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Preliminary Results of Density Measurements From an Air Force Satellite

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SPACE PHYSICS LABORATORY PROJECT 6690

AIR FORCE CAMBRIDGE RESEARCH LABORATORIES, OFFICE OF AEROSPACE RESEARCH, UNITED STATES AIR FORCE, L.G. HANSCOM FIELD, MASS.

Abstract

Atmospheric density was determined from a singly mounted ionization gauge flown on an Air Force satellite. Included is a brief description of the experiment and theory as well as a discussion of some of the problems involved in performing these measurements. Density data are given for the altitude range of 370 to 400 km during early morning hours for the two days 17 and 18 June 1961. Results are compared with those of the 1961 revised U.S. Standard Atmosphere.

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1. INTRODUCTION

Two presently employed, well known methods for determining atmospheric density at high altitudes are the satellite-drag and ionization-gauge techniques. The drag method, which is the calculation of density from orbit-decay data, is an indirect measurement that possesses inherent limitations. Among these are the restriction to measurements near perigee altitudes and the inability to detect short-term density fluctuations. On the other hand, since the ionization-gauge technique is a direct measurement, density is determined instantaneously and continuously over the entire orbit of a satellite. The ability to detect rapid density changes is a valuable and powerful tool for investigating the atmosphere. For example, drag techniques have successfully linked density variations with solar activities and day-to-night changes. With sufficient direct density measurements the dependence of these variations upon solar activities could, however, be more accurately formulated. Combinations of both methods can provide a clearer picture of the numerous events which are continually altering the structure of the atmosphere.

In May of 1958 the USSR performed the first successful direct density measurements[1] from a satellite, Sputnik III, using ionization gauges as detection sensors. The preliminary results given in this paper are believed to represent

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the first ionization gauge measurements performed from a U.S. satellite.

2. APPARATUS

The instrumentation employed on the Air Force satellite for density measurements is shown in Figure 1. It consists of two units, a sensor and an electronic unit. The sensor unit contains the detection apparatus: an ionization gauge, a decapping mechanism, a pressure switch, a thermistor, and explosive bellows. This entire unit is oriented to face in the direction of motion. Accompanying each sensor is an electronic unit located within the satellite. Included in this unit are a current amplifier, calibrating and timing circuits, and power supplies. Figure 2 shows a block diagram of the apparatus circuitry.

The density-sensing element of the experiment, the ionization gauge, is a cold-cathode type gauge developed in AFCRL laboratories to provide a light, reliable, rugged, and flyable sensor capable of continuous and extended operation throughout a satellite's lifetime. Incorporated in the gauge design are the geometry improvements for cold-cathode type gauges first employed by Hobson and Redhead,[2] National Research Council, Canada. These improvements provide faster and more reliable starting ability and a greater range of measurement. Operating characteristics and parameters are very similar to those fully described by Redhead[2] for his "inverted magnetron gauge". The AFCRL gauge is some forty times greater in sensitivity and considerably lower in power than the conventional hot-filament ionization gauge; these were determining factors in the selection of a cold-cathode gauge for atmospheric density measurements.

Prior to vehicle installation the ionization gauge is baked, outgassed, evacuated, and sealed. This conditioning procedure serves to minimize gauge contamination and to facilitate preflight checkouts by allowing gauge operation during ground checks. The assembled sensor unit is then mounted on a boom installed in the satellite vehicle. When orbit is obtained, the boom is erected to its proper position and the gauge opened to the atmosphere.

Atmospheric molecules flowing into the gauge are ionized and collected to produce a signal proportional to ambient density. This signal when fed to the electronic unit is amplified and converted to a form suitable for telemetry transmission. The amplifier is a five-decade logarithmic, direct-current amplifier utilizing a Raytheon CK5886 electrometer tube in the input stage and negative-feedback circuitry to increase response time. A programmed timer periodically interrupts and short-circuits the sensor signal for a ten-second period while calibration currents are fed through the amplifier. Following this, normal operation is restored. The remaining components in the electronic units are power sources which supply operating voltages to the ionization gauge, amplifier, and timer.

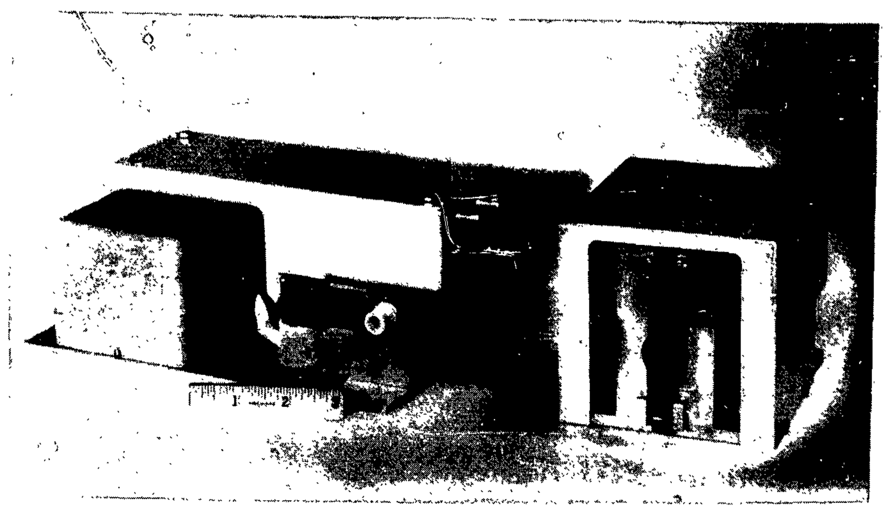


Figure 1. Photograph of the Equipment used for Density Measurements

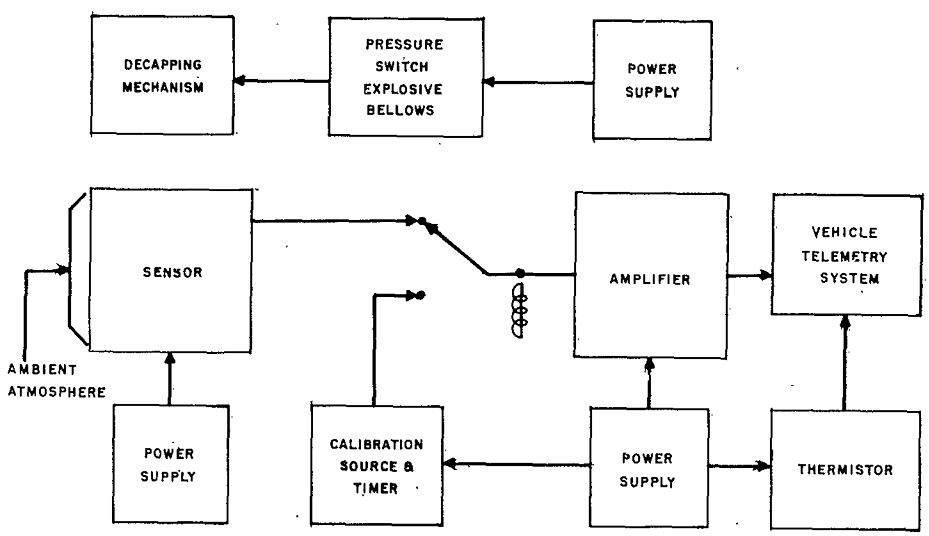


Figure 2. Block Diagram of the Apparatus

Total-power requirement for both units is less than six watts and the weight is approximately eight pounds.

3. THEORY

In determining atmospheric pressure from a satellite-mounted ionization gauge the relationship between gauge pressure and ambient pressure must be ascertained. With the gauge opening mounted in a forward direction along the satellite-velocity vector ($\phi = 0^{o}$) and if one assumes a Maxwellian gas in a region where free molecular flow theory is valid, then the relationship between ambient and gauge pressure[3] can be stated as

$$P_a = \left[\sqrt{\frac{T_a}{T_g}}\right]\left[\frac{1}{f(s)}\right]\left[\frac{W^*(0,L/r)}{W^*(s,L/r)}\right] P_g \,, \qquad (1)$$

where

P_a is the ambient pressure.

P_g is the gauge pressure.

T_a is the absolute atmospheric temperature.

T_g is the absolute gauge temperature.

$f(s) = e^{-s^2} + \sqrt{\pi}\, s(1+\Phi(s))$, when $s > 0$.

$s = U/V_m$.

U = is the orbital velocity.

L = length of tube.

r = radius of tube.

V_m is the most probable velocity of atmospheric molecules.

$W^*(0, L/r)$ is the probability that a molecule entering the gauge tube will pass through the tube when there is no mass velocity.

$W^*(s, L/r)$ is the probability that a molecule entering the gauge tube will pass through the tube when there is a mass velocity.

The first factor of Eq. (1) gives the effect of gauge and atmospheric temperature; the second factor the effect of satellite velocity; the third factor the effect of the tube connecting the gauge to the atmosphere.

From the above equation ambient pressure is seen to be a direct function of atmospheric temperature; however, in determining atmospheric density from ionization-gauge readings, the dependence on atmospheric temperature is less critical, appearing only indirectly in the calculation of the parameter $W^*(s, L/r)$.

Combining Eq. (1) with the ideal-gas law produces the following relationship between ambient density and gauge pressure:

$$\rho_a = \left(\frac{M}{2\pi R_m T_g}\right)^{\frac{1}{2}} \frac{W^*(0,L/r)}{U W^*(s,L/r)} P_g, \tag{2}$$

where

ρ_a = mass density of ambient gas,

M = mean molecular weight,

R_m = gas constant per mole of gas,

U = orbital velocity.

In applying the above relationship, M and T_a at given altitudes are the values given in the revised U.S. Standard Atmosphere[4]; T_g is measured directly on the satellite; f(s) is approximated by $2\sqrt{\pi}s$, for $s \geq 3$, the approximation is correct to six significant figures (s>6 for this flight); $W^*(0,L/r)$ and $W^*(s,L/r)$ can be calculated from gauge geometry and other known quantities.

The errors introduced by the assumption of values for M and T_a from the model atmosphere are not large; for example, assuming a value of M at 200 kilometers in place of M at 400 kilometers, a change in molecular weight from 26.32 to 19.56 causes ρ_a to change less than 14 percent. An equivalent change in T_a would produce less than a 2 percent change in ρ_a.

4. RESULTS

At Vandenberg Air Force Base on June 16, 1961 an Air Force vehicle was successfully launched and placed in orbit. Included in the satellite payload was the AFCRL density gauge.

The vehicle's orbit was at an inclination of 82.1° to the equator with a period of approximately 91 minutes and an apogee and perigee of 410 and 225 km respectively.

Density data was transmitted during real-time readout periods of six minutes duration. A total of 50 of these data acquisitions were processed and, of these, 21 were suitable for data reduction. Weak telemetry signals, signal-tracking failures, and noise all caused some loss of data, although the primary data loss resulted from a shift in experimental sensitivity. Low equipment temperatures, less than -30°C, caused an upward shift in amplifier sensitivity from 3×10^{-5} to 5×10^{-6} amperes. This shift meant that the highest readable gauge pressure would be 9×10^{-7} mm Hg. Above this value amplifier saturation occurred. In addition the experiment was designed to operate in an orbit which was considerably higher in altitude than the obtained orbit. The combination of the two just mentioned factors restricted density measurements to above 370 km.

Three-axis stabilization was maintained throughout the flight by means of six gas jets located on the forward face of the satellite. The jets were used constantly to control and correct for horizontal and vertical drift. Although stabilization was necessary for the proper orientation of the sensor, this particular method of stabilization introduced complications and bias to the interpretation of data. One's first reaction is to discount any possibility of density measurements under such circumstances. Although telemetry records show interference from gas emissions, they also indicate meaningful measurements were performed.

In seeking an explanation for the intermittent effects of the gas jets three possibilities are offered:

(1) That continuous use of gas jets is not continuous in effect but rather that a certain small angle of drift is allowed before the stabilizing gas jets are activated.

(2) That an accidental or unintended torque acted to place the satellite in its planned attitude. This would activate the stabilizing sensors to cut off all jets until drifting again deoriented the satellite.

(3) That during certain phases of stabilization the vehicle itself provides a gas shield for the gauge. The ionization gauge is favorably located with respect to certain jets. In the operation of these jets a flow of gas would be directed away from the vehicle by a source situated on the opposite satellite surface to that of the gauge. During this time the interposition of the vehicle serves as a shield to prevent backstreaming molecules from reaching the vicinity of the gauge.

At the present time the above explanations represent a "best guess" for the action of the gas jets upon density readings. That the stabilization system was automatically controlled in flight and independent of ground control is known and well confirmed. Other available information about the operation of the system is either too contradictory or inadequate to attempt a quantitative assessment of gas-jet effects. Gas-jet monitoring information, presently not available, will aid in resolving this difficulty.

Density results are given in Table 1, column headings are self-explanatory except for the heading entitled "duration" which requires some description. Figure 3 is a reproduced portion of a telemetry record typical of this flight. Sections AB and EF above zero volts represent a gauge signal indicating density values far in excess of ambient values ($> 2 \times 10^{-11}$ kg / m^3). In section BC the density signal decreases (voltage increases) until a levelling off region, section CD, is reached. Following this, the density signal increases, section DE, until it once again indicates values in excess of ambient values. The time span of section CD is

TABLE 1. Density results

Station	Date	Local Time	Location Lat., Long	Orbit No.	Duration Sec	Altitude KM	Density KG/M^3
New Boston	6/17/61	2:45 A.M.	33°N, 60°W	6	29	399	4.81×10^{-12}
New Boston	6/17/61	4:16 A.M.	35°N, 83°W	7	29	397	11.32×10^{-12}
*VAFB	6/17/61	2:47 A.M.	35°N, 105°W	8	30	396	6.07×10^{-12}
VAFB	6/17/61	4:17 A.M.	32°N, 129°W	9	24	398	5.01×10^{-12}
		4:19 A.M.	36°N, 128°W	9	52	395	6.16×10^{-12}
Hawaii	6/17/61	3:42 A.M.	7°N, 153°W	10	88	409	6.22×10^{-12}
		3:48 A.M.	33°N, 151°W	10	53	397	6.63×10^{-12}
Hawaii	6/17/61	5:14 A.M.	14°N, 176°W	11	9	408	4.56×10^{-12}
		5:17 A.M.	25°N, 175°W	11	12	402	6.51×10^{-12}
		5:19 A.M.	33°N, 174°W	11	51	397	4.49×10^{-12}
New Boston	6/18/61	3:01 A.M.	43°N, 64°W	22	11	385	4.75×10^{-12}
VAFB	6/18/61	2:59 A.M.	29°N, 112°W	24	13	396	4.44×10^{-12}
		3:01 A.M.	32°N, 111°W	24	34	393	3.98×10^{-12}
		3:02 A.M.	36°N, 110°W	24	35	386	4.67×10^{-12}
VAFB	6/18/61	4:28 A.M.	22°N, 135°W	25	55	400	3.14×10^{-12}
		4:30 A.M.	29°N, 135°W	25	58	395	4.08×10^{-12}
		4:35 A.M.	49°N, 131°W	25	14	378	3.02×10^{-12}
		4:36 A.M.	52°N, 130°W	25	12	373	6.02×10^{-12}
Hawaii	6/18/61	3:49 A.M.	22°N, 158°W	26	152	~399	3.64×10^{-12}

*Vandenberg Air Force Base

that which is listed under the "duration" heading of Table 1. The density-trace sections AB, EF, and DE are attributed to the action of the gas jets. In section BC, for unknown reasons, this action diminishes or ceases. Following this is the stable region CD. The density value in this region is taken as ambient density and is given in column 8 of Table 1. From the data given in Table 1, curves of density versus altitude, Figures 4 and 5 were plotted for the days June 17, 1961 and June 18, 1961, respectively. As previously mentioned only measurements at apogee altitudes were possible; therefore, comparison with density values acquired from drag measurements would not be pertinent. In order to provide some reference standard the experimental data is shown with day and night density curves from the most recent model atmosphere, 1961 U.S. Revised Standard Atmosphere. Similar solar conditions existed for all curves, the 10.7-cm solar flux for the model atmosphere curves is 130×10^{-22} watts/cm/cycle/sec and for the experimental values 136×10^{-22} watts/cm/cycle/sec. Data values in Figure 4 cover a time span of approximately 3 hours in local time from 2:45 a.m. to 5:20 a.m., over a latitude range varying from 7°N to 36°N while data in Figure 5 represents a shorter time span of $1\frac{1}{2}$ hours from 3:00 a.m. to 4:30 a.m. local time, over a latitude interval of 30° from 22°N to 52°N latitude. In Universal Time, data from Figure 4 represents an 8-hour spread and that from Figure 5 a 6-hour spread.

The mean density value of data taken 17 June 1961 is 5.6×10^{-12} kg/m^3. This is over the altitude range from 395 to 409 km.

The results given for 18 June 1961 (Figure 5) are more encouraging. The previously mentioned circumstances surrounding this flight raise a question regarding the validity of this data. In considering this question, it must be acknowledged that to deny that the gauge achieved atmospheric equilibrium implies that the gauge was in equilibrium with emitted gases. Whichever hypothesis is chosen the significance of Figure 5 can not be discarded. Either the values given in this figure represent true atmospheric density or, at worst, they represent the upper limits of atmospheric density. Any combination of the above two hypotheses will not alter these facts.

The strongest evidence in favor of atmospheric equilibrium is the well defined decrease in density shown in Figure 5. This decrease agrees both in magnitude and shape with our present day density knowledge as reflected in the Model Atmosphere.

5. SUMMARY

Although little or no information can be deduced from the available data pertaining to such effects as day-to-night and latitude variations, nevertheless these results do represent instantaneous density measurements confirming our present knowledge of atmospheric density and placing greater reliance in its acceptance. In addition, the successful measurements, despite the involved shortcomings, prove the practicality of direct density measurements with a single satellite-borne ionization gauge. With future refinements in instrumentation one can conduct extensive investigations of the state of the upper atmosphere in terms of the underlying causes of density variations.

ERRORS:

No extended effort has been attempted to evaluate or estimate the error due to contamination from stabilization-gas emissions. As previously mentioned, sufficient information is not available at this time. The final report on the results of this flight will include a full discussion of the effects of the satellite stabilization system.

Let it suffice to caution that stated density values can be considered as maximum limits of ambient density for the stated altitudes. Or, more specifically, the values represent the sum of ambient plus ejected gas densities.

The main sources of error are instrument and gauge-effect errors. Apparatus error is computed to range between 45 to 55 percent. Included in this figure is electronic equipment, ionization gauge calibration, telemetry, and

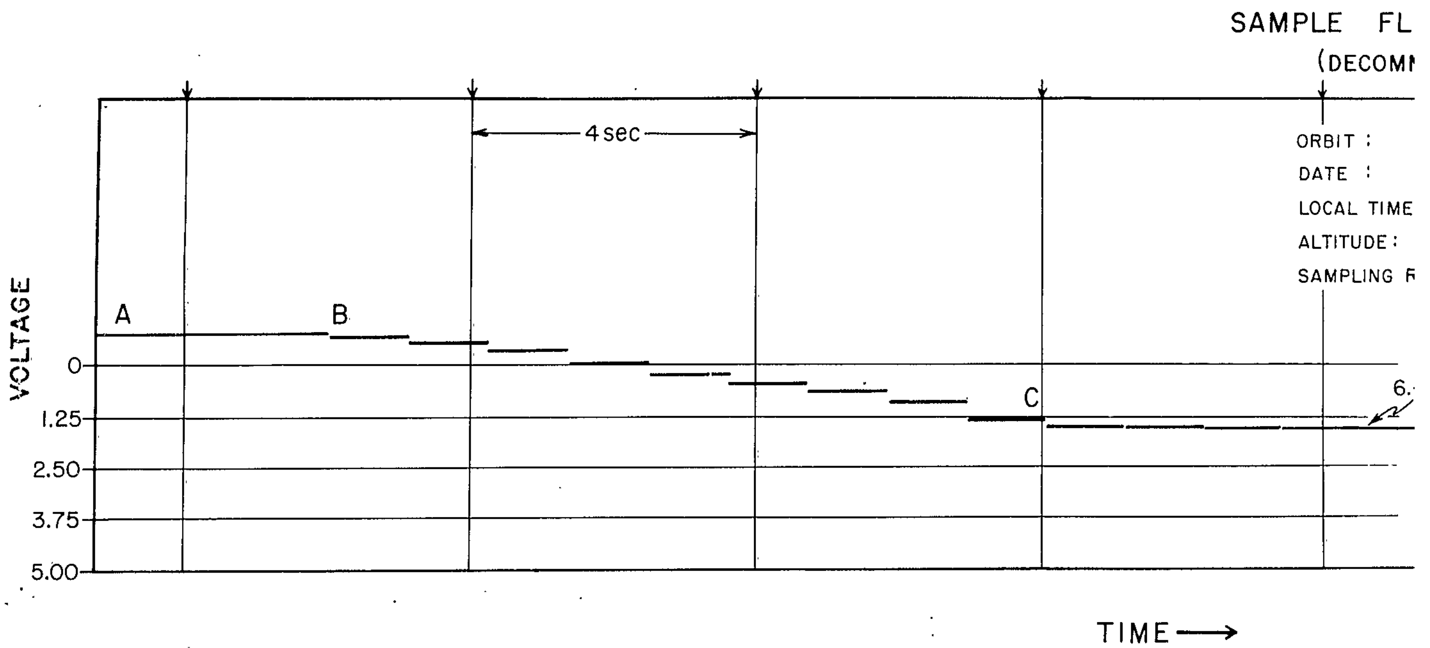
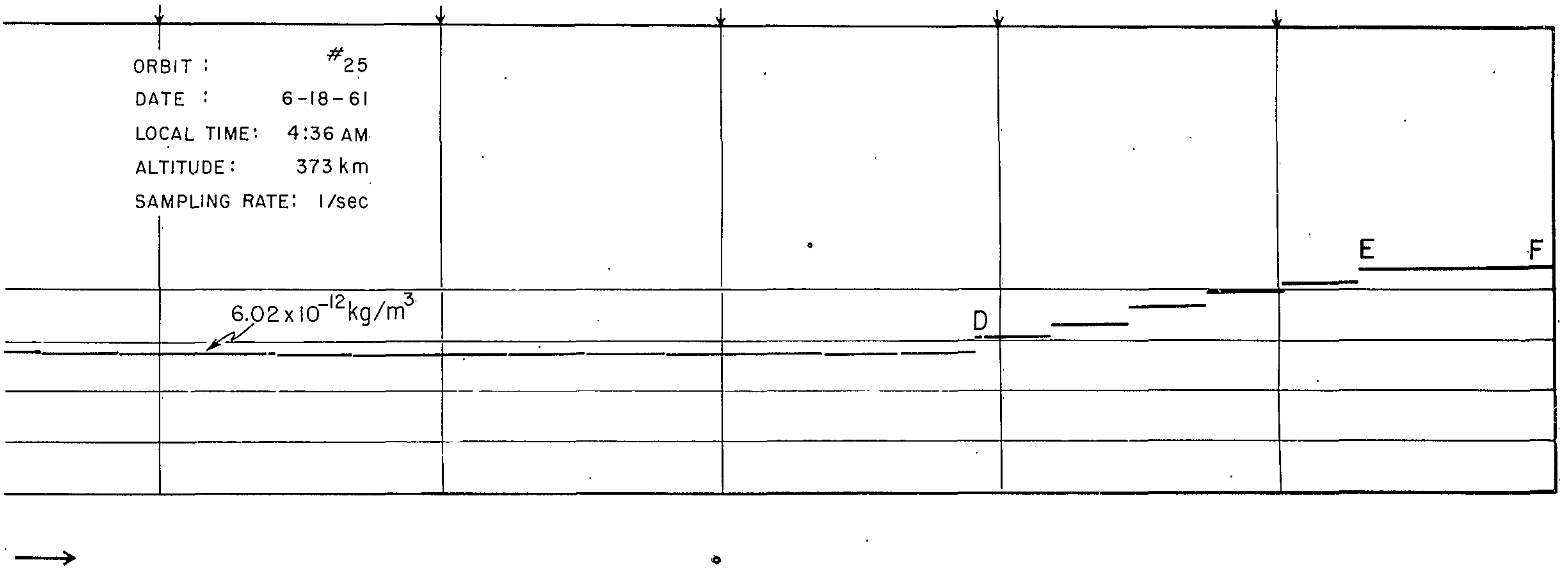


Figure 3. Portion of a Telemetry R

1

SAMPLE FLIGHT RECORD
(DECOMMUTATED)



tion of a Telemetry Record Typical of this Flight

2

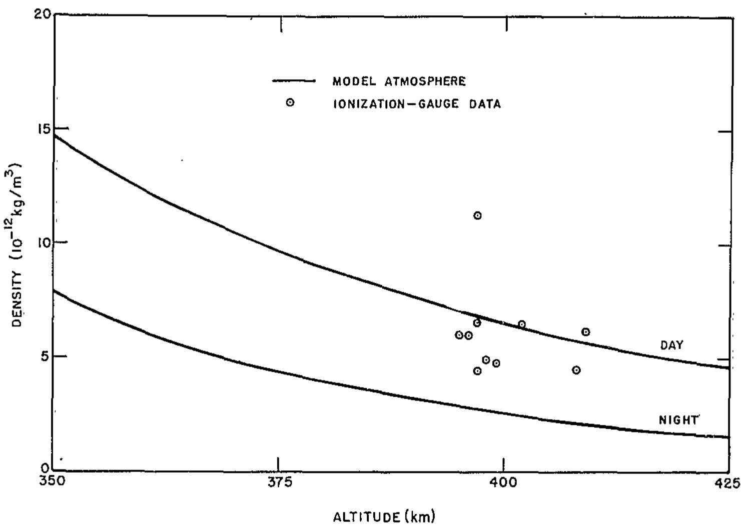


Figure 4. Graph Showing Density vs Altitude Results for June 17, 1961

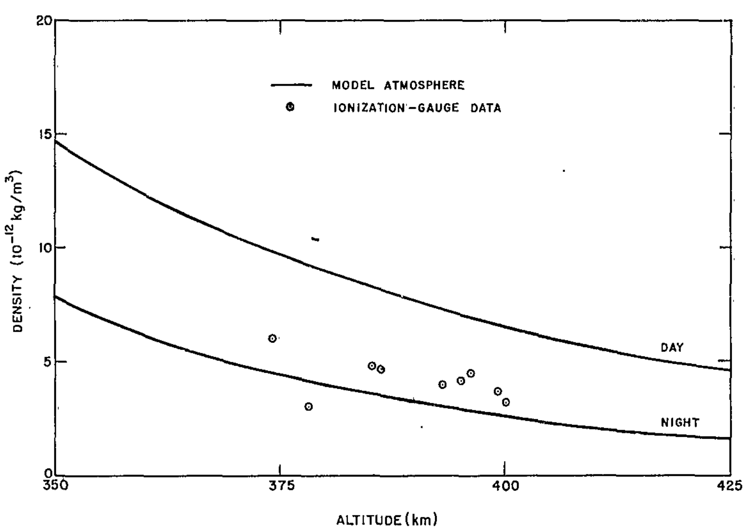


Figure 5. Graph Showing Density vs Altitude Results for June 18, 1961

stabilization uncertainties. The low temperatures experienced by the apparatus during flight contributed significantly to the above error. Gauge-effect errors such as recombination and composition changes are computed to be no greater than 40 percent; this is considering total recombination of atomic oxygen at the gauge walls.

A preliminary breakdown of the overall error would be +90 percent and -50 percent.

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AF Cambridge Research Laboratories, Bedford, Mass. Geophysics Research Directorate
PRELIMINARY RESULTS OF DENSITY MEASUREMENTS FROM AN AIR FORCE SATELLITE by J. McIsaac, H. Pond and C. Stergis. 12 pp.
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UNCLASSIFIED

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2. Atmosphere models
3. Density sensitive indicators

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