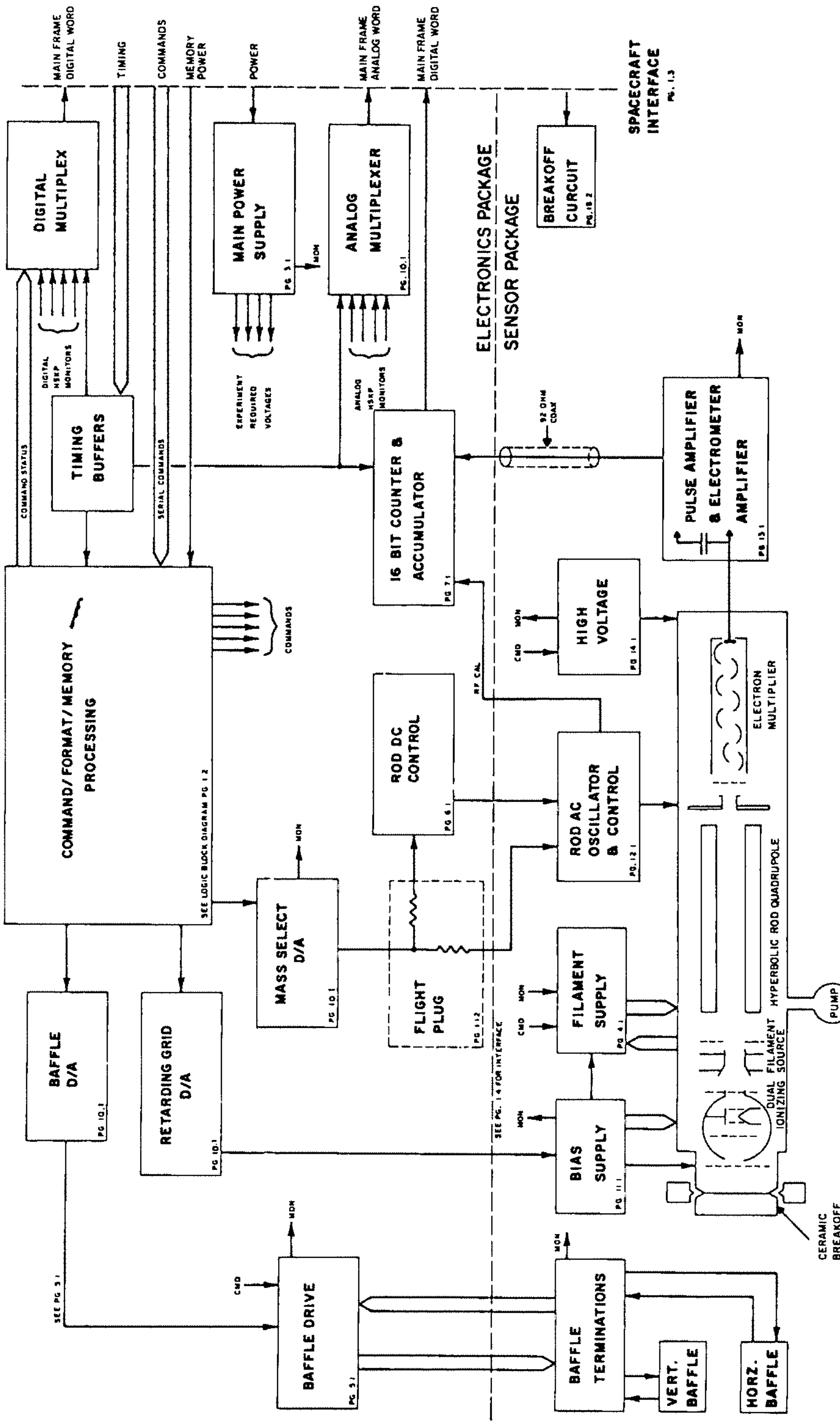

Fig. 4. Block diagram of WATS instrument.

per torr, N_2), the associated oscillator high voltage power supply, pulse amplifier, baffle drive torque motors, optical sensors (for baffle position measurement) and other elements whose proximity to the quadrupole sensor is required. The electronics assembly contains the logic, power supplies and other circuits which may be mounted relatively remotely from the sensor assembly, but connected through coaxial lines as shown. Figure 4 is a block diagram of the overall system, showing the sensor schematic, the major component circuits and other elements of the system. The block diagram labels are largely self-explanatory. A description of many of the circuit designs not previously reported appears in an accompanying paper [8].

The sensor package is mounted in the spacecraft to allow orientation of the antechamber orifice plane normal to be parallel to the nominal spacecraft velocity vector at perigee (quadrupole, Figure 3, long axis colinear with velocity vector, spacecraft $+ x$ axis). The two baffle drive torque motors are mounted in the sensor package to allow scanning of the baffles in the vertical plane, and normal to the orbit plane as described above.

The rectangular planar baffles (shown in Figure 3) are about 1 by 5 cm with the short end oriented tangent to the scan path. They are machined from beryllium stock and brazed to solid 1/8″ beryllium shafts. The shafts, of slightly different lengths, place the baffles' scannings arcs about 10 cm from the antechamber orifice. The baffles are scanned $\pm 15°$ with respect to the orifice by dc torque motors employed in a dc follower circuit driven by highly linear ramp voltages. The mechanical design of the system, including the choice of beryllium, was dictated by the need to assure uniform, highly linear non-oscillatory motion of the baffles.

To measure the wind component magnitudes to an accuracy of 15 ms^{-1} requires a knowledge of baffle position to about 0.1°. The baffle system design permits attainment of this precision, assuming knowledge of the orientation of the spacecraft to better than 0.1° (see appendix, [9], 'Galactic Monitor' for a discussion of spacecraft attitude determination).

The use of a special solid state optical sensor allows a check of baffle motion. A disk, which is secured to the baffle shaft hub, has 2 radial slits about 5° apart. As the baffle scans, the disk passes between an LED (light emitting diode) and the sensor. The associated circuitry counts the time between initiation of the baffle scan and the times of passage of the slits. The initiation time (position) is commandable. The sensor, which is a quad photodiode, is employed in a bi-cell mode and acts as a dual circuit device exhibiting a crossover characteristic which provides a null. This leads to a slit position indication that has positional accuracy of 2.5×10^{-4} cm, or 0.01°, for the scan rate of 15° per second. Through ground calibration of the baffle motion and in-orbit time measurements of the initial position and sensor crossings, the average speed of the baffle can be calculated. A time history of these data allows continuing evaluation of its motion.

During final preparation of the instrument the sensor is baked under vacuum (at 350 °C) to assure cleanliness, and sealed, following calibration. After a suitable time in orbit to allow spacecraft outgassing, it is opened on command using pyrotechnic devices. The mass spectrometer vacuum sealing device also physically restrains the baffle arms prior to pyrotechnic release, preventing damage to them that might otherwise be realized during the launch phase of the satellite.

Ground support equipment for the instrument uses a hardware and software system built around an LSI-11 computer. The unit, which simulates the necessary spacecraft interface functions, allows full operation and control of the instrument, employing checkout command sequences, while providing the appropriate CRT and printout records of test data.

4. Data Formats and Data Analysis

A series of four sequentially occurring 'slots', each a two-second-long measurement interval, has been adopted for the basic measurement format of the instrument. A variety of functions may be commanded into these slots in any combination, one per slot. These choices include (a) any gas (amu) measurement to which the quadrupole may be tuned for wind, temperature or concentration measurements (either neutrals or ions), (b) any one of the three possible wind component measurements, (c) a variety of special modes to be used primarily in support of other measurements, or for diagnostic purposes, such as a mass sweep (scan of a full spectrum by the mass spectrometer).

During each 2-s slot 128 data samples are obtained. Each sample is equivalent to the number of electron multiplier counts accumulated during the integration period, which is about 15 ms. In the RPA mode data are taken at 16 commandable retarding potentials for a single mass, or 8 each for 2 commandable masses. Each sample corresponds to a quantity of ions having energies exceeding the selected potential. In the composition mode data are taken for 32 sequences of 4 commandable masses. The baffle mode consists of 128 data samples taken during a 15° baffle sweep.

For both the RPA and the baffle mode the measurement of velocity involves only the relative shape of the experimental curve, therefore to facilitate processing the data obtained are transformed in the data analysis process into a normalized form which is

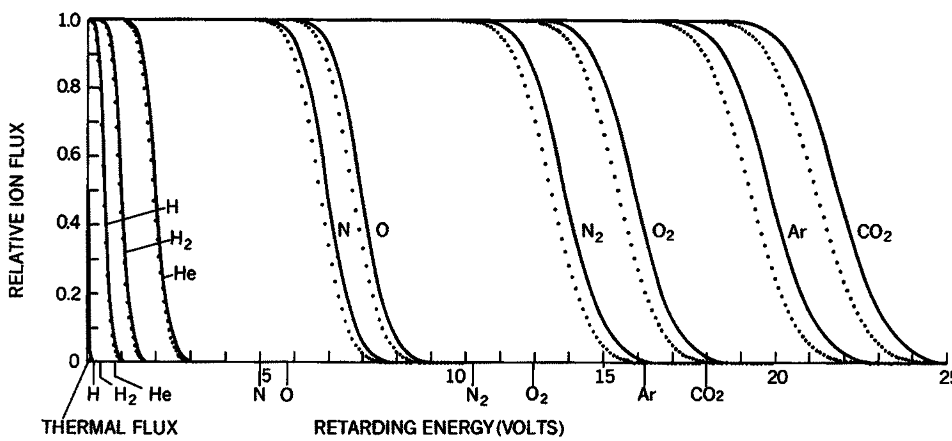

Fig. 5. Plot of idealized retarding functions for various atmospheric gases.

independent of background particle concentrations. In the RPA mode the voltages are selected to insure that some particles are retarded as the retarding grid voltage is scanned, and that at least one sample is taken both in the fully retarded region and in the non-retarded region to provide a measure of the unretarded background. The background is subtracted from the data and the unretarded background is divided into the data to yield a normalized RPA curve which varies between values of 0 and 1. This curve corresponds to the fraction of particles with energies exceeding the retarding voltages. Figure 5 illustrates the idealized characteristics of relative ion flux versus retarding potential for various components.

In the baffle mode the sweep rate and angular range of the baffle have been selected sufficiently high to allow an unmodulated flow of particles for a portion of the measurement period. The data are then subtracted from this unmodulated level, which appears as the flat portion of the curve in Figure 1, to yield the so-called baffle wake curve. The baffle wake is then divided by a normalization factor to yield the normalized baffle curve which varies between values of 0 to 1. This curve corresponds to the fraction of particles that are obscured by the baffle.

The formulation given by Brace *et al.* [10] extended to include more general geometries is used to describe the baffle curve. The form given by Hanson and Heelis [7], modified to include effects due to the orifice, is used to describe the RPA curve. In the neutral RPA mode the counting rate is proportional to the density of particles in the ionization region rather than the flux of particles as in [7] and the curve is modified accordingly.

The normalized RPA and baffle curves may be fit to the theoretical characteristics with a non-linear least-squares technique. A more efficient but less accurate moment technique has been developed which is used in lieu of least-squares fitting when a reduction in computer usage time is required. In this procedure moments (sums of the normalized data points with a given weighting function) are calculated and interpreted in terms of the temperature and wind velocity using a multidimensional Taylor series expansion. For

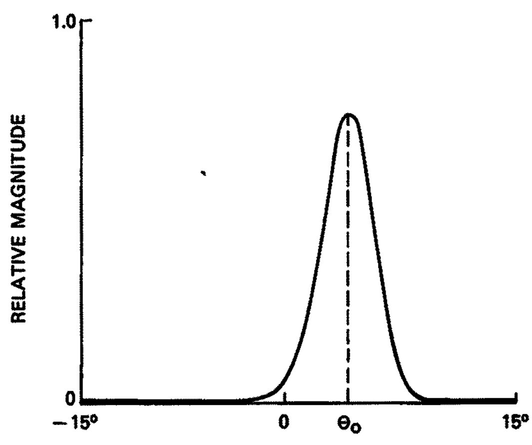

Fig. 6. Typical curve of fraction of particles obscured by baffle for stream entering θ_0 from mass spectrometer orifice normal.

example suppose the baffle wake has been shifted as shown in Figure 6, so that it is centered at some shaft angle θ_0 due to the presence of winds. One then defines the moment M by $M = \sum_i \theta_i w_i$ where θ_i and w_i are the shaft angle and the value of the curve respectively for data point i. The M would be approximately proportional to θ_0 which in turn may be expressed in terms of wind velocity. In addition to this wind sensitive moment one must evaluate a temperature sensitive moment which emphasizes temperature dependent quantities such as curvature of the sides of the curve in Figure 6 which result from the particle velocity distribution. The Taylor series expansion then provides a mapping from these two moments to the temperature and wind. Figure 7 shows data obtained with Atmosphere Explorer E using this technique.

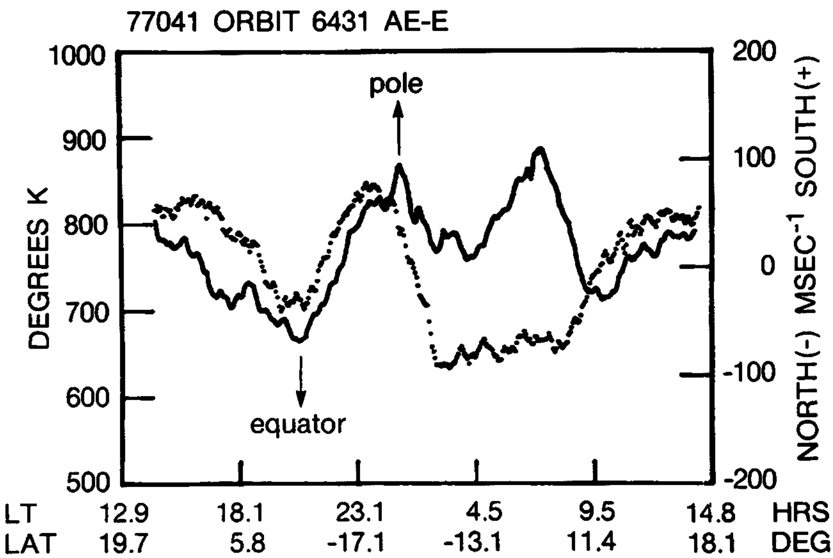

Fig. 7. Example of wind and temperature data obtained with the Atmosphere Explorer E WATS instruments. The dotted curve is temperature.

5. Calibration

Calibration of the instrument involves two specific activities: (1) determination of the sensitivity of the instrument (concentration of each gas in the ion source corresponding to counts provided by the electron multiplier at the output of the quadrupole), and (2) determination of the position of the baffles during a scan with respect to identifiable physical points on the instrument (and hence relatable to the spacecraft frame of reference). In the case of (1) the mass spectrometer is calibrated on a special vacuum system at the Goddard Space Flight Center (GSFC) against standards whose calibration constants have been carefully determined. The various gases are employed independently as well as in mixtures; however, only the non-reactive gases N_2, He, Ar are used as reliable calibration procedures for reactive gases, specifically atomic oxygen (O), do not exist. Molecular oxygen is also employed in the calibration, allowing evaluation of the sensor for this relatively chemically active component, although the instrument has insufficient sensitivity for its detection in the ambient state in the DE-B orbit. The accuracy of the instrument for measurement of non-reactive gas densities is expected to be about 20%, consistent with calibrations for previous missions. Calibration of the system for the ambient ion mode is not performed. Its sensitivity will be determined in orbit through cross checks with the RPA.

To obtain a baffle position calibration, a special optical telescope set-up is established to observe baffle edges at selected positions. Accurate measurements of the positions of the baffle edges with reference to the mass spectrometer antechamber orifice edge are made, when the baffle is in either of the two positions defined by the internal optical calibration sensors. The assumption of linear scanning motion, well established through independent high-speed photography of the baffle motion, then makes possible an angle measurement accuracy of about 0.1–0.2°. The measurements of the relative position of the baffle, and the spectrometer orifice with respect to a reference optical mirror (cross hair) permanently affixed to the instrument allow determination of baffle position with respect to the spacecraft. Knowledge of the instrument reference mirror (cross hair) orientation with respect to the spacecraft axes measured during spacecraft tests completes the requirements for wind direction and magnitude identification.

The anticipated performance of the instrument is summarized in Table I.

Acknowledgment

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