THE NEUTRAL MASS SPECTROMETER ON DYNAMICS EXPLORER B

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Abstract. A neutral gas mass spectrometer has been developed to satisfy the measurement requirements of the Dynamics Explorer mission. The mass spectrometer, a quadrupole, will measure the abundances of neutral species in the region 300–500 km in the earth's atmosphere. These measurements will be used in concert with other simultaneous observations on Dynamics Explorer to study the physical processes involved in the interactions of the magnetosphere – ionosphere – atmosphere system.

The instrument, which is similar to that flown on Atmosphere Explorer, employs an electron beam ion source operating in the closed mode and a discrete dynode multiplier as a detector. The mass range is 22 to 50 amu. The abundances of atomic oxygen, molecular nitrogen, helium, argon, and possibly atomic nitrogen will be measured to an accuracy of about ±15% over the specified altitude range with a temporal resolution of one second.

1. Introduction

The objective of the Neutral Atmosphere Composition Spectrometer (NACS) on the lower altitude spacecraft of the Dynamics Explorer (DE) mission is to characterize the composition of the neutral atmosphere with particular emphasis on variability in constituent densities driven by interactions in the atmosphere – ionosphere – magnetosphere system. A quadrupole mass spectrometer with electron bombardment ionization and employing an electron multiplier in the counting mode for detection is used to meet the measurement objectives. The atmospheric sample to be analyzed is allowed to undergo many (> 100) surface collisions before analysis so that it is in chemical and thermal equilibrium with the instrument surfaces leading to a rigorous formulation of the relationship between the inside sample and the outside atmosphere [1].

The instrument and the details of its implementation are derived from an extensive history of mass spectrometric measurements in the atmospheres of the earth and other planets, dating back to the instrument flown on OGO-VI [2] to the most recent on the Pioneer Venus Orbiter [3]. Included in this history are the mass spectrometers flown on Atmosphere Explorers C, D, and E [4] to which the instrument on Dynamics Explorer bears a close resemblance. From the measurements provided by these instruments and others, including 'open' ion source measurements on Atmosphere Explorer [5], an empirical model of the global behaviour of the neutral atmosphere has been constructed. This model [6], which also incorporates radar backscatter observations, effectively describes the altitudinal, latitudinal, diurnal and seasonal atmospheric behaviour. These

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same instruments have observed profound changes in atmospheric composition associated with magnetic storms [7–9] but a quantitative description of the processes that would lead to a useful model is not yet available.

On Dynamics Explorer, the neutral mass spectrometer will be operated in concert with the other instruments on the two spacecraft to isolate and quantify the processes which are responsible for variability in constituent densities beyond that which can be explained by variation in the direct solar photon insolation. Secondarily, the data obtained during the Dynamics Explorer epoch will serve to further refine the generalized description of the neutral atmosphere as defined by the current empirical and future physical models. Additionally the mass spectrometer will have the capability of measuring the two components of the neutral wind vector perpendicular to the satellite velocity vector. This measurement which employs baffles to interrupt the streaming gas is a complement to the measurements of the Wind and Temperature Spectrometer (WATS). The details of the technique are described in an accompanying paper [10].

2. Measurement Requirements

The scientific objectives require measurements of the abundances of atomic oxygen, helium, argon, molecular nitrogen, and if possible atomic nitrogen over an altitude range of at least 100 km from perigee (nominally 300 km) upward. The absolute accuracy of the measurements should be better than $\pm 15\%$ and the relative accuracy $\pm 5\%$. The temporal resolution should be less than one second to enable observation of the smallest scale variations.

These requirements are generally met with a few limitations. The helium abundance in some parts of the orbit is too low to achieve the desired accuracy due to statistical limitations. The range of altitudes over which argon can be measured is about 50 km rather than 100 because of its rapid decrease with increasing altitude. The atomic nitrogen measurement assumes the recombination of $N + O + O = NO_2$ within the instrument and the measurement of the product at 46 amu and its daughter, NO, at 30 amu. The method is on a sound qualitative basis but the accuracy of the measurement has not been established.

Some requirements are exceeded. In many regions the helium abundance can be measured to altitudes above 1000 km. Generally atomic oxygen and molecular nitrogen can be measured to altitudes of at least 500 km. The temporal resolution of a data set is 0.128 s although eight such sets will usually be averaged to improve statistics while achieving the desired one second resolution.

3. Implementation

The application of mass spectrometry to atmospheric measurements in earth orbit involves several considerations in addition to the normal requirements of mass spectrometry. A few of these factors are of particular significance and have a major impact on the design. The features which are believed to be particularly distinguishing are discussed below.

3.1. Measurement regime

On the Dynamics Explorer measurements are made at altitudes above 300 km where the gas composition is primarily atomic oxygen and/or helium, the densities are very low ($< 10^9$ cm^{-3}) and the instrument is moving with respect to the free stream at about 8 km s^{-1}. Various approaches to composition measurements have been used under these conditions. For the NACS on DE, the atmospheric sample enters an antechamber through a knife-edged orifice. The design of the antechamber assures that a typical gas particle will undergo more than 100 collisions with the walls before being ionized and analyzed. This technique has the disadvantage that atomic oxygen and other reactive species are not measured directly but in some reacted form – in the case of atomic oxygen as molecular oxygen. The closed source has the advantage, however, that since recombination and accommodation are essentially complete, uncertainties in these coefficients play a minor role and the measurement accuracy is improved. Moreover, a significant density enhancement results from two factors: (1) the pressure buildup in the antechamber due to the high spacecraft velocity and (2) the reduction in temperature of the hot ambient gas (typically 1000 K) to the 300 K surface temperature. These enhancements are extremely valuable in reducing the statistical uncertainties in the measurements of helium and argon; for these species the enhancements are roughly factors of 25 and 80 respectively, as can be seen from the relevant gas kinetic equation:

$$n_s = n_a \left(\frac{T_a}{T_s}\right)^{1/2} F(S) \tag{1}$$

where

$$F(S) = \exp(-S^2) + \pi^{1/2} S[1 + \mathrm{erf}(S)]$$

and

S = $V(\cos\alpha)/c$,
n_s = the source density,
n_a = the ambient density,
T_a = the ambient temperature,
T_s = the source temperature,
V = the vehicle velocity,
α = the angle between the orifice normal and the velocity vector, and
c = the most probable velocity of the ambient gas particles.

Accurate measurements of the low densities that are encountered in this regime require great care in eliminating background gas sources that would obscure the measurement of the ambient abundances. The sensor must be sealed in vacua, typically 10^{-9} torr, until opened in orbit and must be located on the spacecraft where little or no external surface area has a line of sight path to the instrument orifice.

3.2. Sensor

The sensor is comprised of the antechamber and vacuum closure, ion source, analyzer and electron multiplier detector as illustrated schematically in Figure 1. After ejecting the

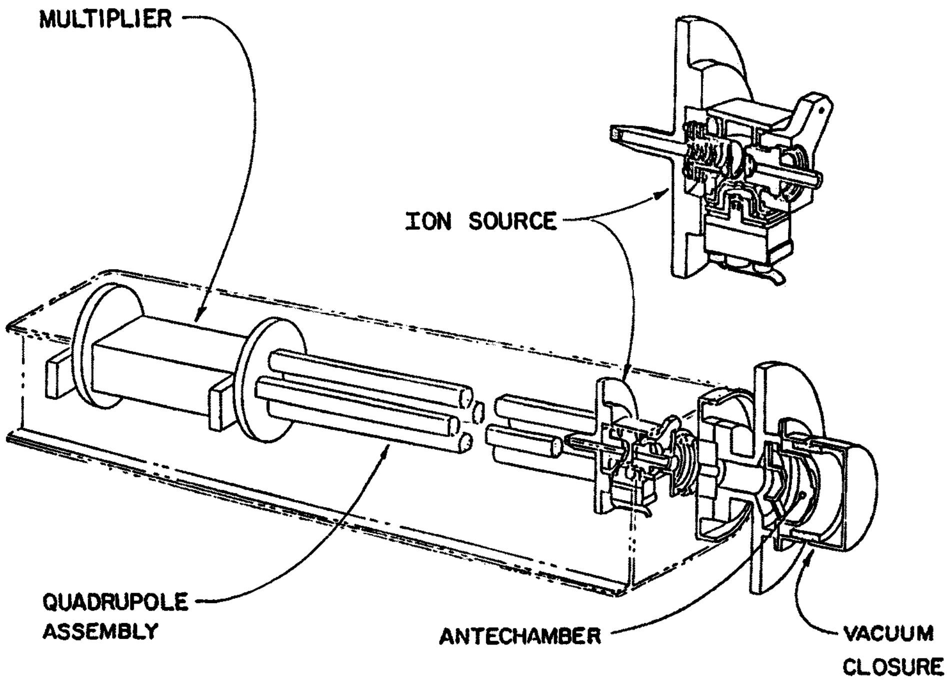

Fig. 1. Outline of the sensor showing the vacuum closure, inlet, ion source, analyzer and detector.

cover in orbit, gas admitted to the antechamber is sampled by the ion source which incorporates two redundant orthogonal electron guns. The operational electron gun generates a beam of 75 eV electrons of 50 μA which ionizes a small fraction of the gas sample. The source focuses the resultant ions onto the entrance aperture of the analyzer.

The analyzer is a quadrupole with 15 cm long rods of hyperbolic surface with a characteristic radius of 1 cm. Appropriate AC and DC potentials are applied to these electrodes to enable mass selection at a nominal resolution of 1 amu over the range of 2 to 50 amu. At the stated resolution, the contribution of a mass to an adjacent mass is less than 1 part in 10^4.

Ions of the selected mass to charge ratio are stable in the field and traverse the length of the rods. These stable ions strike the first dynode of a 16 dynode multiplier in which each ion produces a pulse of about 2×10^6 electrons. The number of pulses per unit time is proportional to the source density of the selected mass and thus constitutes the basic measurement.

The sensor is made of stainless steel with gold plated interior surfaces for potential uniformity. Insulators are high purity metal oxides, mostly aluminium oxide, and the entire assembly is bakeable to 330 °C to enable sealing in an ultra clean vacuum. The sensor is provided by Perkin Elmer Aerospace Systems.

The sensor includes the baffles and associated drive systems to enable the wind measurements. The details of these baffle systems are described in the accompanying paper [10].

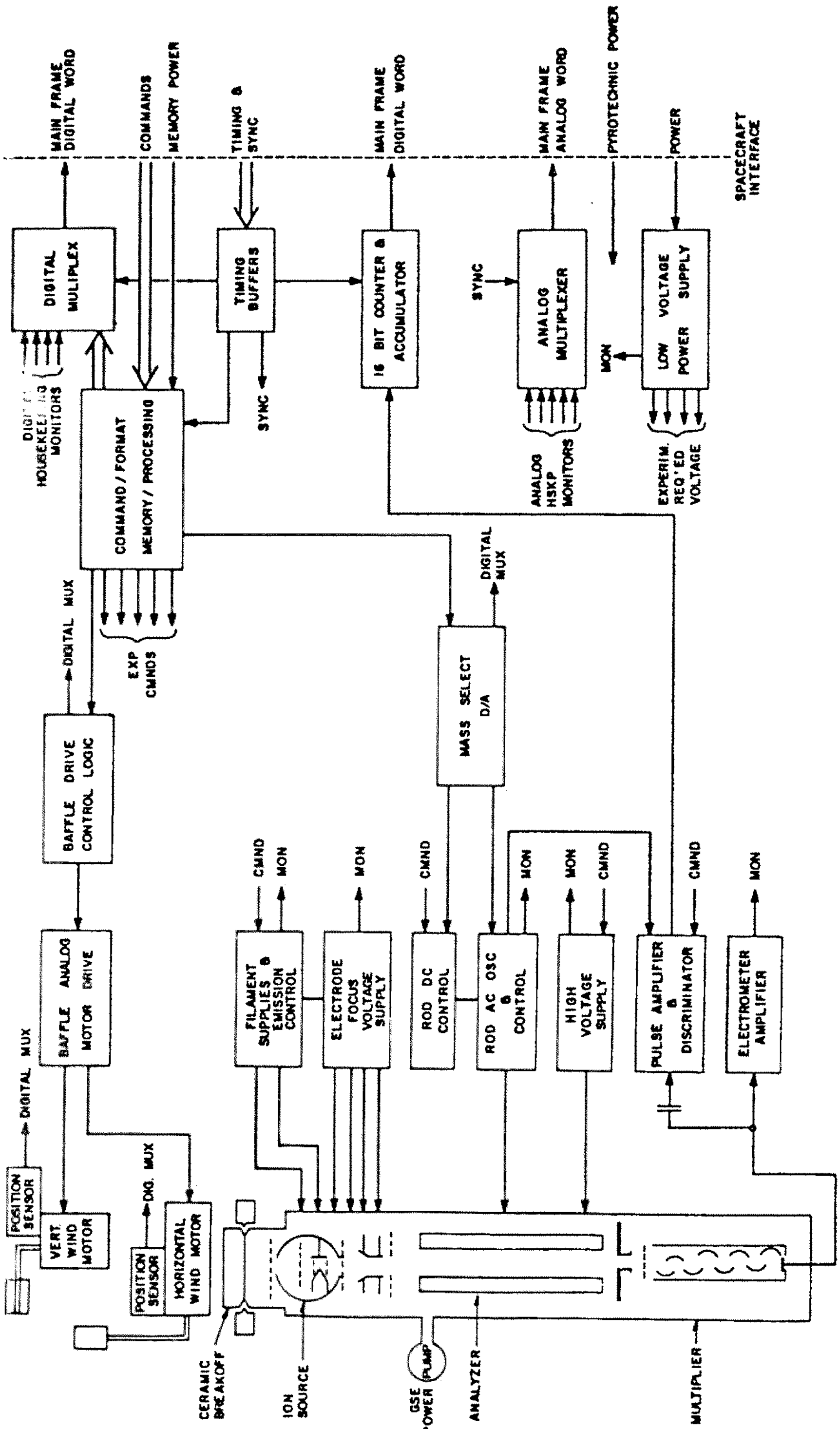

Fig. 2. Block diagram of the Neutral Atmosphere Composition Spectrometer.

3.3. Electronics

The electronics required to operate the sensor are shown in block diagram form in Figure 2. The various subsystems provide the required potentials and currents to power the sensor electrodes or to process the output pulses for counting and subsequent telemetering. Internal voltages are derived from the spacecraft regulated power buss by use of a DC-DC converter. Certain voltages, such as the high voltage required for the electron multiplier, are generated by additional conversion. The use of CMOS-technology integrated circuitry and efficient power conversion techniques results in a nominal power consumption of 12 W.

Also shown is the command processing system which accepts experimenter commands to configure instrument variables. These variables are stored in a small, random

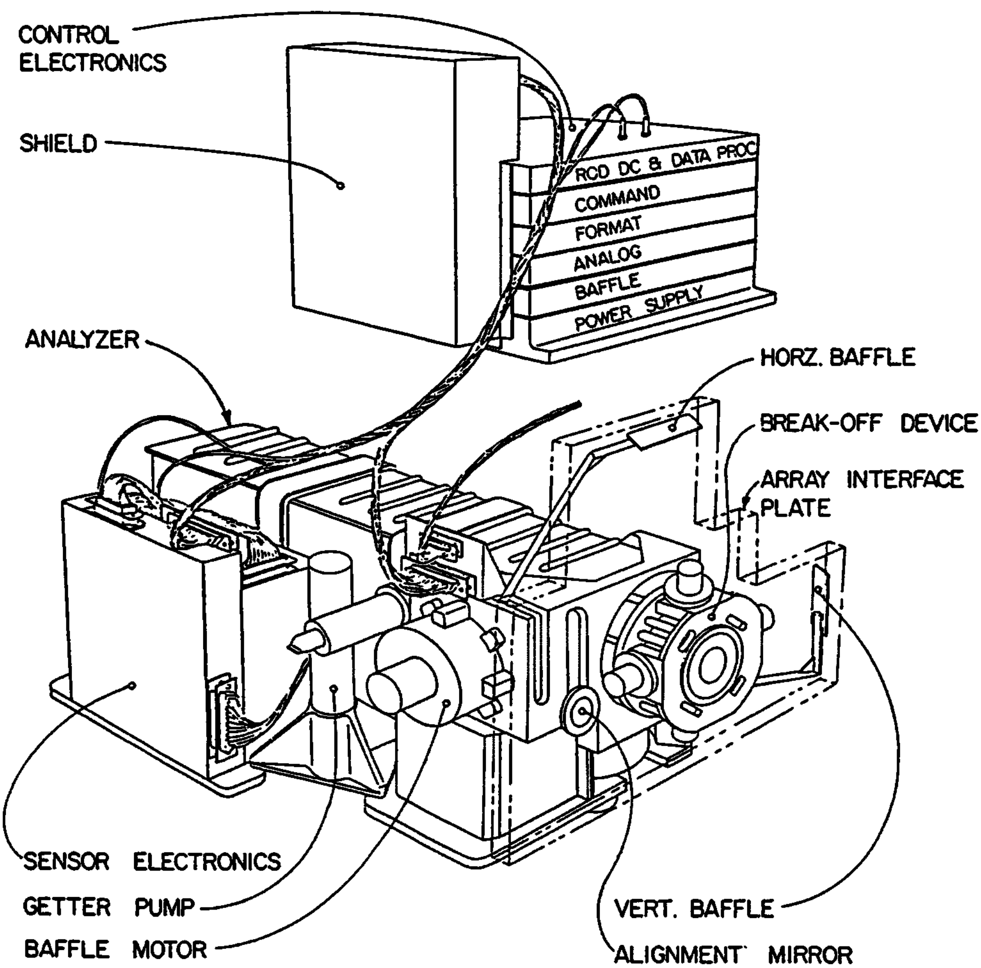

Fig. 3. Pictorial view of the assembled system. The instrumentation is divided into two packages to facilitate accommodation on the spacecraft.

access memory (RAM) which is powered continuously by a separate power buss allowing retention of the instrument state through power on-off cycles. Should the RAM or any component within the command processing system fail during flight, the instrument may be commanded to effectively bypass the failed system and thus place the instrument in a somewhat less flexible, but completely useful operating mode.

The electronics required to operate the baffle system are described in the accompanying paper [10]. A pictorial view of the assembled instrument is shown in Figure 3.

3.4. Operation and functional control

The most novel aspect of the mass spectrometer on Dynamics Explorer is the method of mass selection and measurement formatting. The mass select system provides for 256 mass values between 0 and 51 amu or each 0.2 amu; 0, 0.2, 0.4, 0.6, 0.8, 1.0 . . . 50, 50.2, 50.4, 50.6, 50.8, 51. Any one of these mass numbers can be called into each of eight

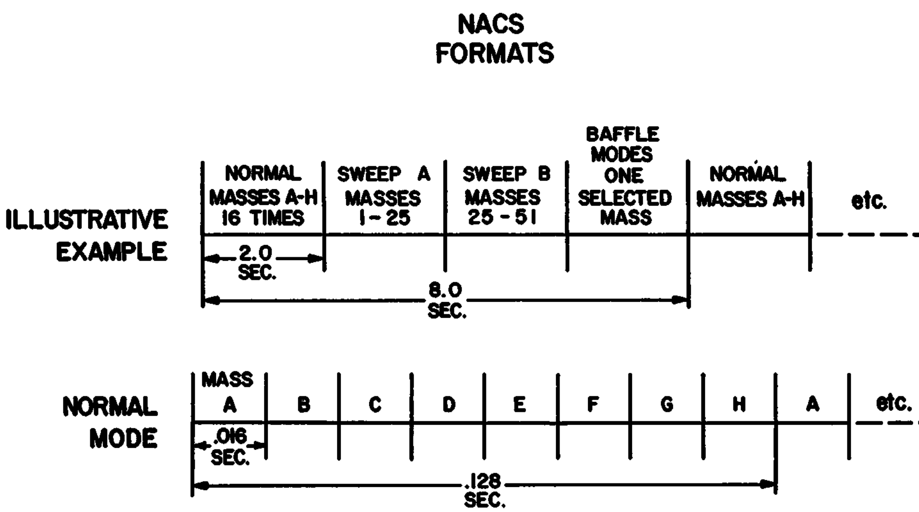

Fig. 4. Line sketch illustrating the formatting scheme. The top panel illustrates the slot choices and the bottom, the mass select.

0.016 s intervals. This sequence is repeated each 0.128 s as illustrated in the bottom panel of Figure 4. Two extreme cases are (1) a different mass in each interval e.g.,

A 2
B 4
C 14
D 16
E 28
F 32
G 40
H 46,

and (2) the same mass in all intervals, e.g., A-H Mass 40. Between these extremes are many combinations which permit tailoring the integration periods of a few masses to their abundances or to the requirements of a particular scientific investigation. The helium to argon ratio, for example, might be optimally determined by putting mass 4 in two intervals and mass 40 in the other six.

In a typical application the eight mass cycle would be continuously selected with masses versus interval as below:

Slot	Mass	Gas
A	4	He
B	4	He
C	40	A
D	40	A
E	28	N_2
F	46	$N(NO_2)$
G	32	$O(O_2)$
H	23.6	Background

Beyond this normal mode of operation the 256 different masses can be put into 256 successive intervals creating a 5 point per mass spectrum as shown in Figure 5 from a laboratory gas sample. The plot is presented with the count per integration period on a log scale to convey information over a wide dynamic range. The plotting routines are performed in a computer which serves as the ground support equipment.

The formatting scheme enables a measurement cycle with a mixture of spectra, partial spectra and the eight mass cycle. During each of four two-second slots: sixteen eight-mass cycles, the spectrum from 1–25, or the spectrum from 25 to 50 can be inserted. The wind measurements, which require a single mass and a baffle sweep, can also be selected. The intrinsic flexibility is analogous to that of the masses in the eight intervals, i.e., the same function can be put into each slot or different ones in every slot and all combinations between those limits can be selected. A typical example is illustrated in the top panel of Figure 4.

3.5. Command System

To enable experimenter control of the measurement routines described in the previous paragraph and also to select among other instrument variables, one of the spacecraft 32 bit digital command words is employed. A summary of the selection capability is shown below:

Command utilization

Mass select (8 intervals, A-H),	Mass index values 0–255 (0–51 amu),
Slot options (4),	0–7 (COMP, SWEEP A and B, 5 Baffle modes),
High voltage,	0–7,
Filament,	1, 2, or both OFF,
Baffle offsets,	Baffles 1 and 2 values 0–255,

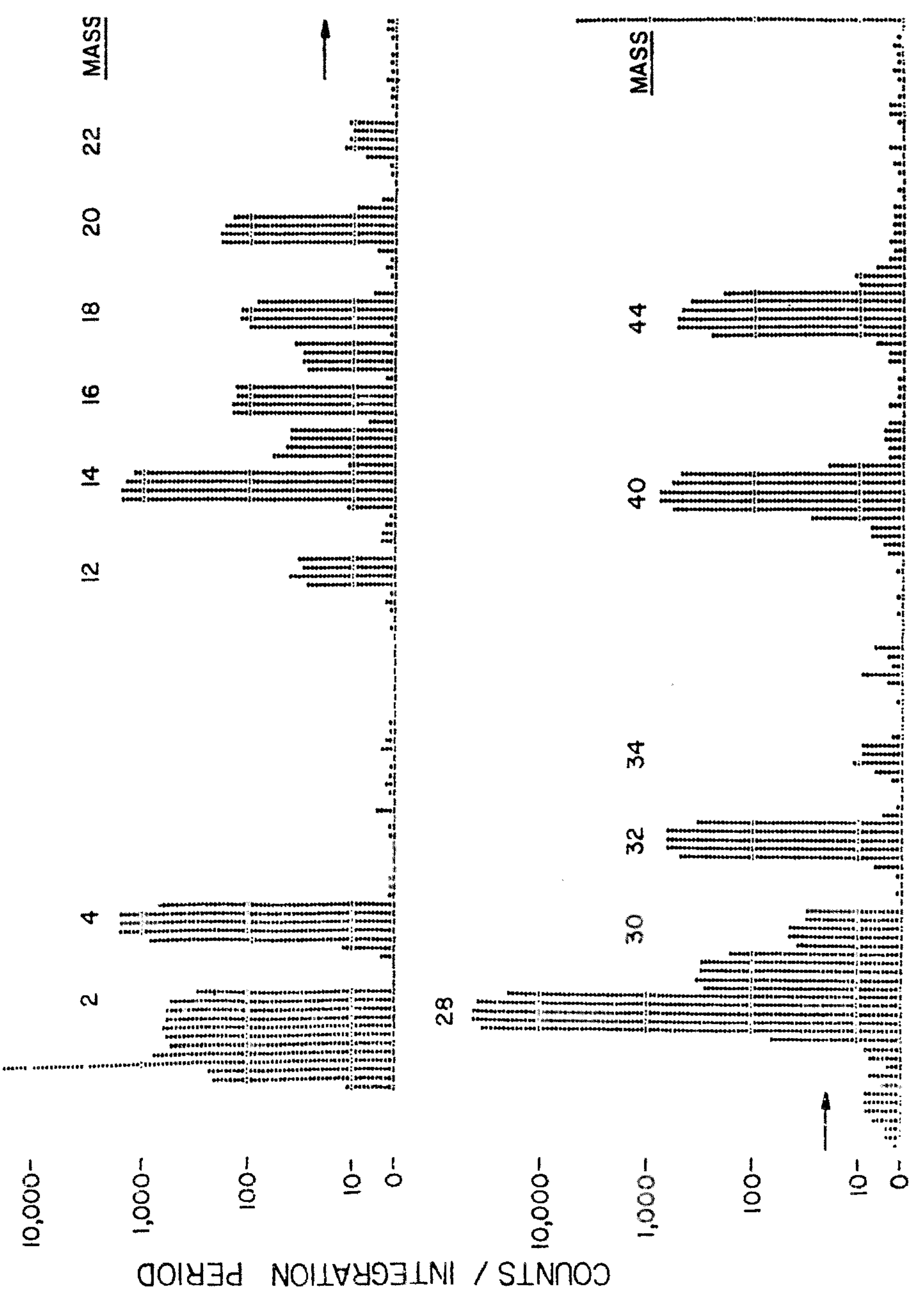

Fig. 5. 256 point spectrum of a laboratory gas sample. The counts below Mass 2 are characteristic of a quadrupole at low amplitudes of the AC field.

3.6 Ground support equipment (GSE)

A powerful hardware and software system built around an LSI-11 computer is used for control, test and evaluation of the instrument prior to integration on the spacecraft and can be used for detailed evaluation of the instrument after integration and in orbit by directing the spacecraft data stream into the appropriate input port. The GSE enables command of the instrument by engineers and investigators using the terminal keyboard with descriptive mnemonics and displays the data on a CRT and/or printer in various useful ways. The semi-log spectrum in Figure 5 is one example of the display capabilities of the support system.

4. Calibration

The instrument has been calibrated on the Goddard Space Flight Center facility which was used for the calibration of the Atmosphere Explorer series of instruments. The system was described in the published description of those instruments [3]. The instrument sensitivity has been determined for helium, molecular nitrogen, molecular oxygen and argon. The instrument count rate as a function of pressure over a dynamic range of about 10^3 is measured for the parent species and for the dissociated and/or doubly

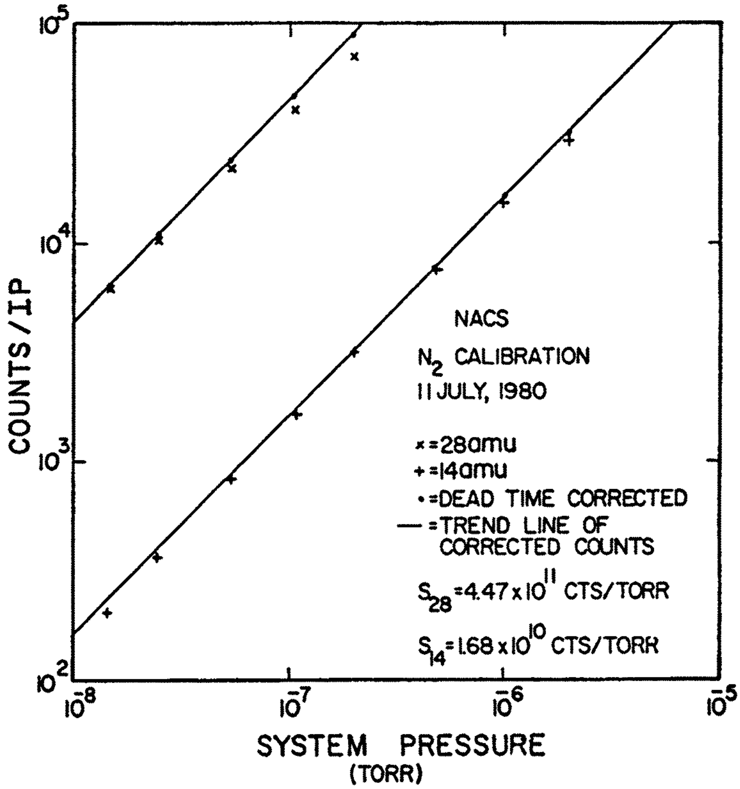

Fig. 6. Plot of counts versus pressure of N_2 obtained during instrument calibration. The mass 14 counts result from dissociatively and doubly ionized N_2. The integration period (IP) is 0.016 s.

ionized fragments. A sensitivity factor for each species is thus determined and the linearity of the response evaluated. A typical result, for nitrogen is shown in Figure 6. The plot shows the sensitivity to the parent molecule N_2, and also indicates the fraction of the molecules that are dissociatively or doubly ionized and seen at mass 14. The effects of the finite counting speed of the detector system, usually referred to as dead time, can be seen at the high count rate end. This effect is known and can be corrected for as it is in calculating the points through which the trend-line is drawn.

The warm-up characteristic of the instrument is also evaluated during calibration. As the temperatures surface in the ion source region rise due to heating by the filament, the effective source temperature, T_s in Equation (1), increases, thus decreasing the source density for a constant ambient density. The total decrease in sensitivity from a cold start is about 35% and the thermal time constant is about 10 min. A temperature in the source region is measured and telemetered for the purpose of correction but the preferred technique is to allow a 30 min warm-up prior to measurement since the variation cannot be exactly characterized by the temperature measurement. Three thermal time constants are sufficient to reduce the effect to a level that can be ignored in the analysis.

The accuracy of the calibration is believed to be $\pm 10\%$ for molecular nitrogen, helium and argon and $\pm 15\%$ for molecular oxygen. The stability over two weeks of calibration was $\pm 2\%$. In the counting mode the sensitivity to multiplier gain changes is minimal, but nevertheless the gain is determined in orbit by periodically making a simultaneous measurement of counts and current. The small count rate change, as a function of multiplier gain, is determined during calibration so that corrections for in-orbit gain changes can be made. Most processes that modify the instrument function are likely to modify it for all gases so the relative accuracy of $\pm 5\%$ specified as a requirement is believed to be met if a 30 min warm-up is used.

The overall accuracy of the measurements is a function of several variables including the calibration accuracy. For all measurements there exists a statistical uncertainty that is equal to the one-half power of the number of counts. This can be the dominant uncertainty for helium and argon measurements. For O and N_2, the accuracy is limited at low altitudes by calibration uncertainties and at high altitudes by background contributions to the relevant mass numbers. For atomic nitrogen, no absolute accuracy is claimed. The contributing uncertainties in the results are summarized in Table I.

5. Data Analysis

The measured constituent abundances in the form of number of counts per interval are merged with other data from the Dynamics Explorer B satellite and stored on a satellite tape recorder for subsequent telemetry to ground stations during overflight. The telemetry data are forwarded to the Science Data Processing System at the Goddard Space Flight Center which serves the entire Dynamics Explorer Program. Routines are resident in the processor to read the telemetry, average the counts for a single species over a one second interval, correct for counter deadtime and multiplier background, and compute source density. Source densities obtained in the satellite wake (on orbits which have the satellite

TABLE I

Error summary

Gas	Estimated errors (± %)			
	Calibration	Statistical[a]	Background	Σ
Helium				
300 km	10.0	2.2	0	12.2
400 km	10.0	2.8	0	12.8
500 km	10.0	3.3	0	13.3
Argon				
300 km	10.0	4.3	0	14.3
400 km	10.0	33.0	0	43.0
500 km	10.0	Very large	0	Very large
N_2				
300 km	10.0	0.1	0.1	10.2
400 km	10.0	0.4	1.6	12.0
500 km	10.0	1.8	26.0	37.8
O				
300 km	15.0	0.1	0.5	15.6
400 km	15.0	0.2	2.8	18.0
500 km	15.0	0.5	14.0	29.5

[a] Based on 1 s resolution for an 8 mass data set.

spinning) are used to establish the gas residual or background for a particular species on subsequent non-spinning orbits. Corrected source densities and spacecraft attitude data (available in the processor) are then used with Equation (1) to compute the ambient densities. The repository of the analyzed data is the extensive library of all Dynamics Explorer data in the Mission Analysis Files (MAF). This data base is accessed by the investigators at their remote terminals to interpret the results of combinations of measurements in terms of the interactions of the magnetosphere – ionosphere – atmosphere system.

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