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ROCKET SOUNDINGS IN THE MESOSPHERE

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William Nordberg

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Rocket Soundings in the Mesosphere

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Institute of the Aerospace Sciences
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ROCKET SOUNDINGS IN THE MESOSPHERE

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PHYSICS OF THE MESOSPHERE

The feature of a steadily declining temperature with altitude has been recognized as a distinct characteristic of the atmospheric region between 50 and 90 km long before the onset of systematic exploration of the upper atmosphere by means of sounding rockets. It was then proposed that this region be named "mesosphere."

The mesosphere is bounded by the "stratosphere" at the bottom and by the "thermosphere" at the top, both regions of generally positive temperature gradients with altitude. During recent years a variety of rocket-borne experiments have contributed to put the numerous characteristics of these regions into clearer focus. We have learned that there are consistent exceptions to the steadily declining temperature-altitude profile in the mesosphere(1) and that persistent, large scale circulation systems which characterize the dynamics of the lower mesosphere change their behavior rather abruptly at the higher altitudes.(2) These features are perhaps of equal or even greater significance that the existence of a temperature lapse rate. The eventual goal of the rocket experiments in the mesosphere is to explore these characteristics to the extent that the physical processes which determine the state of this region can be fully understood. Characteristics such as temperature profiles, wind fields and compositional structure are simply manifestation of the underlying physical processes.

The thermal structure of the mesosphere is thought to be determined mainly by the absorption of solar ultraviolet radiation by ozone and by the loss of energy through the emission of infrared radiation by ozone and carbon dioxide. Heating rates ranging from about 15°C per day near the summer pole at the bottom of the mesosphere to no heating near the winter pole at the top of the mesosphere have been computed.(3) Computed cooling rates due to the emission of infrared radiation by carbon dioxide and ozone are of comparable magnitude but the distribution of these energy sinks with latitude and season is substantially different from the distribution of the heating sources.(3) The global variation of this radiative energy balance profoundly affects the wind patterns which in turn relate to the convective exchange of energy.

On the basis of these physical processes the mesosphere is unique in many respects. It is the highest region of the atmosphere where the existence of circulation systems in the meterorological sense have been observed; systems which change periodically with season and are primarily driven by latitudinal temperature gradients. [2] At higher altitudes, above 70-90 km, the nature of the circulation changes abruptly probably due to the predominance of oscillatory forces such as tides and possibly due to interaction of the medium with electric and magnetic fields. Wind fields above 80 km have not exhibited any seasonal regularities. This boundary at 80 km also coincides roughly with the level where diffusive separation between the heavier and lighter constituents of the atmosphere begins to overcome the mixing processes which dominate below 80 km and which are responsible for keeping the gross composition of the atmosphere nearly constant from the ground up to about 80 km. Despite this constancy of gross molecular weight, the thermal structure of the mesosphere is highly sensitive to minor variations in the concentration of photochemically active constituents such as atomic oxygen and ozone which take place in this region. Up to the 80 km level these constituents have no effect on the gross molecular weight. Above 80 km dissociation of molecular oxygen in addition to gravitational separation between lighter and heavier gases contributes to a rapid decrease in molecular weight.

The interactions between short term variations in solar radiation and the state of the atmosphere in the 50-90 km region are also of profound interest. At higher altitudes (200-300 km) such direct interactions have been positively identified, [4] while in the stratosphere and troposphere they are not known to exist nor are they likely to occur. It is more likely that certain concurrent features may be found in circulation from the troposphere through the stratosphere well into the mesosphere. If, on the other hand, we can also find a direct influence of fluctuations in the shortwave solar radiation on the structure of the mesosphere a link between such fluctuations and "weather" in the lower regions of the atmosphere may very well have been established.

Most of the rocket experiments conducted to date have been either too sparse or not adequately instrumented to permit a fundamental exploration of the physics of the mesosphere. This region is inaccessible to sounding balloons and indirect, ground based or satellite measurements have not been very successful yet in obtaining satisfactory measurements of the mesosphere. Therefore, the sounding rocket remains the only useful tool.

The fundamental physics of this region must then be derived from the results of a large number of rocket soundings which should take place at various key locations in the world and which should be conducted within the framework of a globally coordinated program. These soundings should consist of measurements of the typical structure parameters:

temperature, pressure, density, wind and composition. Such measurements are well within the capability of existing instrumental techniques except perhaps for the measurement of composition. Measurements of the trace constituent composition in the mesosphere, though very important, has been grossly neglected during past years.

Finally with the advent of large spacecraft and manned spaceflight, the exploration of the mesosphere has taken on a new aspect. In many instances, launch vehicles as well as re-entering spacecraft are expected to pass through critical phases of their flight in the 50-90 km region. In order to design appropriately for these conditions, engineers are keenly interested to obtain the best possible knowledge of the anticipated flight environment. Density and winds are the parameters of greatest importance for these purposes. This practical application, plus the fact that the basic physical processes which take place within the mesosphere still pose many, most challenging questions, clearly spell out the necessity for further experimental exploration. In the subsequent sections, therefore, the techniques employed in recent measurements, the various coordinated programs leading to a systematic exploration and the results of many typical soundings will be described.

EXPERIMENTAL TECHNIQUES

Launch Vehicles

Rocket vehicles used for upper atmosphere exploration can be generally classified into three categories. This classification applies to the aspect of cost, size and complexity, as well as to the capability of the rocket to carry a given weight to a given altitude. For the purposes of this discussion the three categories shall be defined as: small, medium and large.

"Small" rockets generally carry payloads of about 1-5 kg and small diameters (less than 12 cm) to altitudes of 50-70 km. They are relatively inexpensive with the rocket and payload costing approximately $2,000. The entire launch operation can be performed with a minimum of complexity, generally requiring only a simple, easily transportable launching tube and crew of less than five. Simple sensors carried by these rockets perform temperature and wind measurements in the stratosphere and wind measurements in the lower mesosphere. The rockets can be launched frequently and in fairly large numbers. This has made them useful as launch vehicles in synoptic soundings as part of the United States Meterorological Rocket Network.[5] In the United States the "LOKI II" also called HASP and the "Arcas", are typical for such vehicles. These rockets and their associated instruments have been described in connection with the Meterological Rocket Network.[5]

"Large" sounding rockets carry payloads of up to 100 kg and large diameters (30-40 cm) well into the thermosphere (200-300 km). They are relatively expensive (>$25,000) and require fairly complex launch installations with crews of more than ten. A typical example of a United States rocket of this category is the Aerobee.(6) Because of the expense and complexity it is not practical to use such rockets in synoptic programs.

Rocket vehicles of "medium" category are the best suited for experiments in the mesosphere. They posess sufficient thrust to carry payloads of 30-40 kg and 15-20 cm diameters to altitudes of 100-200 km. The cost (about $10,000-25,000 including payload) is such that "semi-synoptic" programs at several sites with launchings at periodic intervals— though not continuous— are permissible. A crew of less than 10 can usually handle the launch operation from not a too complex rail launcher. In the United States, two stage rockets, using the "Nike" booster as a first stage, are most common. The "Cajun" rocket(7), which has been most commonly used as a second stage since the International Geophysical Year (IGY) has now been succeeded by the more powerful "Apache."(8) A typical Nike-Cajun rocket configuration is shown in Figure 1.

Radar Tracking of Chaff

The only experiment which has been successfully performed in the mesosphere using "small" type rocket vehicles is the measurement of wind by means of dispersing chaff,(9) whereby the drift of the chaff with the wind is tracked by radar on the ground as the chaff descends from altitudes of 80 km or below. In the upper part of the mesosphere, however, it is very difficult to measure wind by methods of dispersing solid materials such as chaff because the fall velocity of the chaff approaches free fall very rapidly with increasing altitude.(9) Another disadvantage of the chaff method is the fact that the chaff, ejected from the rocket near apogee disperses rather rapidly (in many cases within about 20 km), as it falls through the atmosphere.

Sodium Vapor Ejection

Efforts have been made very early in the history of rocket soundings to measure winds by means of ejecting and tracking aerosole type particles or vapors from rockets. These payloads usually consist of smoke generators or vaporizors and require therefore, rockets of the "medium" category. The most successful of these techniques has been the method of injecting sodium vapor into the atmosphere between 70-200 km during twilight conditions. Interaction of sunlight with the sodium vapor (resonance radiation) causes the sodium trails to be luminous, and with the proper ejection technique the sodium remains visible for periods up to 30 minutes at middle latitudes.

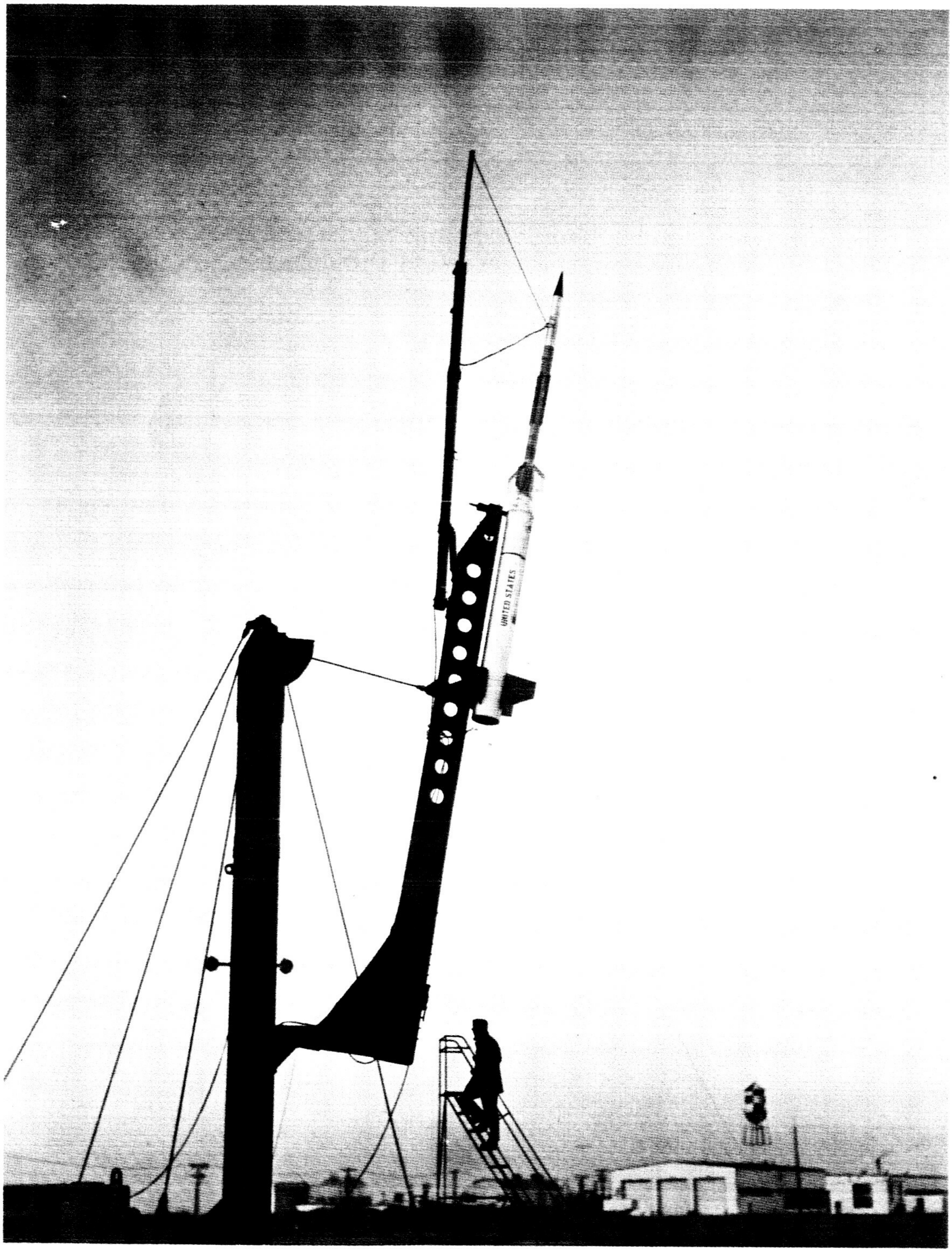

Figure 1. Nike-Cajun rocket with grenade experiment ready for launch at Wallops Island.

The trail moves instantly with the atmospheric wind field and its track is recorded by an array of cinetheodolite cameras which are spread over the ground on very long baselines (>50 km). The drift motion is determined by triangulation of significant features such as a sharp kink in the trail (Figure 2). This method was originated by Manring[10] and an estimated order of 50-100 soundings have been carried out at many locations of the globe. Figure 2 also shows how two different techniques namely the sodium release and acoustic grenade techniques (described below) were combined in one experiment. Flashes from the grenades can be seen in the center of Figure 2.

A disadvantage of the sodium technique is that it can only be carried out during a few minutes every 12 hours, during a time when the region above 70 km is illuminated by the sun, in order to produce the glow in the trail and when the cameras on the ground are in darkness, in order to permit proper exposure of the film. Also, the experiment must be carried out in clear skies.

Although this experiment functions only in the upper mesosphere—the resonance glow cannot be induced below 60-70 km because of the absorption of the incident sunlight by natural sodium in the atmosphere—it has produced valuable information on the tremendous wind shears in the transition region between the mesosphere and thermosphere. The great advantage of this technique is that the continuous trail enables the observation of the fine structure of the wind with great detail. Research is progressing at this time on selfluminous vapors which glow for a sufficient time and with sufficient intensity to permit this type of wind measurement throughout the night.

Acoustic Grenades

The direct measurement of temperature which can be performed in the stratosphere by means of extremely small resistance thermometers[5] (thermistors) becomes questionable at altitudes above 50 km,[11]. In the mesosphere therefore, temperature must be measured by more complex, indirect methods. The method most commonly used in the Rocket-Grendade technique.

In this experiment grenades are ejected and exploded at altitudes up to 90 km at regular intervals during the ascent of the rocket. They are cylindrical in shape and are ejected forward through the nosecone of the rocket (Figure 3) and contain high explosive, mainly TNT, which is detonated mechanically by means of a lanyard tied to the rocket. The explosives weigh between one and two pounds. Average temperatures and winds in the medium between two grenade explosions are determined by measuring exactly the time of explosion of each grenade, the time of arrival of each sound wave at various ground-based microphones, and the exact position of each grenade explosion. Thus the speed of sound in the layer between two explosions is measured and temperatures can be derived since

Figure 2. Photograph of sodium trail exposed with simultaneous grenade experiment. Flashes from grenade explosions can be seen near center of photograph. Distinct features such as sharp bends in the trail which indicate extreme wind shears are used as identifying reference when triangulating the trail from various camera sites.

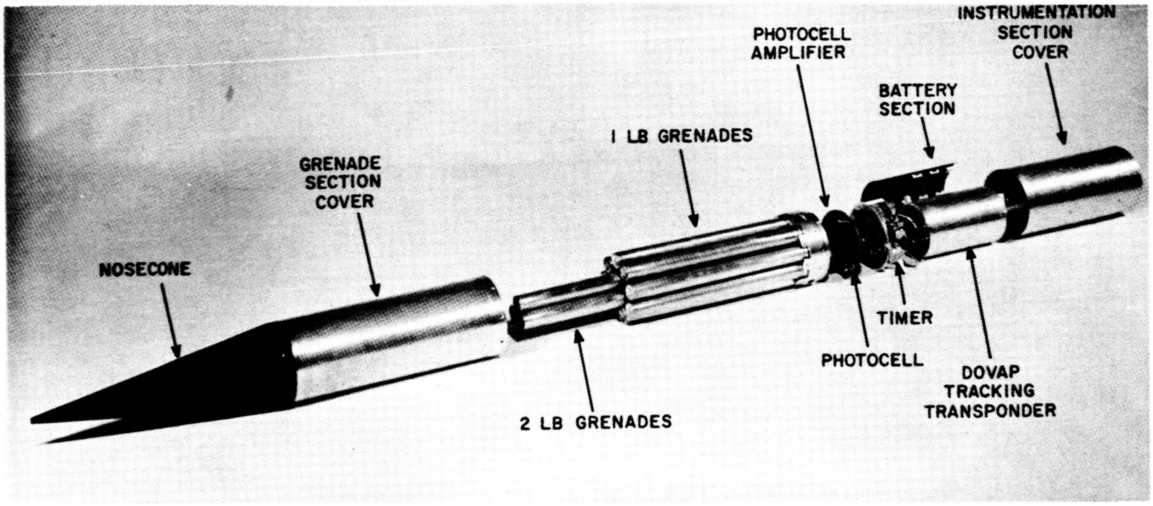

Figure 3. Grenade experiment payload, exploded view.

the temperature is proportional to the square of the speed of sound. Molecular weight is contained in the proportionality factor. Wind speed and direction can be derived from the horizontal drift of the sound in the layer.

The grenade experiment requires a highly accurate tracking system. A network of ballistic cameras or Doppler tracking stations, or a high precision radar of the FPS-16 type are used to determine the coordinates of explosions. A schematic diagram of the essential components of the grenade experiment is shown in Figure 4. The highest altitude from which sound returns can be received with present explosive charges and existing sound ranging techniques is about 90 km. The greatest advantage of this experiment is that temperatures and winds can be measured simultaneously which is of great importance in describing the dynamics of the atmosphere, and that the resulting measurements are very accurate. The drawbacks are that only average temperatures and winds in the layer between two grenades can be measured and that a fairly elaborate system of ground instruments for tracking and sound ranging is required. A detailed description of this experiment which has been successfully performed more than fifty times during the past decade is given in (12).

Falling Sphere

In the altitude region concerned, pressure and density are more susceptible to measurement by in situ techniques than temperature.

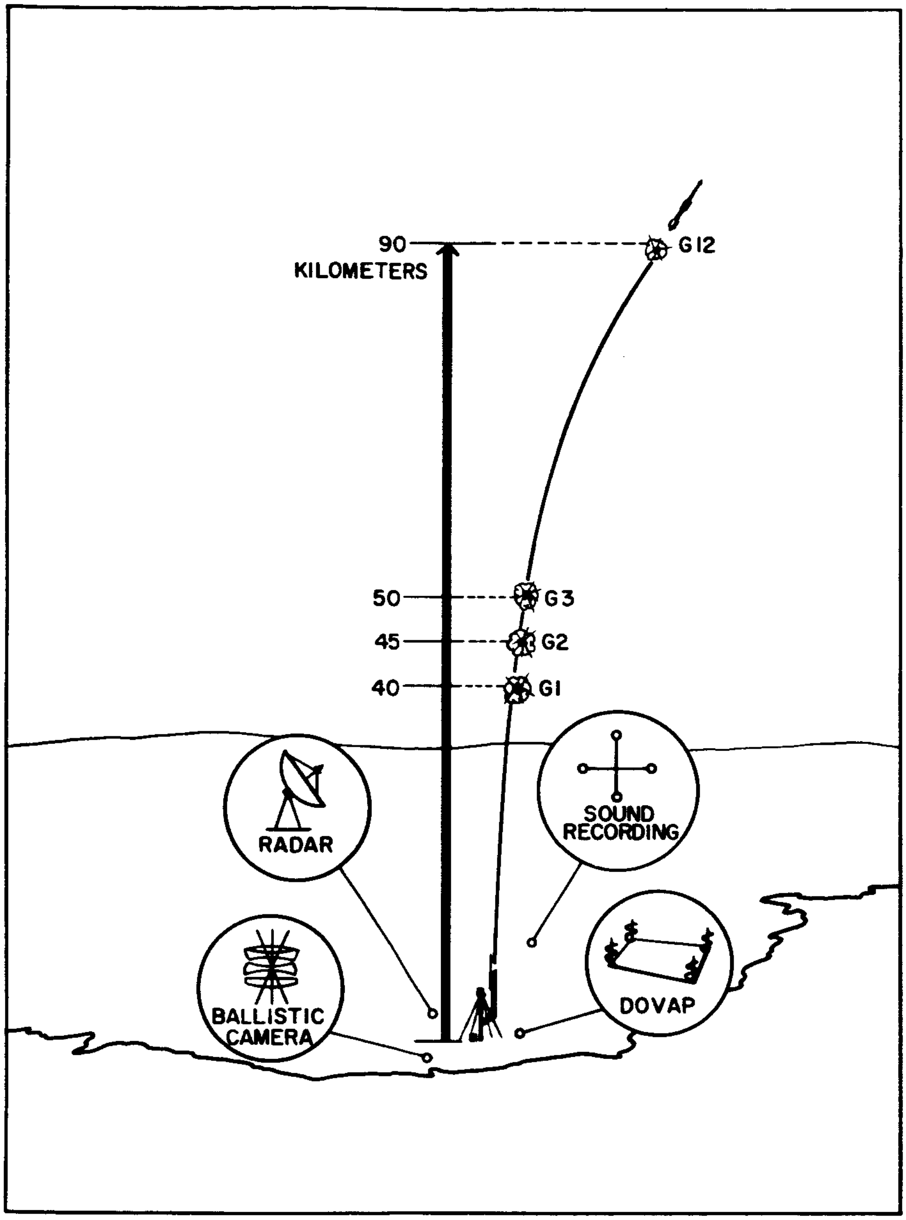

Figure 4. Schematic diagram of grenade experiment system; radar, ballistic camera, and Dovap tracking systems are indicated. Each individual system or a combination thereof suffices for the experiment. Sound recording site is preferably located directly under trajectory of rocket. G-1 through G-12, indicate altitudes of grenade explosions

The simplest method in concept is the measurement of density by means of the falling sphere technique. This technique has been originally developed at the University of Michigan,[13] and a large number of successful flights have been carried out since 1952.

In the sphere experiment the drag force (D) excerted on a perfect sphere dropped from a rocket at high altitude is measured and ambient density (ρ) is derived by means of the relationship:

$$mg + D = m\ddot{h} = \tfrac{1}{2}\rho \dot{h}^2 C_D A + mg \tag{1}$$

where h is the altitude of the sphere, A the cross sectional area and C_D the aerodynamic drag coefficient which is a function of Mach number and must be determined empirically; m is the mass of the sphere and $\dot{h}$ indicates the time derivative of h; g is the acceleration of gravity and depends on h.

Falling spheres have been used in many different combinations: as rigid shells (as shown in Figure 5) or as inflatable balloons; with built in accelerometers (active sphere), to measure $\ddot{h}$ directly (Figure 5), or with high precision radar tracking (passive sphere) to determine the drag acceleration from the second derivative of the altitude vs. time function given by radar track. Differentiation of the tracking data or integration of the measured accelerations, in case of the active sphere, leads to the velocity, $\dot{h}$, required to solve equation (1) for ρ.

The spheres are usually ejected from the rocket at an altitude of about 60 km and travel along a ballistic trajectory up to about 140 km. Acceleration is determined both along the upward and downward leg of the trajectory. Winds can be measured with inflatable spheres at altitudes below 50 km from the horizontal drift determined by radar. Density measurements with large (1-2 meters) passive inflatable spheres have been obtained up to 110 km.[14] Results from smaller, rigid, active spheres have been reported by Jones[15].

Above the 120 km level the cross section over mass ratio of the sphere is too small to detect any deviations from free fall; at low altitudes there is usually a region where the velocity of the sphere approaches a Mach number regime in which C_D is not known accurately enough and where horizontal winds affect the fall of the inflatable sphere. This depends largely on the type of sphere used, but in general density data have been obtained down to 40 km with inflatable passive spheres and down to 20 km with rigid, active spheres.

The advantage of this technique is that for the active sphere the ground instrumentation is exceedingly simple (one telemetering receiver and recorder) and that, the flight instrumentation is quite compact although a high degree of perfection and engineering skill is required to

Figure 5. Photographs of 7" diameter falling sphere (active, rigid). Left sphere, fully assembled, shows telemetering antenna slot. Open sphere on right shows built-in accelerometer.

manufacture the spheres and accelerometers. With the passive sphere the costs are greatly reduced, but the ejection and inflation mechanisms are of critical importance and high precision tracking radar must be available. Also, the fall velocity of the inflatable sphere is near the speed of sound in the vicinity of 70 km. Errors may be introduced at this altitude by insufficient knowledge of C_D which changes rapidly with fall velocity near M = 1. The drag on the inflatable sphere could also be greatly affected by imperfect inflations and by strong horizontal winds. These problems, of course, do not exist with the active, rigid sphere.

Pitot Static Tube

A variety of techniques exist to perform in situ pressure measurements from rocket vehicles. These techniques are always based on the premise that ambient conditions of pressure, density or temperature can be derived from the direct pressure measurements carried out on board the vehicle by applying aerodynamic theories which relate the measured pressure to the ambient parameters. The accuracy of the derived ambient pressure, density and temperature thus depends not only on the precision of the pressure measurement itself, but also on the validity and applicability of these aerodynamic theories. This applicability is generally ensured by keeping such rocket performance parameters as velocity and angle of attack within tolerable limits during the time of measurement. Effects on the pressure measurement by gases carried along with the sounding rocket must be carefully avoided.

In general, the pressure measurement is performed at least two aerodynamically different locations along the surface of a Pitot-static tube carried at the tip of the rocket (Figure 6). Pressure sensors are usually placed in chambers which are exposed to the air flow by means of orifices in the skin of the rocket. In one chamber the stagnation pressure (P_i) at the tip of the Pitot tube is measured, and in a second chamber a measurement of static pressure (P_s) along the wall of the same tube is made, several calibers to the rear of the stagnation point.

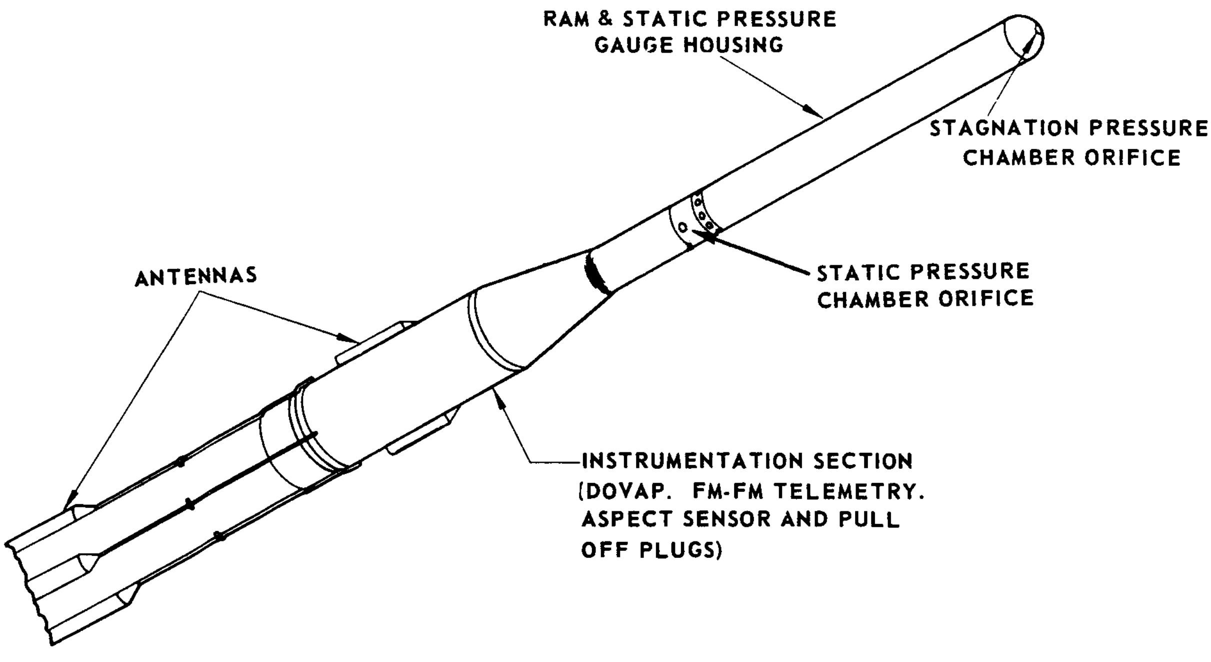

Figure 6. Configuration of Pitot static tube experiment.

Aerodynamic tests of this configuration show that the pressure measured at this point is equal to ambient pressure. Additional chambers may be provided for redundancy. As a pressure sensor each chamber consists of a radioactive ionization source and a multi-range electrometer which measures the pressure sensitive ion current. The current, calibrated as a function of chamber pressure and susceptible to measurement in the altitude range of about 40-120 km, is telemetered to the ground. This technique which has been developed in its present state by J. J. Horvath et. al.(16) is based on pressure measurements originally developed by Spencer(17) and LaGow(18). During various developmental stages, about 10-20 successful flights of this basic technique have been carried out since 1953.(18), (19), (20).

Ambient density ρ is derived from the interpretation of the basic Pitot static tube equation (Rayleigh Equation) and from the equation of state:

$$\rho \sim \frac{P_i}{V^2} \qquad (2)$$

This proportionality holds essentially over a Mach number range of $3.5 < M < 7.5$; V being the tangential velocity of the rocket which must be determined by accurately tracking the rocket. This is usually done with a Doppler velocity tracking system.

The above proportionality relating impact pressure to ambient density as well as the ability to measure ambient pressure directly at the side of the Pitot tube hold only in the region of continuous flow where the mean free path between molecule collisions is small compared to the dimensions of the sensor. At higher altitudes, in the free molecular flow region, where the mean free path becomes larger than the sensor dimensions, these methods break down. The transition between continuous and free molecular flow occurs near the upper boundary of the mesosphere at about 90 km. Above that altitude the above proportion is replaced by the following expression, which relates the ambient density ρ to the impact pressure P_i in the region of continuous flow:

$$\rho = \frac{P_i}{KV} \cos \alpha \qquad (3)$$

where α is the angle of attack of the rocket and K is a function of the temperature in the chamber and of the molecular mass. With present techniques this type of density measurement can be performed up to 120 km. Ambient pressure can only be measured directly in the continuous flow region (up to 90 km).

Complete profiles of density (ρ), pressure (P) and temperature temperature (T) can be derived from each one of the three experiments described above, although the primarily determined parameter is pressure in the Pitot tube experiment, density in the sphere experiment and temperature in the grenade experiment. The three parameters are related through two well known relationships which are derived from the equation of state and from the hydrostatic equation:

$$-\frac{dP}{dh} = P(h)\,\frac{Mg(h)}{RT(h)} = \rho g(h) \qquad (4)$$

where g is the acceleration of gravity; M is the molecular mass (usually assumed constant up to 90 km) and R is the universal gas constant. Because these three parameters are so interrelated the need for a comparative measurement between the three experiments is obvious. A nearly simultaneous experiment involving the grenade, Pitot tube and falling sphere techniques was conducted on 6 June 1962, and the results are discussed below.

A summary of these four, most successful techniques for the measurement of temperature, pressure, density and wind with an indication of their altitude ranges is given in Figure 7.

In comparison to the number of pressure, density, temperature and wind soundings the number of rocket flights measuring composition of the mesosphere has been very small. At higher altitudes, in the thermosphere, mass spectrometers have been successfully used. These measurements, however, are not readily applicable at lower altitudes. Below 100 km two types of composition measurement are of greatest interest: the determination of the gross molecular mass; and of the concentration of trace constituents such as ozone, water vapor, and atomic oxygen important to the radiative equilibrium of this region. Water vapor measurements with balloons already become very difficult in the upper troposphere and in the stratosphere and at this time cannot be carried out at higher altitudes. Ozone content has been measured in occasional rocket flights by observing the increase in the intensity of solar radiation in the near ultraviolet with altitude. Originally this involved elaborate spectrographs carried aboard Aerobee rockets where the films had to be recovered.[21] More recently attempts have been made to simplify this technique and adapting it to smaller rockets by measuring the absorption of sunlight by ozone in several narrow parts of the 2700-3300 Å regions sensing the light intensities with phototubes. The phototube signals are telemetered to the ground, thus eliminating recovery.[22] Ozone measurements in the upper stratosphere and mesosphere would be highly desirable during the polar night but, so far, all rocket-borne techniques are based on the absorption of sunlight. Research is presently directed toward the development of rocket-borne ozone sondes which are independent of sunlight.

A technique for measuring composition of the atmospheric constituents in the 70-90 km is the collection of air samples by means of evacuated steel bottles. The sealed bottles are carried to the desired altitude,

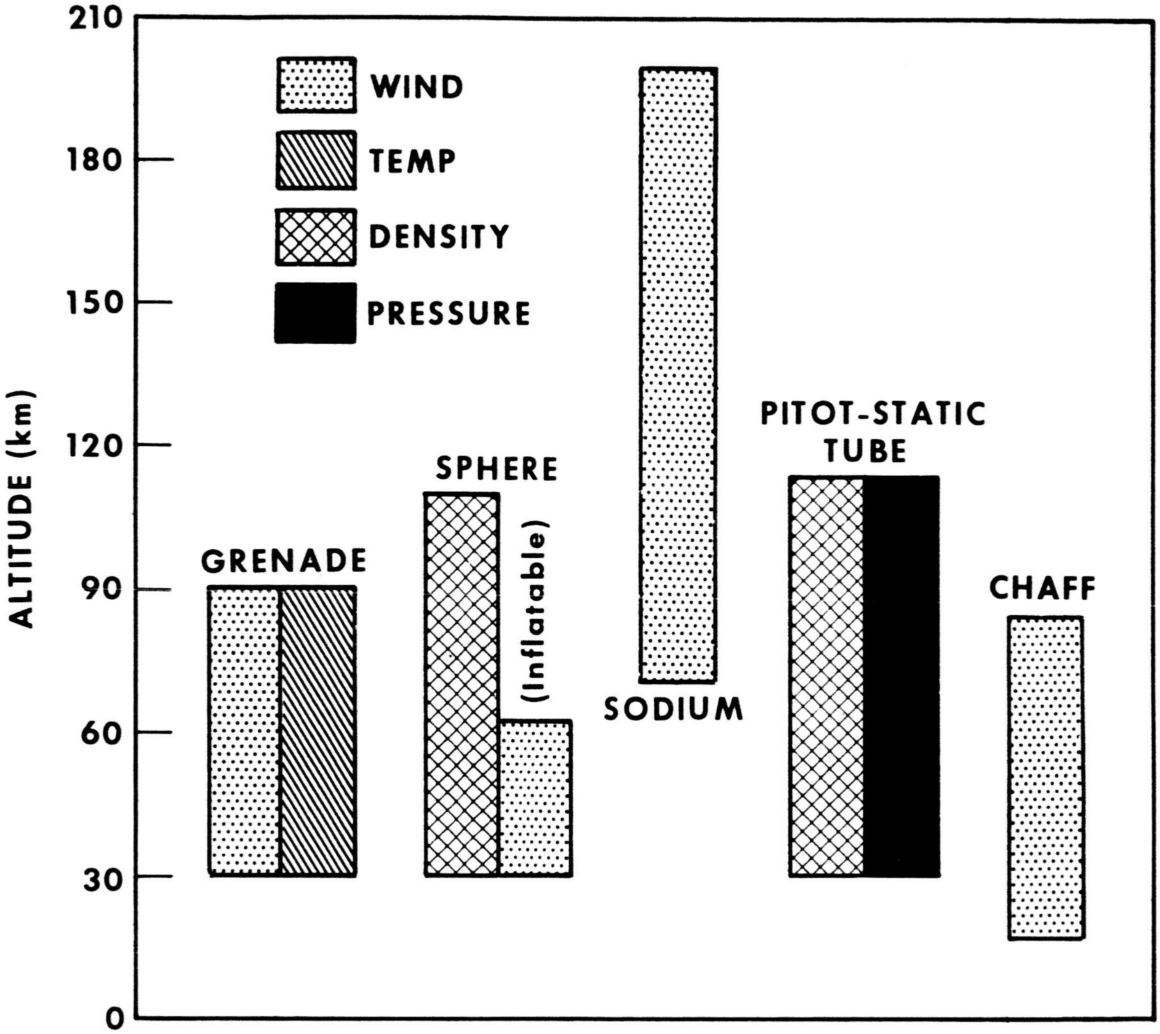

Figure 7. Theoretical altitude range of experiments measuring winds, temperature, pressure and density in the mesosphere.

opened for about five seconds, and then sealed again. About six successful samplings were carried out in the United States[23] during 1953-1956, and some in the Soviet Union[24]. After recovery of the bottles the contents were chemically analyzed. Only the inert gases were susceptible to analysis; thus the ratios of Helium, Neon and Argon to Nitrogen were determined. This measurement permits the determination of the altitude level above which the gross molecular mass begins to decrease due to gravitational separation of the lighter constituents from the heavier ones.

A different technique has been used recently to obtain samples of particulate matter from the 70-90 km region.[25] In this experiment, particles of sizes in the order of 0. 1 micron were collected, recovered and analyzed to determine the nature and composition of noctilucent clouds, one of the most outstanding mesospheric phenomena at high latitudes.

PRESENT ROCKET SOUNDING PROGRAMS

Being geophysical measurements, atmospheric soundings should ideally be conducted as worldwide programs at all geographical locations and seasons. A concerted effort during the International Geophysical Year (IGY) brought about the first measurements from which geographical variations of the structure of the mesosphere could be derived. In fact, the four methods mentioned above: Sodium Release, Grenade, Pitot static tube and Falling Sphere reached their stage of full development during that period and their success during the IGY is the reason why the measurements of pressure, density, temperature and winds in the 50-90 km region still evolves around these four techniques.

Much progress has been made since IGY in extending the geographical coverage of the soundings. The world map, (Figure 8), indicates the sites at which rocket soundings employing the techniques described above were conducted during recent years. Many of these soundings were internationally coordinated as a first attempt toward a synoptic program. It is hoped that a further realization of synoptic soundings, as well as an increase in the number of launching sites will be accomplished during the forthcoming International Quiet Sun Year. (IQSY)

In the United States, a program directed by the Goddard Space Flight Center of NASA has been in progress since 1959. This program is oriented toward the following objectives:

1. The exploration of the mesosphere during all seasons of the year over Wallops Island, Virginia, (38°N), a typical mid-latitude site.

2. A direct comparison of the four techniques described above and a mutal "calibration" of these techniques by means of simultaneous soundings. Such a comparison was accomplished on 6 June 1962, at Wallops Island, Virginia.

3. The observation of continuous wind profiles throughout the lower atmosphere by combining radiosonde balloons, "small" meteorological rocket sondes, grenade and sodium experiments. On four occasions during 1961-1963, this resulted in wind profiles from the ground up to above 150 km. The various circulation regimes in the various sections of the atmosphere were very well demonstrated in these experiments.

4. To conduct simultaneous soundings at mid-latitudes (Wallops Island, 38°N), in the subarctic (Churchill, Canada, 59°N) and in the tropical Atlantic (7°S). Simultaneous launchings at Churchill and Wallops Island started in December 1962 and it is hoped a tropical site can be added by late 1963.

The program started with two sodium soundings each in August and November 1959 and in May and December 1960 at Wallops Island. One successful grenade sounding was conducted in June 1960 at the same site. Between 1961 and 1963 a total of 22 successful grenade experiments were launched at Wallops Island and five at Churchill during December 1962, February and March 1963. In the same period, 16 sodium releases were made at Wallops Island, 13 of which simultaneous with grenade experiments.

During November 1962 an international series of sodium releases coordinated with various sites around the world (Figure 8) was conducted. On several other occasions coordinated sodium releases were made between Wallops Island and Italy and between Wallops Island, France and North Africa. One sphere experiment was conducted in 1961 and another simultaneously with grenade Pitot tube and sodium experiments at Wallops Island on 6 June 1962. On 1 December 1962, a simultaneous Pitot tube and grenade experiment was successfully launched at Wallops Island. Four grenade experiments were conducted during July and August 1963 in northern Sweden, two of them during the display of noctilucent clouds. These four experiments were carried out through the cooperation of the Swedish Space Committee and the NASA.

A summary of all firings at Wallops Island and their range of data recovery is shown in Figure 9.

RESULTS OF RECENT ROCKET SOUNDINGS

The following features of the mesosphere had been derived as a result of earlier sounding programs during IGY:

1. A large variation of the temperature profile in the 60-90 km region between high and low latitudes or between summer and winter at Churchill with large and multiple temperature maxima in the winter mesosphere at Churchill.

2. The existence of an extremely strong cyclonic circulation up to 80 km over the entire winter hemisphere, which extends, though greatly diminished, into the equatorial zone. This vortex is replaced by anti-cyclonic circulation of lesser intensity for the summer hemisphere, again reaching far into the tropics.

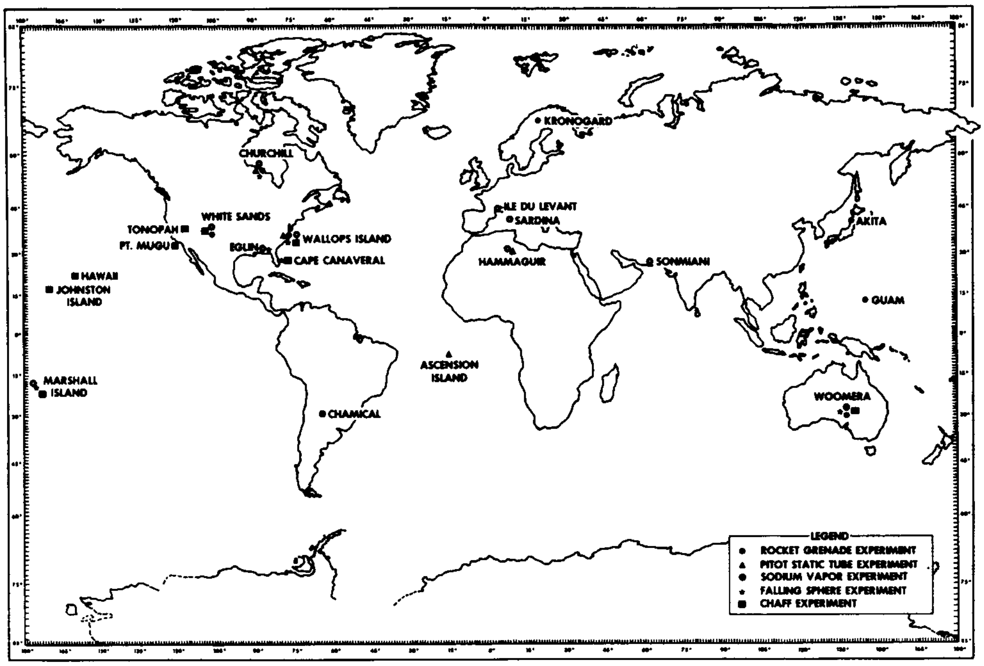

Figure 8. Map of locations from which rocket soundings in the mesosphere have been conducted during and since IGY. The type of experiment performed is indicated at each station.

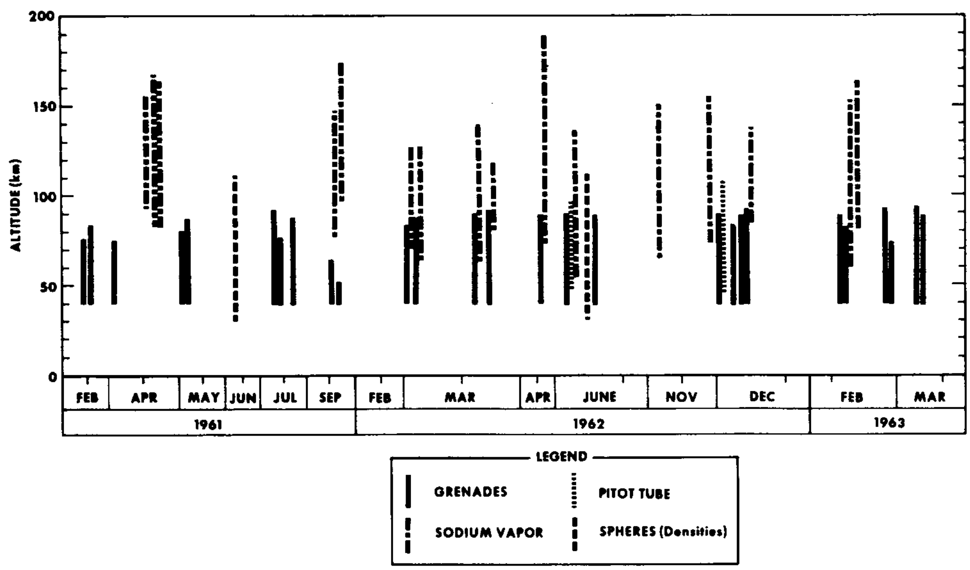

Figure 9. Summary of mesosphere rocket soundings performed at Wallops Island, 1961 through 1963, showing time of launching, type of experiment and approximate range of actual data recovery for each sounding.

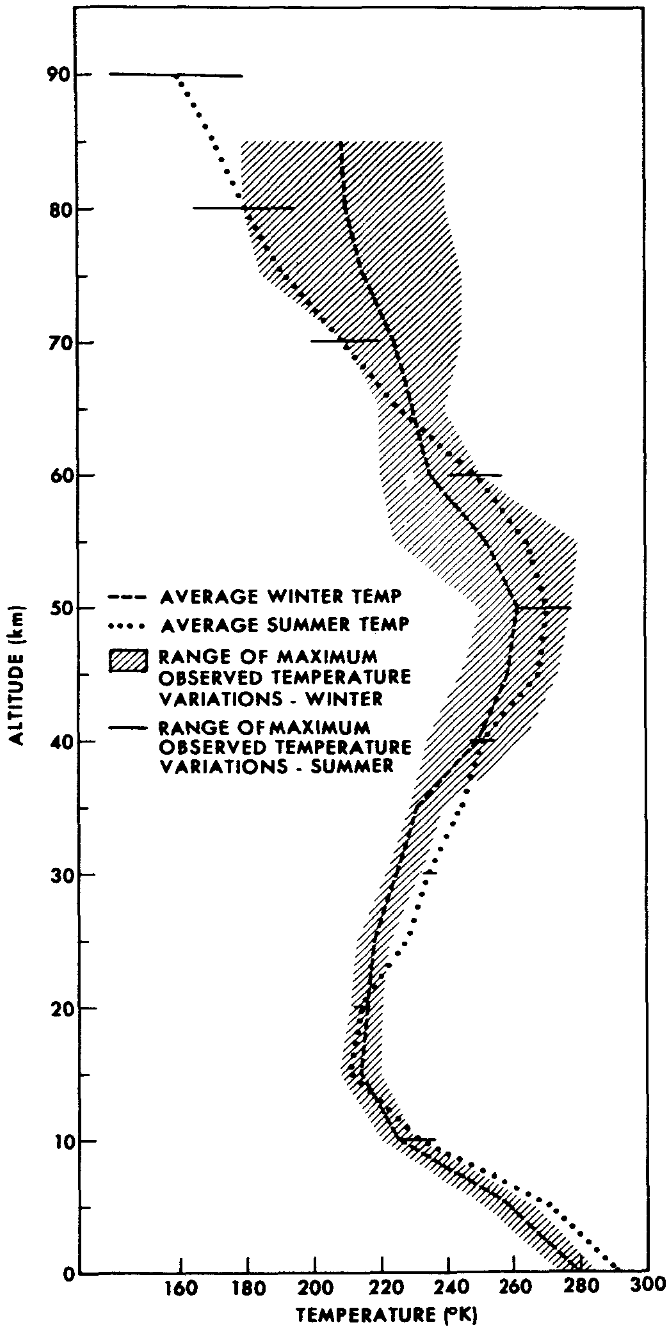

Figure 10. Average profiles of temperature versus altitude for winter and summer over Wallops Island, Va., (38°N). Summer average was obtained from 5 soundings 1961 through 1963, and Winter average from 9 soundings 1961 through 1963. Maximum variation in temperature between soundings is indicated by shading for winter and by horizontal bars for summer soundings.

3. A breakdown of the wintertime circulation up to 70 km at Churchill where meridional circulation in the stratosphere and mesosphere preceded the occurrence of a typical explosive warming at lower levels.

4. A systematic seasonal variation of pressure, temperature, and density at high latitudes where variations by a factor of two in density were observed between summer and winter at 60 km.

Results from the recent soundings confirm the behavior of the temperature and wind structure previously derived from only 10 soundings at Churchill during IGY[1],[2]. This picture holds generally also for a typical mid-latitude site such as Wallops Island, (38°N). Average temperatures for summer and winter over Wallops Island and their variability from day to day are shown in Figure 10. The averages were derived from five soundings in June 1962 and July 1960 and 1961, and from nine soundings in December 1962, February 1961 and 1963 and March 1962 and 1963. Although the temperature difference between winter and summer above 60 km is not as large as previously observed at Churchill, the temperatures at

38°N are still considerably higher during the winter months than during summer. The temperature variations between individual soundings are also much larger in winter than in summer. The maximum variation at 70 km during summer covers a range of about 23°K, while in winter the variation at the same altitude amounts to 39°K. At about 60 to 65 km summer and winter temperatures coincide; this has also been observed at Churchill during IGY. At the 50 km level summer average temperatures at Wallops Island are about 15°K higher than winter temperatures. Individual temperature and wind profiles for the Wallops Island soundings up to June 1962 have been published previously.(26) Results from four soundings in April and May indicate that temperatures during these transition months fall between the summer and winter profiles above 65 km but, that in the upper stratosphere, at the 50 km level and below, springtime temperatures are usually about 10° higher than summer temperatures.

These temperature variations have a profound influence on the seasonal variations of density with altitude. Figures 11 and 12 show

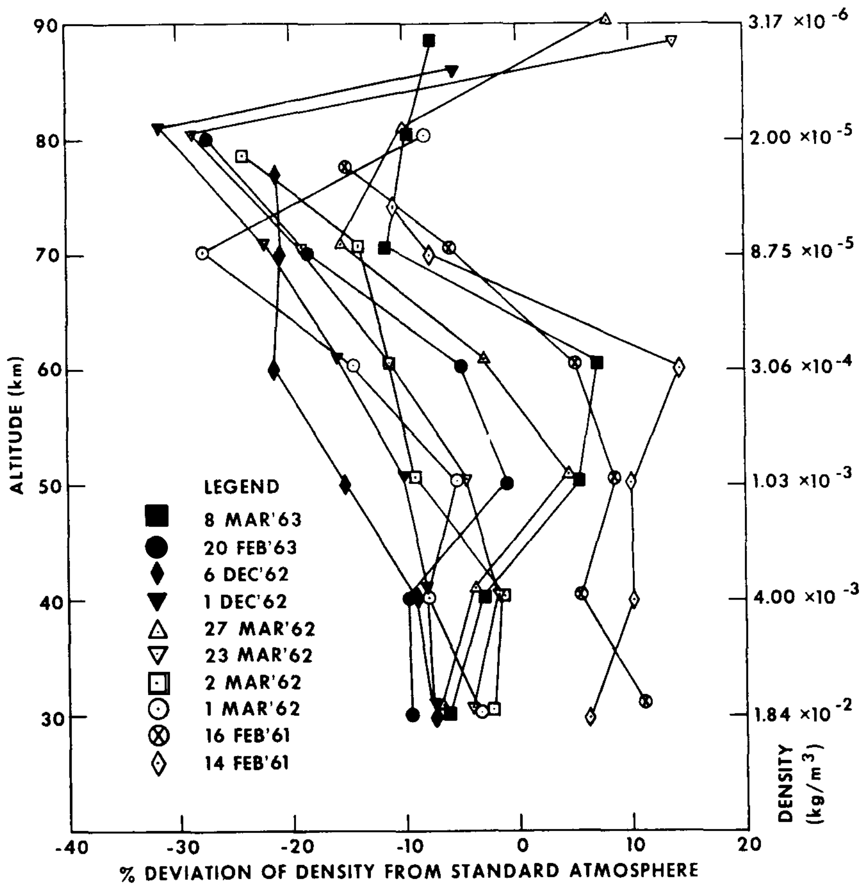

Figure 11. Winter densities as a function of altitude derived from individual temperature soundings obtained with the rocket grenade experiment over Wallops Island, Va. (38°N). Densities are shown as percent deviation from 1962 U. S. Standard Atmosphere.(27)

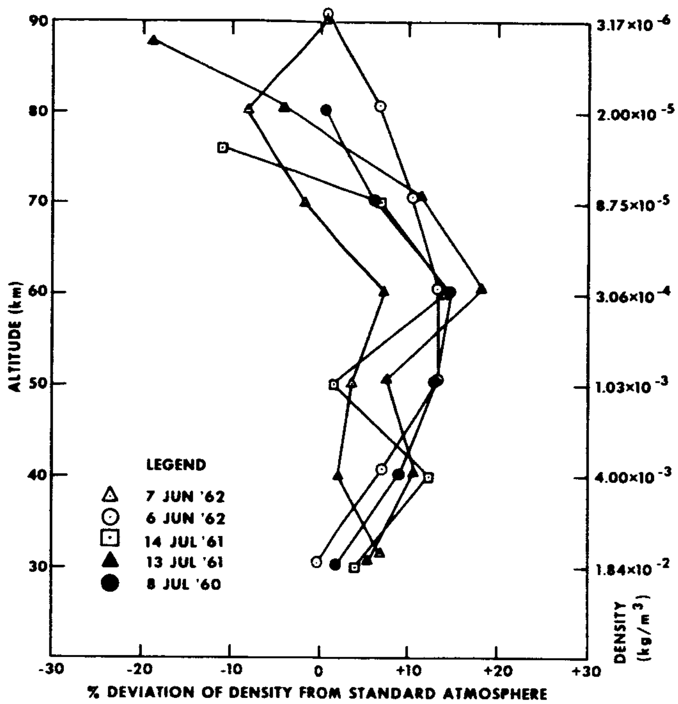

Figure 12. Summer densities as a function of altitude derived from individual temperature soundings obtained with the rocket grenade experiment over Wallops Island, Va. (38°N). Densities are shown as percent deviation from 1962 U. S. Standard Atmosphere.(27)

deviations of observed densities from the 1962 United States Standard Atmosphere(27) for each individual sounding as a function of altitude. The magnitude of this density variation at Wallops Island is not as large as previously observed at Churchill(28), but winter densities throughout the 30-80 km region are still appreciably lower than summer densities. Maximum seasonal variation occurs between 60-80 km where winter densities are lower than summer densities by an average ratio of about 0.8. During IGY at Churchill, this ratio was about 0.5. Supplements to the United States Standard Atmosphere are now in preparation to reflect these seasonal and latitudinal changes.(29) It is interesting to note that the two profiles for February 1961 are closer to a summer than winter condition. This is attributed to a very warm stratosphere which prevailed at that time at altitudes below 40 km. These high temperatures, at lower levels, cause the higher densities throughout the mesosphere.

The wind field again shows the same features as those found in IGY, namely easterly flow in summer and westerly in winter with strong meridional flow during the transitions in February and March. However, an additional feature stands out from the Wallops Island results.

(Figures 13 and 14). This feature, described as follows, is also obvious from the comparison between grenade and sodium winds in the 60-90 km region which can be made from Figure 15.

A sharp and remarkable boundary seems to separate the circulation below 80 km from the circulation in the regions where ionization of the atmosphere and dissosiation of oxygen sets in. This boundary lies near 80 km and seems to suggest that the physical causes which sustain the motions of the atmosphere are quite different in the two regions. As described above, the winds below 80 km conform to the pattern of uniform zonal flow, regularly reversing with season, interrupted only by occasional breakdowns during the spring transition. Above this altitude, however, the flow is no longer uniform and exhibits no regular seasonal pattern. Some features are common, nevertheless, to most of the wind profiles taken above 80 km; namely, the strong, but highly variable winds sandwiched between zones of relative calm resulting in extreme wind shears. Thus far, every sounding conducted has shown these wind shears between 90 and 110 km. Above 120 km greater uniformity seems to return but samples at these altitudes are too few to derive any definite circulation patterns.

A most interesting and important result of the sounding program at Wallops Island has been the direct comparison of various experiments at various altitude regions. We had previously reported[26] the rather discouraging disagreement between temperatures measured directly by the thermistor method, used in the small meterorological rockets, and by the grenade method at the 50 km level. From recent results (Figure 16, December 1962), it seems that this discrepancy has been greatly reduced and in the February and March 1963 comparisons (Figure 17) has all but disappeared. This is attributed to a substantial improvement in the thermistor temperature sensor which is now flown in the HASP rocket at Wallops Island.

A comparison of wind measurements between the grenade method and the various methods used with small meteorological rockets in the 40 to 60 km region, in most cases, shows very good agreement.

Comparisons between the grenade technique which yields average winds in layers of a few kilometers thickness and the sodium experiment yielding a continuous wind profile with altitude show that there is fair agreement in many but not all cases where the flow pattern is still uniform (below 80 km) and where the violent wind shears usually observed at the higher altitudes do not exist. In the shear regions the agreement is generally very poor, obviously because the average winds obtained by the grenade method are not comparable to the rapidly changing instantaneous wind vectors determined by the sodium trails. (Figure 15)

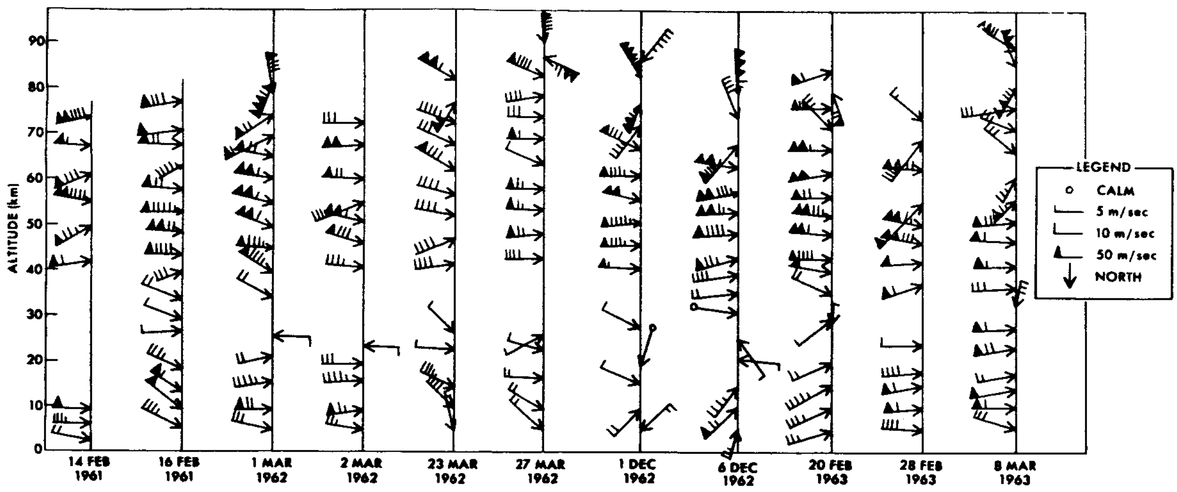

Figure 13. Winter measurements of wind speed and direction versus altitude as measured by the grenade experiment over Wallops Island, Va., (38°N).

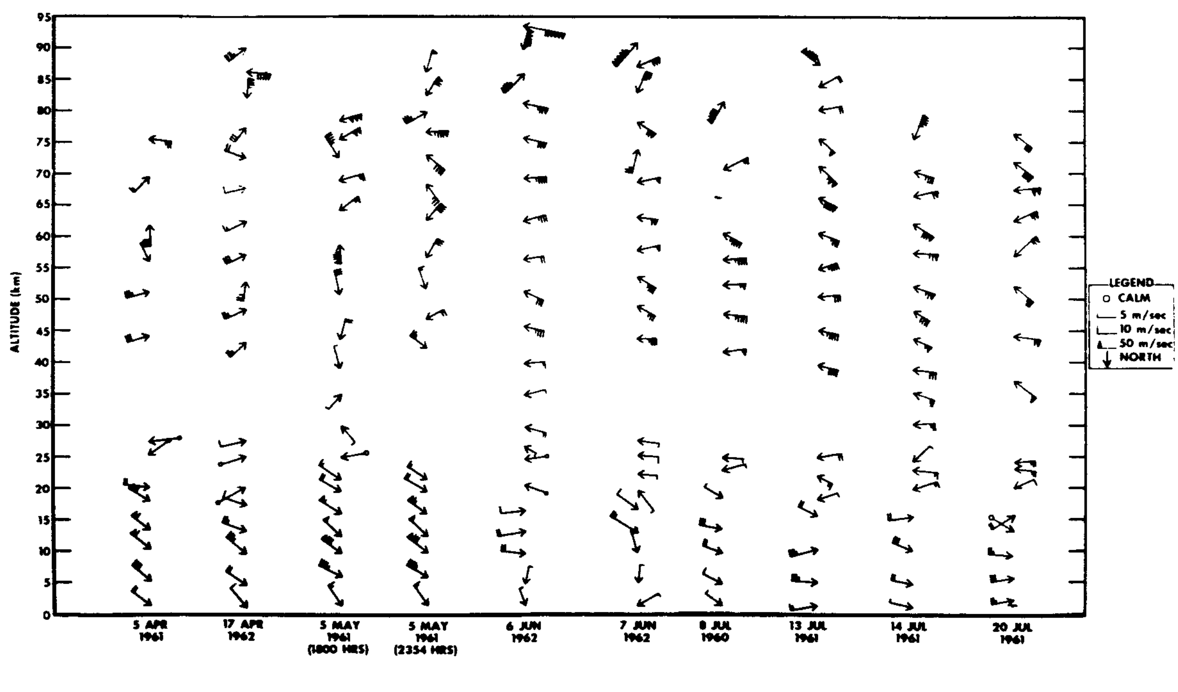

Figure 14. Summer measurements of wind speeds and direction versus altitude as measured by the grenade experiment over Wallops Island, Va. (38°N).

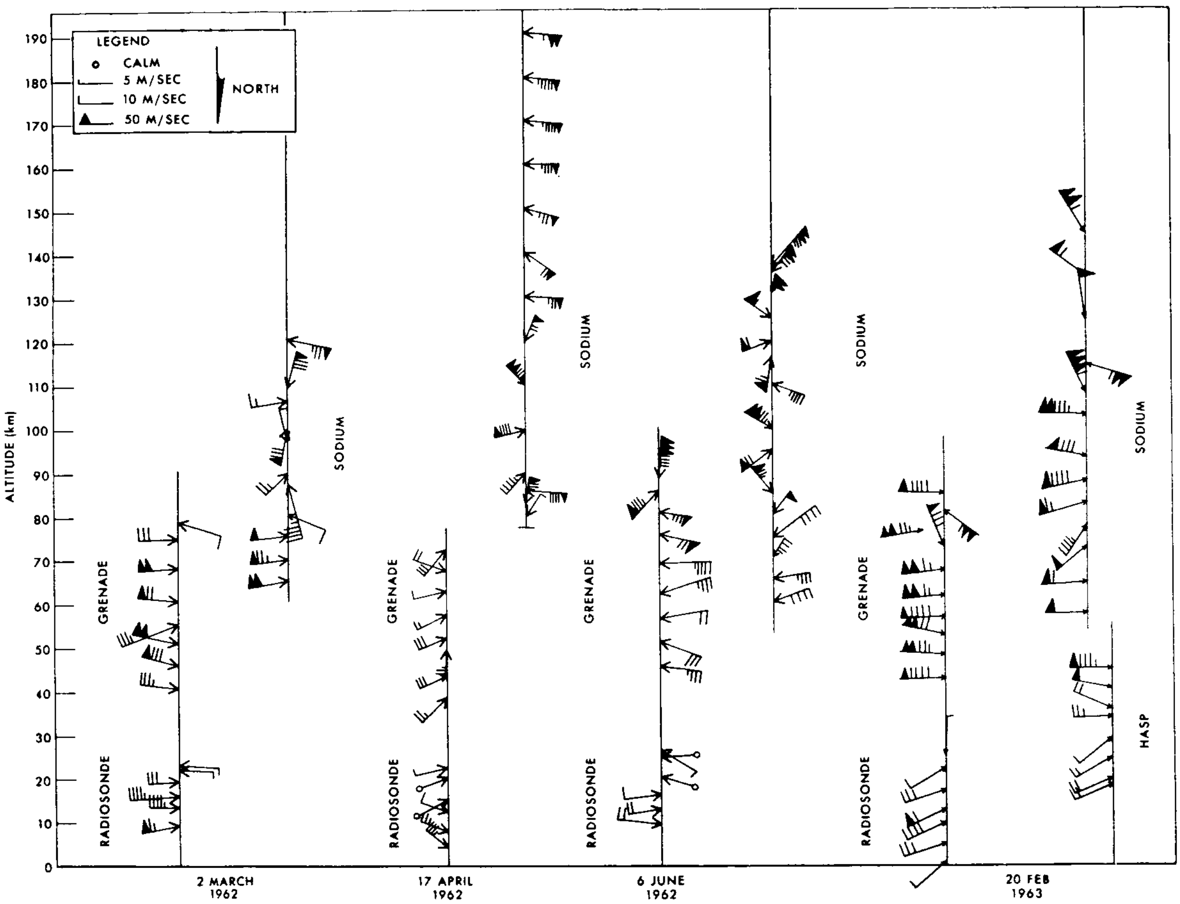

Figure 15. Wind speed and direction versus altitude as obtained nearly simultaneously with balloon-radiosonde, grenade and sodium techniques over Wallops Island, Va. (38°N) on 2 March, 17 April and 6 June 1962, and with balloon radio-sonde, grenade, sodium and meteorological rocket-sonde(HASP) techniques on 20 February 1963.

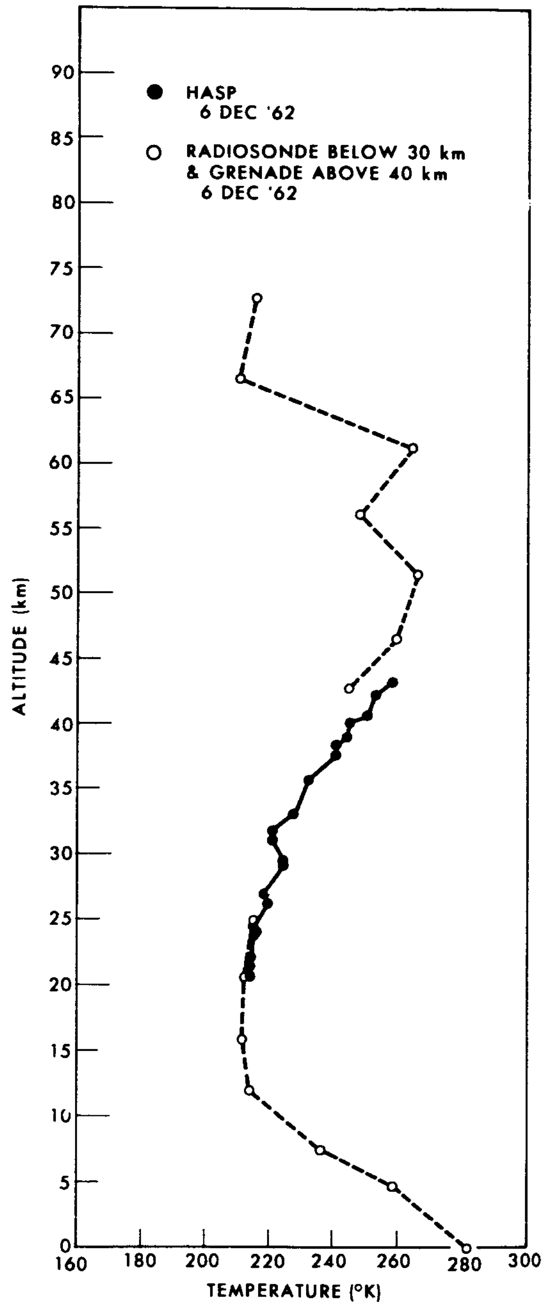

Figure 16. Comparisons of nearly simultaneous temperature measurements obtained with grenade, meteorological rocketsonde (HASP), and radiosonde techniques over Wallops Island on 6 December 1662.

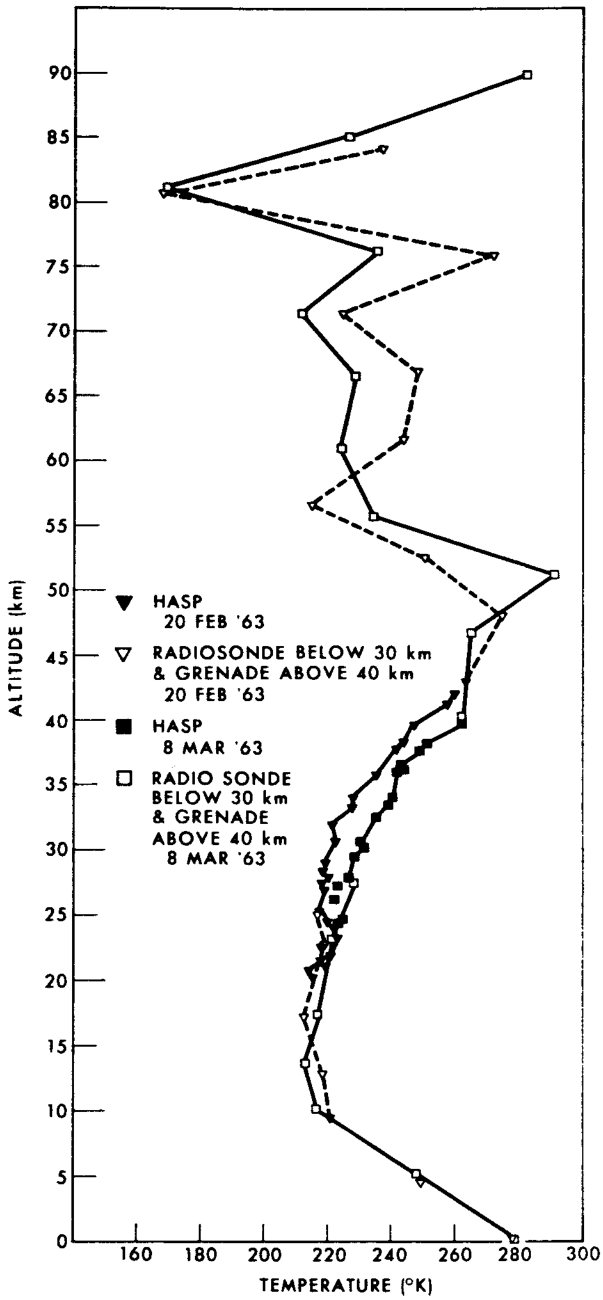

Figure 17. Comparisons of nearly simultaneous temperature measurements obtained with grenade, meteorological rocketsondes (HASP), and radiosonde techniques over Wallops Island on 20 February 1963 and 8 March 1963.

A most interesting comparison was conducted between the sphere, grenade and Pitot tube experiments on 6 June 1962. A passive, inflatable falling sphere was carried on the same rocket as the grenade experiment[14] and a Pitot tube experiment was conducted within less than 1/2 hour. Density profiles resulting from each of the three techniques are shown in Figure 18.*

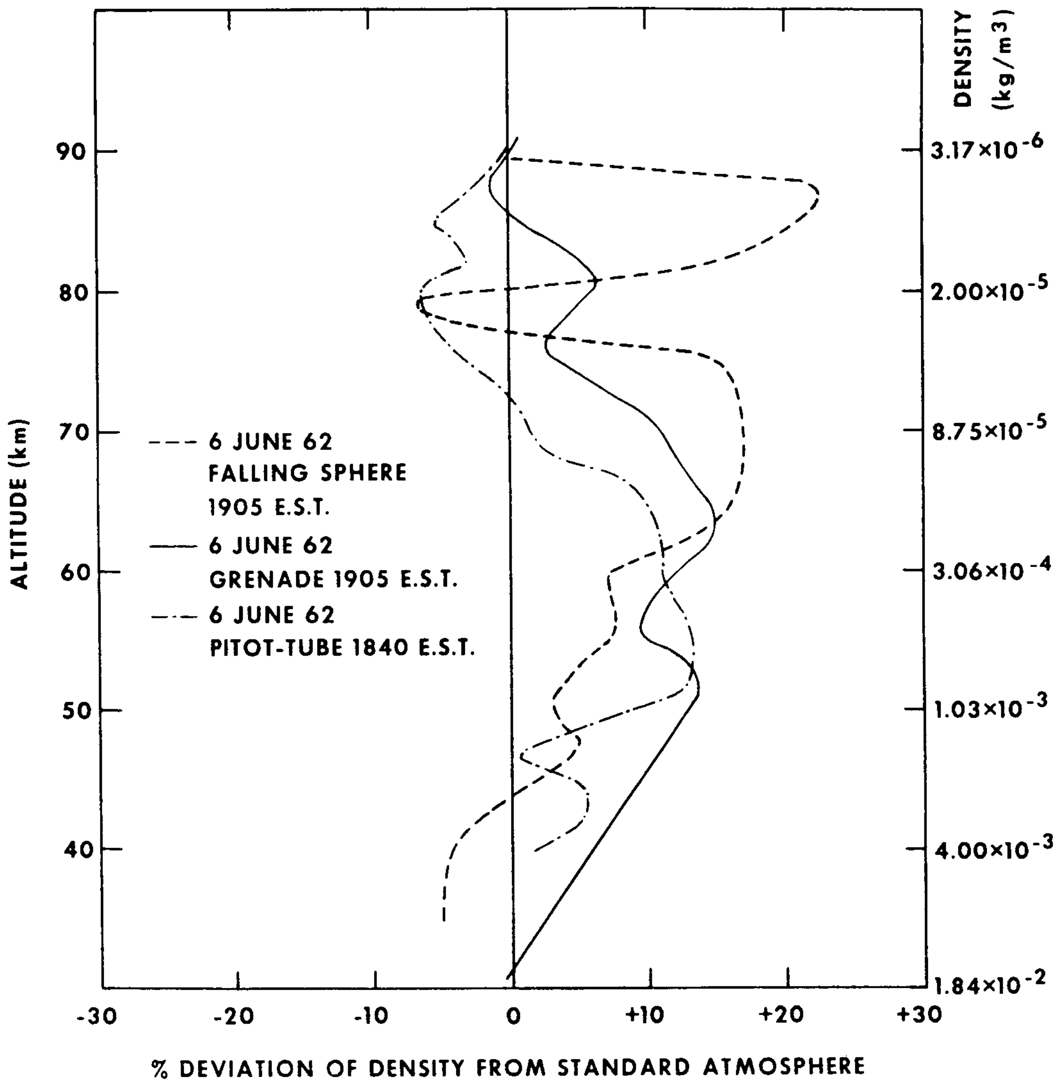

Figure 18. Comparison of densities obtained nearly simultaneously with the falling sphere, rocket grenade and Pitot tube techniques on 6 June 1962, over Wallops Island, Va. (38°N). Densities are shown as deviations from 1962 U. S. Standard Atmosphere.[27]

* The Pitot static tube experiment was conducted by J. J. Horvath, the falling sphere experiment by J. W. Peterson, both of the University of Michigan, Ann Arbor, Michigan. The grenade experiment was performed by Wendell S. Smith of NASA/Goddard Space Flight Center, Greenbelt, Maryland. The kind permission of these researchers to use their data for this comparison is gratefully acknowledged.

From 30-65 km and at 90 km the agreement between the Pitot tube and grenade techniques is quite good (better than 5 percent); this can be considered within the measurement errors of the two experiments. Between 65 and 85 km, the disagreement is considerably larger: 9 percent at 70 km and 13 percent at 80 km. The grenade and sphere methods are in fair agreement up to 75 km. Discrepancies there are less than 10 percent. From 65 to 75 km, grenade densities are about 5 percent lower than falling sphere densities and about 5 to 10 percent higher than Pitot-tube densities. Below 60 km falling sphere densities are generally lower than Pitot tube and grenade densities. Over the entire altitude range, the Pitot tube densities are always lower than the grenade densities indicating the possibility of a systematic error.

The largest discrepancies between falling sphere and grenade data (and Pitot tube) occur near 85 km while at 90 km results from all three methods agree remarkably well.

It is possible that the fluctuation in the falling sphere data between 65 and 75 km could be explained by the fact that the sphere passes through the transsonic velocity regime at this altitude range where the drag coefficient (C_D) changes rapidly. In fact, the Mach numbers given for the sphere by Peterson[14] range from 1.46 at 75 km to 0.63 at 65 km and at 72 km M = 1.

Since the passive, inflatable sphere is a relatively recent development difficulties such as those mentioned on page 16 have not yet been fully evaluated. The conclusions which can be drawn from this comparison must therefore be considered highly preliminary.

A similar comparison was conducted between grenades and Pitot tube on 1 December 1962. Preliminary results indicate that the agreement is not as good as on 6 June 1962, but no final conclusions can be drawn until the data analysis is complete.

Finally, we were able to compare results from four simultaneous grenade soundings at Churchill and Wallops Island in December 1962 and February and March 1963. All four temperature profiles exhibit the same feature; one typical pair of soundings for 8 March 1963 is shown in Figure 19. At 90 km temperatures at the two sites nearly coincide. Temperatures at Churchill are higher by 10 to 20°K between 55 and 80 km. Around 55 km temperatures are the same at the two locations and below 55 km, Wallops temperatures are appreciably higher (10 - 20°K). It is assumed that this condition holds throughout the stratosphere although no meteorological rocket (thermistor) data exist for comparison at Churchill and stratospheric temperatures there must be inferred from interpolating between the balloon radiosondes at 20 km and the grenade data at 40 km.

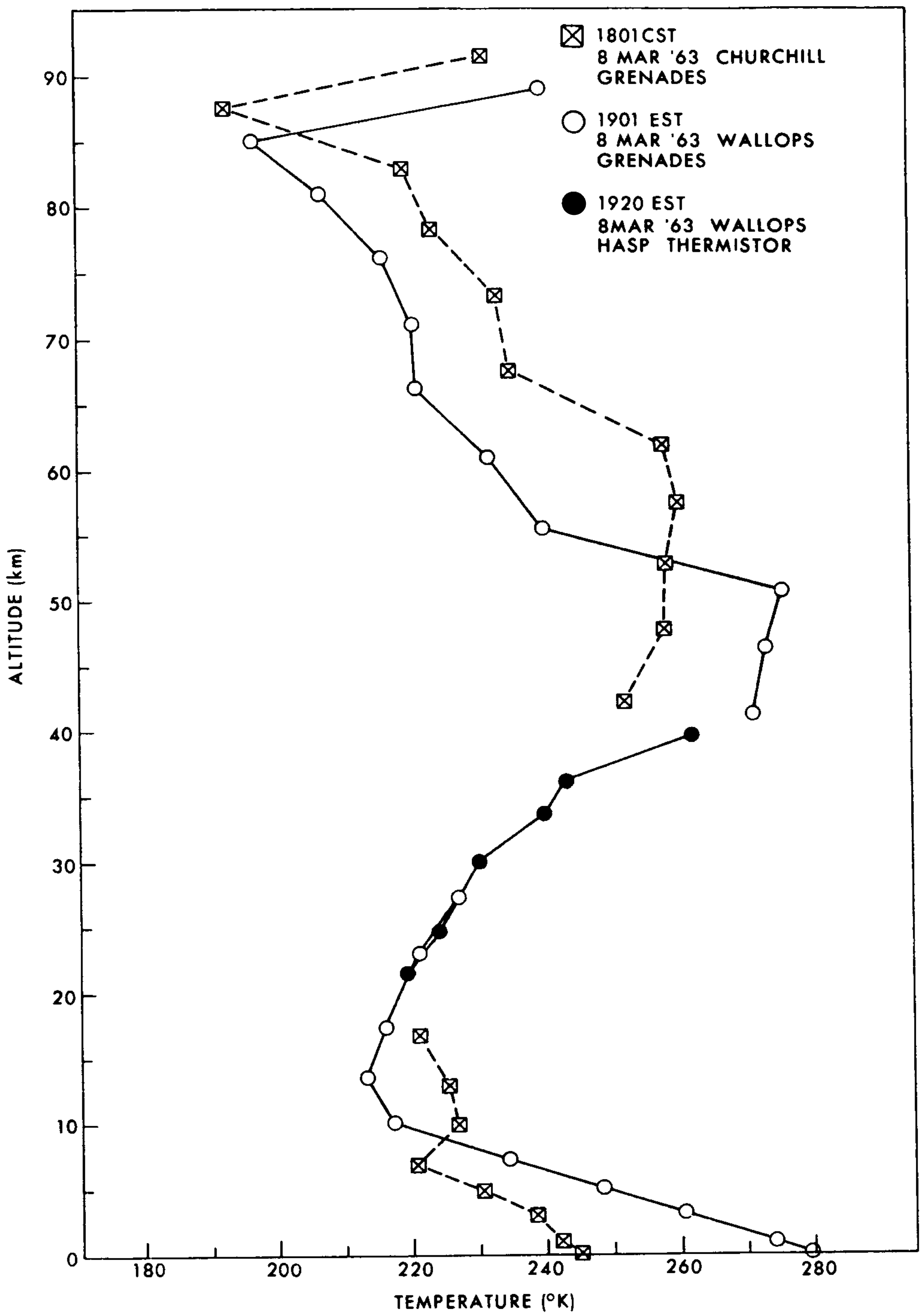

Figure 19. Temperatures as a function of altitude as obtained by nearly simultaneous rocket regnade soundings over Wallops Island, Va. (38°N) and Churchill, Canada (59°N). Radiosonde temperatures at both sites and meteorological rocketsonde temperatures (HASP) for Wallops Island are also shown.

There is, however a strong variation from day to day in the temperature profiles at each site that the above observation can only be made on individual pairs of simultaneously obtained profiles and does not hold for profiles averaged over several soundings. In general one may conclude that the temperature profile between the ground and 90 km becomes more and more isothermal as one progresses from the tropics toward the winter pole.

OUTSTANDING PROBLEMS

The basic techniques used during IGY are still adequate for the measurement of temperature, density, pressure and wind. Because of their long history, their reliability is very high. However, the absolute accuracy of the measurements must be further tested and possibly improved through comparative "calibrations" of the various methods. Depending on the available facilities one or more of these techniques may be appropriately adopted to launching sites throughout the world. By far the greatest task is to increase the geographic coverage with these soundings by soliciting the cooperation of more individual launch sites all over the globe. For instance, lack of adequate launch facilities has made it impossible as yet to obtain structure measurements in the mesosphere during the polar night, which is of foremost importance in answering the question of heating in the mesosphere.

With respect to the physics of the mesosphere, the cause of the high temperatures and their great variability above 60 km during wintertime remains one of the biggest outstanding questions. The entire question of energy exchange between radiation and the potential energy stored in the atmosphere and between potential and kinetic energy should be investigated and more data both at more locations and at more frequent intervals are needed for that purpose.

More synoptic soundings throughout the atmosphere will also enable us to determine the interaction between various circulation regimes in the atmosphere and may possibly lead to a mechanism for the downward propagation of solar-terrestrial relationships.

It is imperative that the technology of composition measurements be improved. A technique must be found which permits the reliable measurement of ozone and atomic oxygen throughout the mesosphere even in the absence of solar illumination.

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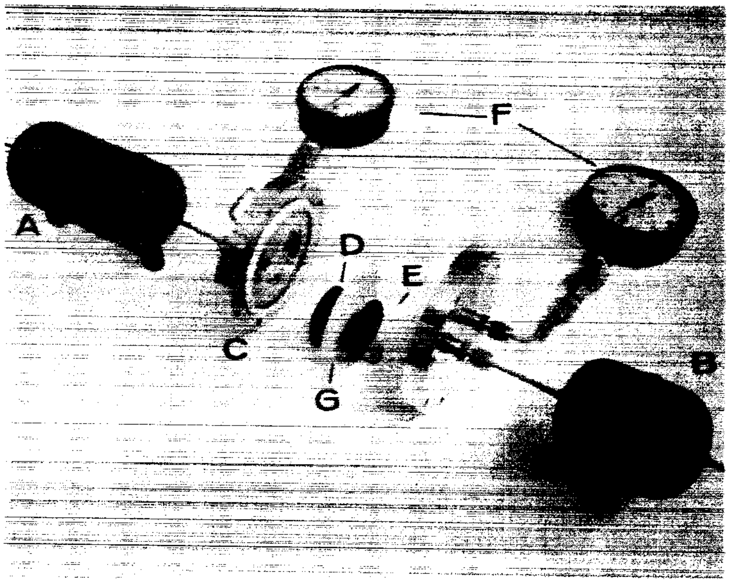

FIG 3

COMPONENTS OF CELL B

A. Hydrogen container
B. Oxygen container
C. Cell frame with "O" ring
D. Hydrogen electrode
E. Oxygen electrode
F. Pressure gages
G. Asbestos bed

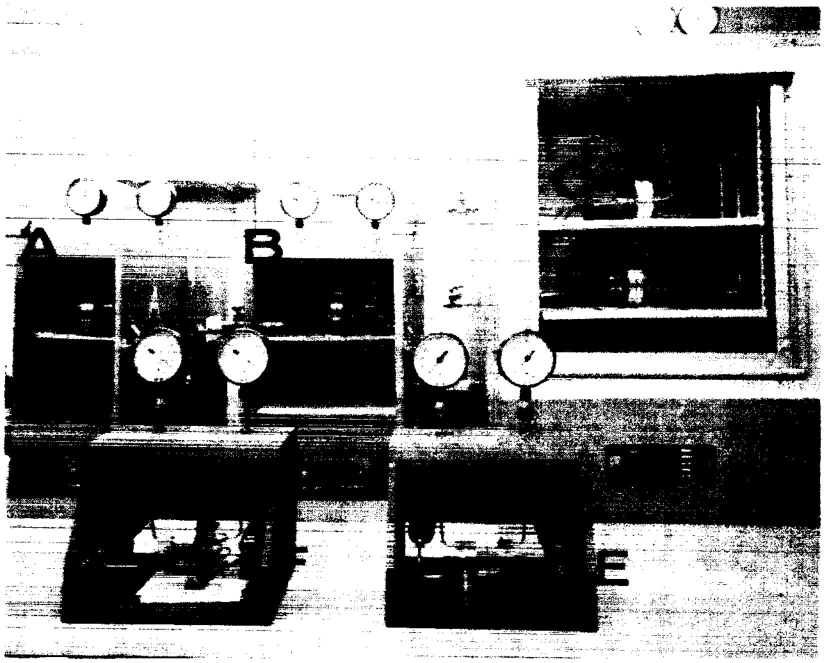

FIG 4

SIX CELL ASSEMBLIES

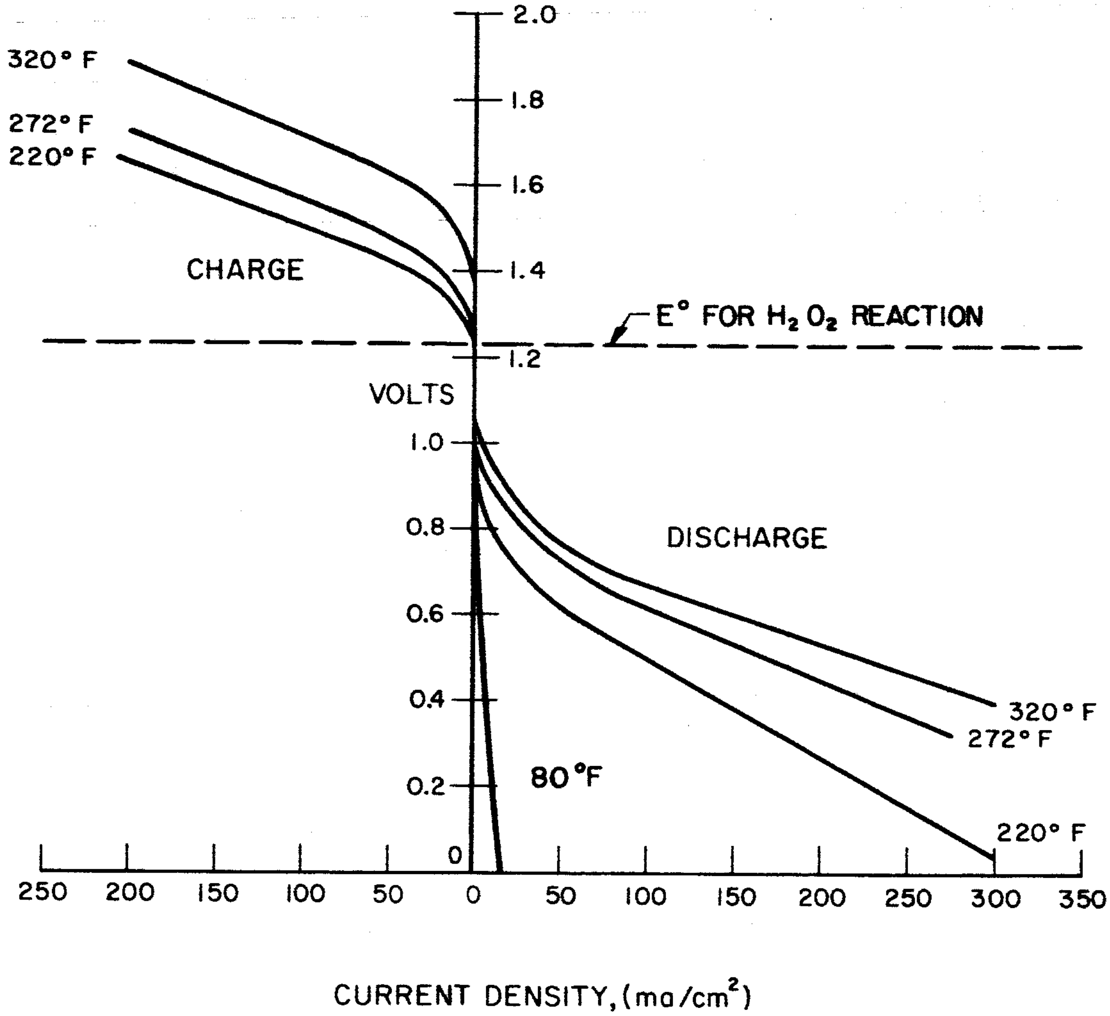

FIG 9 VOLTAGE-CURRENT CURVES OF CELL A