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Report No. 05465-2-F

NASA CR 107408

# Final
# Experiment Data Analysis Report
# for
# The OGO-IV Neutral and Ion Mass Spectrometer Experiment

October 1969

Contract No.: NAS5-3098

Prepared by

The High Altitude Engineering Laboratory
The University of Michigan
Ann Arbor, Michigan

for

Goddard Space Flight Center
Greenbelt, Maryland

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ABSTRACT

The experiment is described from the data processing point of view. The various programs used by this experiment are discussed. The chief ones were two fully automatic programs utilizing the IBM 7090 computer and the IBM 360 computer. Budgetary and operational restrictions forced the abandonment of fully automatic data processing and the adoption of manual methods.

Specific studies based on about 55 hours of processed data are indicated. These are: (1) Atomic oxygen density at sunrise and sunset; (2) Oxygen and helium ion densities in a disturbed ionosphere; (3) Water vapor outgassing rates; (4) Production and loss of mass 8 ions; (5) Rate constant for charge exchange between oxygen ions and neutral hydrogen atoms and (6) Correlative studies with Thomson backscatter stations.

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# I. INTRODUCTION

This report is a summary of the work performed on Contract NAS5-3098 subsequent to the successful launching of OGO-IV and describes the efforts expended to process the data from Experiment 15 on OGO-IV. This report is submitted as required by Article II, Paragraph f.2, Modification No. 19 of Contract NAS5-3098.

Use of OGO-IV pre-launch data tapes permitted the IBM 7090 data extraction program to be nearly completed at the launch of OGO-IV and to be fully available shortly thereafter. Before difficulties with the data extraction from the Attitude-Orbit tapes could be completely resolved, the University began phasing out operations on the IBM 7090 to permit installation of an IBM 360 time-sharing system. This necessitated rewriting all data extraction programs because of the vast differences in the two computing systems.

Use of the University Computing Center facilities was found to be too expensive and operationally unsatisfactory for data reduction purposes. Hence, owing to budgetary reductions, computer techniques for data extraction were abandoned and manual methods were substituted. This change in operational procedures made it necessary to examine only special events or problems where large amounts of data were not required. Several specific investigations are summarized in this report. These studies have not been completed. Interim reports were given at the 1969 Annual Meeting of the American Geophysical Union, Washington, D. C. Technical reports and journal publications will be prepared upon completion of the studies.

## II. PURPOSE

The purpose of the neutral and positive-ion mass spectrometer on OGO-IV is to provide ambient composition data to improve our understanding of the following processes and phenomena in the atmosphere: diffusive separation, photochemical production, photo-ionization, dissociative recombination, ionization by heavy charged particles, reactions involving metastable states, as well as many others.

The most ambitious goal one could set for the experiment would be to obtain neutral and ion composition data of masses 1 to 44 at all local times, latitudes, and altitudes, i.e., map the entire atmosphere of the earth. This goal is not realizable in the design lifetime of a single OGO since it would require approximately 2 years for perigee to move through essentially all local times and latitudes. A more practical criterion for success would be one year of orbital operation. As will be discussed later, this still represents a vast amount of aeronomic data to be explored scientifically.

## III. DESCRIPTION OF THE INSTRUMENT FROM THE DATA PROCESSOR'S POINT OF VIEW

The quadrupole mass spectrometer described below is a first attempt to obtain both neutral-particle and positive-ion composition measurements with a single instrument. It was designed specifically to be flown on an earth orientated satellite having orbital-plane attitude stabilization and orbiting between altitudes of approximately 300 and 900 km.[(1)*] An open ion source design permits sequential measurements of neutral-particle and positive-ion concentrations. Three analog output data channels are included; two provide composition data and the third is a monitor channel for spectrometer housekeeping data.

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*References are numbered consecutively and correspond to the citations collected in the Bibliography section.

Operationally, the spectrometer has the following characteristics:

| | |
|---|---|
| Mass range | 0-50 u |
| Resolution | 20 at 28 u |
| Sensitivity ranges | 6 (linear) |
| Maximum sensitivity | Neutral $-10^5$ particles/$cm^3$ |
| | Ion-10 ions/$cm^3$ |
| Sweep duration | 6 seconds |
| Mass scale | Linear-two segment |

In order to function as a spectrometer, the quadrupole electric field has both a constant component and a time-varying component; these are generated by imposing dc and ac voltages simultaneously on the rods. It is customary to assume that the incident ion beam consists of singly charged particles, and to identify its constituents by a mass number expressed in terms of unified atomic mass units u. Then the mass u allowed to pass completely through the analyzing region is proportional to the amplitude of the ac voltage. By sweeping this voltage, a mass spectrum is generated. The ratio of the amplitudes of the dc and ac electric field voltages determines the instrument resolution, defined as $u/\Delta u$ where $\Delta u$ is the width of a spectral peak at half-maximum amplitude; this quantity is kept constant by constraining the dc voltage to always have a constant proportionality with the ac voltage. Resolution is also dependent upon the frequency of the ac voltage, the field length, and the drift velocity of the ions through the analyzing region. A reasonable compromise between these three quantities must be made to attain a given resolution within given geometric and power constraints.

In addition to the spectral mode of operation, the spectrometer can be operated in a zero-resolution mode. In this mode, the output corresponds approximately to the integral of the spectrum; it is called the "staircase" mode from the resultant shape of the output current curve when plotted versus mass number.

Two internal clocks control the operation of the spectrometer. One controls the duration of the sweep and the other the duration of each monitor step. The basic sweep time is approximately 6 seconds during which the mass scale is swept from approximately 50 to 0 u in the spectral modes, and approximately 40 to 0 u in the staircase modes.

The six decade-ranges of sensitivity incorporated in the instrument are realized by using three range-switching positions. At each range setting, spectrum and staircase operation occur sequentially; therefore, six sweeps are required to complete either a neutral or an ion analysis encompassing the entire sensitivity range of the instrument. At the end of each set of six sweeps, one additional sweep is devoted to the sequential switching of three fixed calibration voltages into the electrometer data channels for the purpose of checking the data link. Thus, a total of 14 sweeps are required to complete one full cycle of operation.

The monitor-channel output consists of a commutated signal that has a rate of approximately 3.5 steps per second. Sixteen steps form the basic repeat pattern which is reset at the beginning of each sweep. The odd-numbered steps indicate the instantaneous dc voltage on the quadrupole rods during spectral analyses and thus provide a mass scale for these sweeps. Each of the even-numbered steps indicates the instantaneous status of each of the following internal functions: steps 2 and 10, filament emission current; step 4, Channeltron on-off; step 6, filament voltage; step 8, B+ voltage; step 12, electrometer range; step 14, filament in use; and step 16, plate temperature of ion source. For each sweep, these monitor-channel data provide a unique set which permits exact identification of the spectrometer mode without reference to monitor data from preceding or subsequent sweeps.

A meaningful sampling of the composition of the upper atmosphere through *in situ* measurements on an earth satellite requires that a compromise be made among the following: mass-range sweep duration, electrometer rise time, and output sampling rate. The sweep rate of the spectrometer must be slow enough to be compatible with the rise time of the electrometer and at the same time be fast enough to provide a useful spatial resolution. A sweep duration of six seconds fulfills both requirements for the OGO spectrometer and provides an average spatial resolution of approximately 0.80 km per mass unit.

The minimum average sampling rate which will permit reconstruction of spectral peaks using computer methods is estimated to be that which results in approximately five samples per mass unit, or approximately 40 samples per second. To realize this sampling rate and store data on the spacecraft tape recorder, which has a bit rate of 4000 bits per second, the flexible format multiplexer use is required. This device is a prewired form of the main multiplexer in which the 128 inputs of the main multiplexer are "cross-strapped" to permit time division multiplexing of only 32 different inputs. By selecting flexible formats in which 16 samples per frame of the main multiplexer are obtained, a sampling rate of approximately 55 samples per second is realized.

The three analog data channels of the spectrometer occupy three inputs of the flexible format multiplexer. Time-division-multiplexed analog data from the flexible format pass through an analog-to-digital converter and are stored on a spacecraft tape recorder. Upon command, the tape recorder plays back through the telemetry system transmitting these data to a ground station where they are re-recorded. Upon separation of the multiplexed data, an appropriate digital data tape is sent to the experimenter for processing. Computer programs are used to extract the data from the digital magnetic tapes, apply the transfer functions described below, and correlate the adjusted data with date, time and spatial location for each sweep of the spectrometer.

Interpretation of neutral particle and positive ion composition measurements must be preceded by the incorporation of transfer functions that take into account the characteristics of the spectrometer and the influence of the spacecraft upon the local environment. Calibration of the spectrometer in a controlled thermal-vacuum environment supplies the parameters necessary to determine particle densities from the signal appearing at the output of the spectrometer. These particle densities are then adjusted, using theoretical and empirical functional relationships, to account for disturbance of the ambient atmosphere due to the presence of the spacecraft and its hypersonic velocity relative to the ambient atmospheric particles, orientation of the spectrometer relative to the spacecraft and flight velocity vector, presence of a potential on the OPEP and the resulting plasma sheath, and the probability of contaminating particles being emitted or reflected from other spacecraft surfaces into the spectrometer.

Laboratory calibration consists of bench testing the instrument for dynamic characteristics of the electronic subsystems and operating it in a thermal vacuum facility to determine its overall operational parameters. Of utmost importance is an accurate determination of the sensitivity of the spectrometer throughout its mass range. This is accomplished by introducing a neutral gas of interest through a controllable leak valve. The spectrometer is used to monitor the relative composition of the gas in the chamber and an ionization pressure guage is used to measure its pressure. A McLeod pressure guage is used to calibrate the ionization guage over the lower end of its pressure range. The pressure level of the system is varied over its useful range to establish the response of the spectrometer as a function of particle density. This procedure is repeated for a series of gases having mass values that permit coverage of the mass range of the spectrometer.

A laboratory ion generator is used to assess the performance of the spectrometer in the ion modes of operation. This generator provides a broad beam of ions to simulate the inlet flux encountered during flight through the ionosphere. Ion sensitivity is checked in flight by making simultaneous in situ and backscatter density measurements while the spacecraft is over a Thomson backscatter station.

In all laboratory calibrations, the effects of variations of several parameters are determined so that sensitivities might be corrected should one of these parameters change in flight. Most important of these are the ac to dc voltage ratio on the rods which controls resolution, the temperature of the base plate heat sink, the power supply voltages, and the emission current in the ion source during neutral modes.

Figure 1 shows a complete set of 14 modes corresponding to one complete positive-ion and neutral analysis. These data were taken from the OGO-IV spacecraft on orbit 77. The ion-spectrum modes are number 1, 3, and 5, in order of increasing sensitivity; neutral-spectrum modes are numbers 8, 10, and 12. The corresponding "staircase" modes are 2, 4, and 6 for the ions and 9, 11, and 13 for the neutrals. The calibration signals appear in modes 7 and 14.

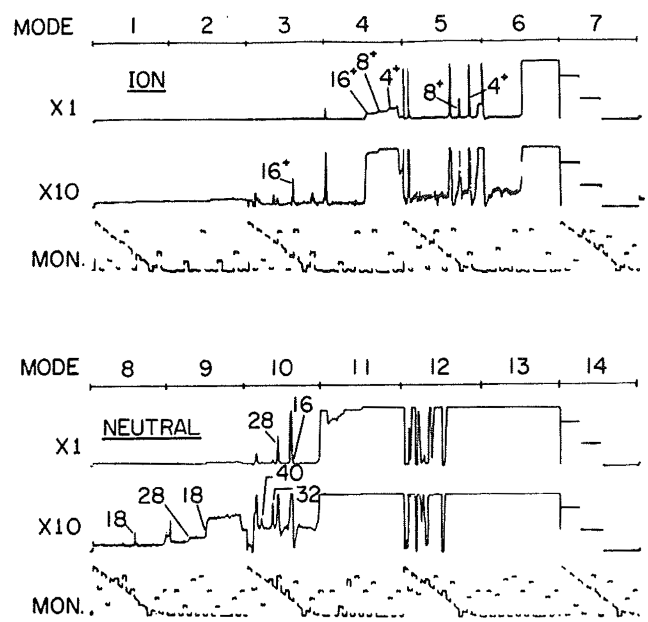


FIGURE 1. Experiment Data

## IV. SUMMARY OF EARLY DATA PROCESSING EFFORTS PERTAINING TO OGO-IV

The data analysis portion of the project was started in June of 1965 and the IBM 7090 computer program became nearly operational prior to the launching of OGO-IV. The availability of some data processing before the launch of OGO-IV provided a means of evaluating the total experiment before launch. Consequently, extensive preflight data were reduced and intensively analyzed (mostly by hand) to study certain effects encountered in the OGO-II flight (for example, baseline temperature drifts). The results were used to make some minor changes in the OGO-IV flight unit.

Programs were written for pre-flight operations to simulate data analysis on flight units, e.g., a program was written to read out the monitor channels of laboratory data recorded on magnetic tape which simulated spacecraft data.

The full IBM 7090 automatic data processing program was available soon after the launch of OGO-IV. The program was used to obtain sufficient data (six orbits) to check the operation of the program itself, and for checking the values of certain calibration parameters.

At this time, the 7090 was being phased out at the University and replaced by an IBM 360. Due to software differences, the 7090 program could not be adapted to the 360. A significant amount of time was spent in re-writing the program for the 360 and the resulting program was demonstrated to work in the fall of 1968. However, the installation of the 360 produced certain peripheral changes which made operation of the program unfeasible. First, the 360 is operated on a time sharing basis; since our program required the use of two seven-track tape transports, and "impossible" queing situation was encountered. Second, although the 360 is nominally cheaper and faster than the 7090, it actually turned out to be slower and more expensive since data words on the tapes supplied by GSFC had to be restructured to accomodate the word length of the 360. Third, the speed at which the program ran was such that the University computing center could not supply sufficient hours of CPU time. The details of this situation are outlined in [(2)]. Nevertheless, the limited data from the 7090/360 programs with about 10 more orbits of data gathered by hand form a valuable body of data on the atmosphere near local times of sunrise and sunset. The scheme of operation of these programs will be outlined in Section 5.

## V. DATA ANALYSIS SCHEME

The programs designed to process the data received from the spacecraft logically divide into three distinct parts: (1) extracting the data from the experiment data tapes, (2) extracting and interpolating the data from the spacecraft attitude-orbit (A/O) tapes, and (3) applying calibration factors and factors taking into account the ambient gas flow about the spacecraft.

The first part, that of extracting the data, entails the fitting of suitable peak-shape models to the output data of the spectrometer. The shape of the model was determined by finding the transfer function of the instrument and, through the use of Laplace transforms, the response of the instrument to a triangular wave input. The model was then adjusted in height using a least-squares technique. The amplitude could then be read directly from the height of the approximating model. The mass number of the peak is found by its position on the monitor sweep. Entailed also in the extraction of the data is a process to minimize the effects of noise in the data and spurious peaks caused either by telemetry-link problems or by data dropout. Output from this program includes the day and time of the sweep, mass numbers, and amplitudes. The time is used in the following portion of the processing cycle.

In order to check the results of the first part, a program to plot the data directly from the data tapes was written. This program was also used to screen the experiment data tapes for quality prior to attempting automatic data extraction and finally to plot data for manual extraction when budget restrictions prevented the use of an automatic data extraction system. The plotting program was originally written for the IBM 7090, and later for the IBM 360. These computers were found to be too expensive if used extensively, so it was rewritten for the DEC PDP-8 computer which formed part of the data acquisition system used during calibration and check-out of the flight instruments. See Figure 2 for a schematic representation of the data handling schemes.

The second section, extracting and interpolating the attitude-orbital data, determines the orbital-position coordinates corresponding to the time calculated in the first part and adds these values to the data output. This output constitutes information about the geographical location, altitude, and orientation of the spacecraft so that the experiment data can be adjusted to account for the orientation of the instrument inlet aperture relative to the flight velocity vector as well as providing the necessary geophysical variables for the subsequent scientific studies.

Unlike the data extraction step which requires a major piece of software, the second step of merging the experiment and A/O data is straightforward. The output of this merging is the raw material for the actual scientific analysis of the geophysical data. This final step is not one that can be prescribed in advance but will change from time to time according to the desires and ingenuity of the analysts, the particular problem area

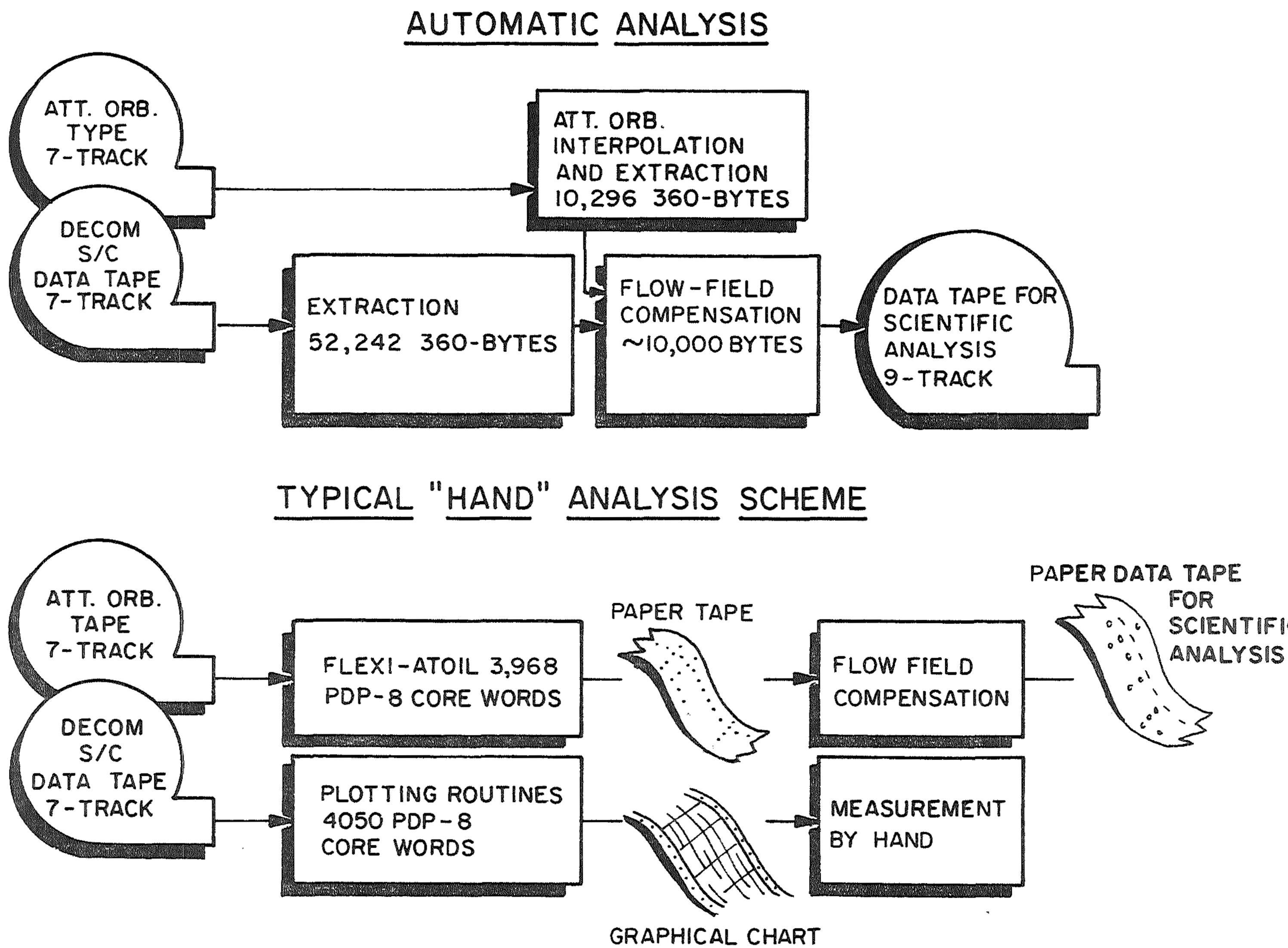


FIGURE 2. Data Analysis Schemes

being investigated, and the results of others published in the literature. It is known that certain solar and geophysical data will be required from sources outside our own experiment. These must be searched out and obtained from the scientific literature and private sources. At a minimum the following are required:

Satellite drag data
Solar X-ray data
Solar EUV data
Solar UV data
Sun Spot-plage data
Magnetic activity (Ap or Kp indices)
Electron and ion density
Electron and ion temperatures
Auroral activity
Solar Radio Fluxes

In addition to the three-step automatic data processing described above, it has been necessary to write several programs for immediate use in data analysis. There is, at present, a family of three ATOIL (Attitude-Orbit Information List) programs which provide orbital parameters, orbit numbers, dates, and universal time for approximately each minute of orbit. One, ATOIL, lists local time, position vector, no-data flags, suspect data flags, body yaw, body pitch, OPEP roll, OPEP angle, solar vector, paddle angle, and paddle yaw. This program has been particularly helpful to the data analysts because it gives a fairly complete picture of experiment condition at all times. An explanation of the A/O data is contained in Ref. [3]. Another of these programs, ATOIL-$V_N$, calculates the normal velocity component and body pitch. These are listed along with magnetic latitude for each minute of an orbit. This program has been particularly useful in the analysis of ion composition data. The third program, FLEX-ATOIL, lists, in addition to orbit number, date, and eclipse start and end, GMT and any other data words on the tapes that the user wishes to inspect per minute of flight. This program has also been used to punch data on paper tape for use in plotting attitude data.

Interrelationships of many of the above parameters can be compared graphically using computer programs and the CALCOMP 565 plotter for plotting these data. It is often useful to plot one of the thirty-seven different parameters used in our studies as a function of time, latitude, or attitude. However, any one of the thirty-seven can be chosen as the independent variable and any of the other thirty-six as the dependent variable.

Because of problems with the quality of the A/O data tapes, a program was written to analyze them record by record. This particular program lists orbit numbers, data, start and end times of the orbit, and the average of the words "no-data flags" and "suspect-data flags". It has been run through orbit 2200 excluding those orbits which are on "bad" tapes or missing.

A rather fundamental difficulty has been that the sampling rate of the spacecraft housekeeping data is not sufficient to give a clear picture of the instantaneous OPEP orientation. This is true since the motion due to the thermal engine, consisting of the long ribbon radio astronomical antenna, and consequent OPEP oscillations is not reconstructed[(4)].

There are two additional important computer studies which bear on the data processing. One is a computer simulation of a theoretical model of the experiment which can be used with certain data from the experiment and attitude-orbital data to verify the necessary assumptions made concerning the effect of varying inlet particle injection conditions on the transmission coefficient of the spectrometer. The second program is a study to determine the validity of the simple analytical model we are currently using to account for the molecular flow field about the satellite.

## VI. CONTINUING WORK ON OGO-IV DATA

Part of the results referred to in Section 4 were presented at the Spring 1969 AGU meeting[5]. Further work is being done on these data at present and neutral data from 25 more orbits is being extracted by hand. Three additional special analysis programs have been written:

(1) The first calculates the CIRA 1965 model atmosphere at each point along the orbit where neutral data were taken so that experimental data can be compared with this model.

(2) The second does the same with the United States Standard Atmosphere 1966;both use solar-geophysical and orbital position data.

(3) The third (which is used with (2)) makes it possible to deduce an "experimental" exospheric temperature from the data.

The results of (1) and (2) were sent to U. Von zahn for inclusion in a comprehensive review to be presented in Madrid, September 1969. This preliminary study covered data taken from August 2 to 18, 1967. The local time of the orbital plane ranged from about 0400 hours to 0590 hours. The mean solar flux during this period was a moderate value, about 140. The range of $A_p$ values was from 2 to 22. The detailed results can be very briefly summarized in the following two statements:

a) The general level of atmospheric atomic oxygen density tended to follow the satellite-drag derived models with respect to the variations they included. That is, when the model predicts an increase in density this is what is observed and so on.

b) There is horizontal structure in the atomic oxygen density over the north polar region in the data which requires new theoretical work to explain adequately.

Presently, an investigation into the response of the ionosphere to a geomagnetic disturbance is underway. Nighttime composition measurements have been obtained in the altitude range 650 to 900 km over the magnetic latitude interval of 60° N to 60° S for an essentially constant local solar time of approximately 0100 h during two magnetic storms occurring in September 1967. Thirty-six orbits are included in this study. Fluctuations in the $O^+$ and $He^+$ number densities are seen to occur which appear to be correlated with the storm-induced variations in the geomagnetic field. Preliminary results of this study encompassing 11 orbits of ion data were presented at the Spring 1969 AGU meeting[6]. Ultimately, this data will be related to the 25 additional orbits of neutral data, referred to above, which cover the same time period. This will be the first significantly sized body of data to exploit the unique capability of the instrument to measure both neutral and ion composition.

A study of water vapor outgassing on OGO-IV over an extended period of time was made and the results compared with similar measurements on OGO-II. These results were presented at the Spring 1969 AGU meeting[7] and at the Optical Contamination in Space Symposium[8]. The rate at which the water vapor concentration diminished was greater on OGO-IV; this effect was most probably due to the absence of a thermal blanket on OPEP-2 of OGO-IV.

A search is being made of the data to find nearly simultaneous measurements of $n(O)$, $n(O^+)$, $n(H_e)$, $n(H_e^+)$ and eclipse data to be used to determine the production/loss scheme of the m/ze= 8 ions. A theoretical model of suitable reactions has been formulated.

The rate coefficient for the reaction:

$$O^+ + H \longrightarrow O + H^+$$

has been obtained using data from the OGO-IV experiment. The value found is in reasonable agreement with other measurements. It is planned to continue this work and extend it to other reactions.

During the lifetime of OGO-IV, simultaneous measurements of positive-ion composition were attempted each time the observatory passed over one of the following Thomson backscatter stations while Experiment D-15 and the stations were operational:

Aerocibo, P.R.
Jicamarca, Peru
Millstone, Boston, Mass.
SRI, Palo Alto, Calif.
San Santin, France

Three purposes will be served by correlating these two types of data, namely, a) evaluation of plasma sheath effects upon the positive ion density measurements, b) when two or more stations are involved during the same orbit, the horizontal distribution at the observatory altitude can be used to check and supplement the vertical surveys at each ground station, and c) attempt to resolve certain anomalies which appeared in some previous backscatter data from different ground stations when correlation with flight data was attempted. The coincidental measurement events are being sorted at the present time. Various data processing difficulties have prevented the sites from determining the times of coincidence and the $O^+$ concentrations at these times. These data should be forthcoming in the future. At that time, we will extract the pertinent data and perform the comparison.

## VII SYNOPSIS

The experiment has been operated over 5000 hours; of these, 1742 hours have been received by the experimenter on magnetic tapes. About 12 percent, a little over 204 hours, have been plotted. The most useful geophysical data have been extracted from about 55 hours of the plotted data.

A retrospective study of the data processing efforts on this experiment and man-power versus the resultant through-put of extracted and analyzed data has revealed to us a great deal of information about the operation of a data processing facility for scientific data reduction. Four different techniques have operated successfully, but with various degrees of efficiency and expediency. Two were fully automatic using large central computers. One was a semi-automatic system using a small computer, and the remaining method was "by hand". Thus comparative data are available on cost, speed, convenience, reliability, and so on. Of the four methods, the semi-automatic method with a small-to-medium scale computer seems the most rational compromise of speed and cost, provided high-speed input-output equipment were available.

Our experience has brought us to an even more fundamental conclusion. Data processing deserves a significant place in terms of time and dollars in the developmental program of new instruments. The electronic data processing hardware and software are as much a part of the experiment as the flight unit itself. The "add-on" concept of data processing as used in the OGO program is inefficient and wasteful of technical manpower. Questions concerning the complex spacecraft system and its dynamical characteristics should originate while the knowledgeable personnel are still associated with the program. On the OGO program, experimenters did not acquire an adequate understanding of the system early in the program because of contract restrictions; hence, many essential details and fundamental concepts will never be known for want of informed personnel. The "add-on" concept virtually eliminates all scientific effort of the program because the quality of the data is never brought to a sufficient level of excellence to make it amenable to scientific analysis.

Nearly all work is devoted to engineering effort directed at evaluation of spacecraft operations and the resulting parameters. Such efforts are merely preliminaries for the scientific effort. The support provided on the OGO program was adequate for the engineering effort, but practically non-existent for any scientific effort because of funding cutbacks and the inability of the OGO program to provide certain fundamental data.

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