A SUMMARY OF AFCRL PASSIVE-SPHERE DEVELOPMENT EFFORTS AND EXPERIENCE

By John B. Wright

Air Force Cambridge Research Laboratories

SUMMARY

A passive falling sphere, ROBIN, has been developed by the Air Force for atmospheric soundings between 100 and 30 km. The rocket vehicles and simple sphere have been developed to permit a relatively low cost per sounding. The radar space - time data are reduced to meteorological parameters in a digital computer thereby providing nearly real time information.

The sphere is a superpressure balloon fabricated from thin plastic (Mylar) and inflated by vaporization of isopentane. Certain problems in sphere hardware reliability have been solved while others remain. Collapse of the spherical balloon 5 - 15 km above the design altitude of 30 km persists. In order to calculate atmospheric density (temperature and pressure), a precise knowledge of the drag coefficient of a sphere over a wide range of flow conditions is required. The wind tunnel measurements currently being used with this system have areas that produce atmospheric data that either do not compare well with other sensors or have peculiar excursions.

With further attention to these problem areas, the ROBIN has the capability of providing the most economical synoptic soundings of all candidate systems except perhaps indirect sensing techniques which are in their infancy.

INTRODUCTION

Early concepts on the use of a rocket-launched, ground-tracked, passive falling sphere (refs. 1, 2, and 3) led to an active development program by the Air Force Cambridge Research Laboratories starting in the late 1950's. The Vertical Sounding Techniques Branch of the Aerospace Instrumentation Laboratory has the responsibility of developing systems to be used for routine synoptic measurements of atmospheric parameters above-ground levels by the meteorological services of the Air Force. In addition to the usual requirements of any measuring system, the concept of operational use adds the additional requirements of ease in field operations and data reduction as well as minimized cost and production adaptability. The small inflatable spherical balloon is in itself a low-cost item and because of its light weight and collapsibility can be carried aloft in a minimum cost and easily launched vehicle. Balanced against the low expendable costs is the need for a high precision radar and a sizeable digital computer such as the 7090.

For simplicity, the AFCRL passive falling-sphere system (fig. 1) has been given the name of ROBIN, denoting ROcket Balloon INstrument. This report is intended to present a broad picture of the history of ROBIN, describe the various vehicle systems, indicate problem areas, and provide references for further study. It would be impossible to present in a single report all of the detailed efforts, but other papers to be presented at this symposium by several of the Air Force ROBIN associates and contractors will cover, in more depth, various aspects of the total system.

SYMBOLS

D	drag force, newtons
m	mass, kilograms
a	acceleration, meters/second^2
ρ	atmospheric density, kilograms/meters^3
V	velocity, meters/second
C_D	drag coefficient, $D/.5\ \rho\ V^2 A$
A	cross-sectional area, meters^2
M	Mach Number
R	Reynolds Number
h	altitude, kilometers
V_B	volume of ROBIN balloon, meters^3
d	diameter of ROBIN balloon, meters

X, Y, Z	rectangular Cartesian coordinates, meters
Z_o	release altitude
$\dot{X}, \dot{Y}, \dot{Z}$	velocities, relative to origin of these coordinates meters/second
$\ddot{X}, \ddot{Y}, \ddot{Z}$	accelerations, relative to origin of these coordinates, meters/second^2
W_X, W_Y	wind components, meters/second
W_Z	component of local horizontal wind along the Z axis, meters/second
W_{EW}, W_{NS}	local horizontal wind components, meters/second
W	total wind, meters/second (converted to knots in computer output)
Φ	wind azimuth, degrees
g_s	gravity acceleration at earth surface, meters/second^2
r	local radius of earth, kilometers
P	atmospheric pressure, newtons/meter^2 (converted to millibars in computer output)
T	atmospheric temperature, degrees Kelvin
R^*	universal gas constant, 8.31432×10^3 Joules $(°K)^{-1}$ (kilogram - mol)$^{-1}$
M_o	molecular weight of air, kilograms (kilogram - mol)$^{-1}$

CONCEPTS

A falling body may be utilized for atmospheric density measurements provided there is full knowledge of its aerodynamic characteristics. A spherical shape has an advantage in that its principal aerodynamic force is drag (if no rotation occurs) and that it presents an equal area in all directions. A very simplified equation for a falling body is:

$$D = ma = 1/2 \; \rho V^2 C_D A \qquad (1)$$

In order to obtain the atmospheric density, all other terms must be known or measured. The acceleration may be obtained directly by means of a builtin accelerometer and the velocity integrated as is done with several systems to be described in other papers. In addition to its high instrument cost such a system is inherently heavy and therefore has a fast fall rate.

Another technique is to measure space - time positions of the falling sphere by means of a precision ground - based radar, differentiate this space history to obtain velocities, and then differentiate the velocity history to obtain accelerations. The ROBIN utilizes this technique. Because of its light weight - area ratio, it is also sensitive to the force created by the horizontal wind.

APPROACH

The program of developing an operational ROBIN was begun in 1958. Major areas in the effort that were broken out were the vehicle, the ROBIN sphere and its hardware, the drag coefficient and other aerodynamic considerations, and the data reduction technique.

Various contractors were utilized in these major areas of efforts as shown in Table 1. In the course of time different vehicles were utilized and certain problems appeared requiring continuing contractual efforts during the 1960's.

ELEMENTS OF THE ROBIN SYSTEM

Vehicles

When the ROBIN effort began, the ARCAS meteorological rocket development phase was just underway and appeared to be the logical vehicle for the falling sphere as an operational sounding system. Rocketsondes were being developed for the ARCAS but at that time the completion of a fully acceptable system had not occurred. Thus, the ROBIN was a parallel and alternate payload development for the ARCAS rocket.

The ARCAS (fig. 2) is an 11.5-cm-diameter end-burning solid-propellant rocket motor capable of attaining an altitude of 70 km. With the ROBIN payload, it has been standardized as Probe, Meteorological PWN-7A and can be procured through Ogden Air Materiel Area at Hill Air Force Base, Utah. The description of this system is given under the ROBIN section.

In 1962, an even older small rocket system, the LOKI - Dart (fig. 2) was being upgraded in performance and reliability by use of the JUDI motor. In a limited type of effort, experiments were made to incorporate the ROBIN in this flight vehicle (ref. 4). After determining the level of the temperature within the dart, which drag separates from the motor at a low altitude (1 km) and a high Mach Number (3 - 4), successful flights were performed in 1964. At that time the LOKI - Dart was not being developed fully as a rocketsonde system, so further work using this vehicle was dropped in the interest of economy obtained in a one - vehicle approach. Recent standardization of the LOKI - Dart (PWN-8B) rocketsonde system and its substitution for the ARCAS, however, would make this a more economical system at a savings of at least 50%. Both of the above systems attain an altitude of approximately 65 km when fired from sea level.

In the mid - 1960's, requirements for density and winds to 100 km and the standard use and acceptance of rocketsonde winds and temperature (density) data to 65 km dictated the obvious effort to develop a method to sound the atmosphere between 65 and 100 km. A Navy - Air Force in - house effort brought together the two - stage SIDEWINDER - ARCAS - ROBIN system which flew reasonably well after some shop modifications including the drilling of extra bolt holes in the fins of some live ARCAS motors. Two drawbacks of this system, inability to meet National Range Safety igniter requirements and too low an altitude (115 km) for ROBIN density measurements to begin at 100 km, caused a change over to the SPARROW - HV ARCAS. The Navy, at the Pacific Missile Range, had developed the system for their various payloads to attain altitudes of 170 km. The system was acceptable from a safety standpoint, and the HV ARCAS was sufficiently strengthened to be compatible with the higher loads imposed as a second stage. Thus, as indicated in figure 2 much of the ROBIN effort was keyed to the ARCAS or boosted ARCAS vehicles.

Knowing the advantages (low cost, less wind sensitivity, and less dispersion) of the LOKI - Dart over the ARCAS in the 65 km regime, in late 1967 the Air Force proceeded to fund the development of a 140 km dart vehicle (ref. 5). The VIPER - Dart - ROBIN (figs. 2 and 3) system evolved over the past two years and appears to be a most attractive vehicle. The projected production cost of $2500 (plus radar tracking aid if desired) is approximately 50% of the cost of a SPARROW - HV ARCAS system. Less dispersion of the dart occurs and less horizontal range is required because of the short burn time (3 seconds) and resulting high velocity at low altitudes preventing as much gravity turning as experienced by slow burning systems.

While the dart part of the system has these favorable ballistic characteristics, the booster (LOKI or VIPER) tends to "float" in an unstable manner immediately after burnout and dart separation. Thus, it becomes difficult to provide assured impact points which are, because of low-altitude separation, generally around the launch area. While the 2.7-kg empty LOKI motor might be acceptable at most ranges, the 19.5-kg empty VIPER was felt to be more hazardous. Accordingly, a post-burnout stable VIPER motor was developed by means of a drag cone or nozzle extension beyond the 6.5-in. diameter. The result is a cleaner dart separation condition and an increase in VIPER motor apogee from 5 km to 17 km. The higher apogee does result in more time in the air for wind drift effects, but for a 95% winter wind condition, all of which is assumed to be a head wind, the impact is theoretically further downrange than in the unstable case.

The high velocity of the dart at low altitudes requires protection of payload from aerodynamic heating. Unlike the ablative coating used on current LOKI - Dart systems, the dart on the VIPER system is designed to insulate the payload from the dart wall temperature by means of an air gap. The nearly finalized dart is shown in figure 3.

ROBIN Sphere and Hardware

The early work in the ROBIN efforts for use in the ARCAS rocket nosecone consisted of theoretical studies, chamber tests, radar reflectivity flights on balloons, and some flight tests. Consideration of sphere materials, fabrication techniques, minimized mass-area ratios, folding and packing techniques, reflectivity requirements, optimum inflation chemicals, techniques of chemical encapsulation and controlled delivery within the balloon, and methods of ejection from the rocket nosecone were some of the many aspects investigated. Early chamber tests indicated that a successful system had been evolved so that in late 1960 some 200 ARCAS ROBIN systems were fabricated for feasibility testing.

The ROBIN sphere (fig. 1) which was developed at this time and which, with a few exceptions, has been the configuration flown in various vehicles to the present time is one meter in diameter. It is fabricated from 1/2-mil clear mylar using 20 gores with butt joints and 1/2-in. heat-pressure sensitive mylar tape. Internally, a 6-point corner reflector fabricated from 1/4-mil metallized mylar is suspended from the balloon skin by means of lightweight springs. Its Government nomenclature is Balloon, Radar Target, Meteorological, ML-568/AM, and the design is covered by Specification MIL-B-27373A, the latest updating being 20 January 1965. (This specification covers the ARCAS configuration which differs from that used in the dart types only in the inflation capsule and packaging procedures.) A lightweight aluminum capsule within the balloon (fig. 4, lower) contains liquid isopentane. At ejection the cover is pushed off the capsule by a small mylar pillow expanding in the low pressure. Isopentane vaporization is controlled by two orifices in the capsule body to prevent explosive inflation found in chamber tests when the inflating chemical was not controlled. The capsule is free to move within the balloon. Packaging of this payload in the ARCAS nosecone includes several sheets of plastic. The first piece of plastic sheet placed forward in the nosecone cavity is rolled up with enough entrapped air to force the system out when the sealed nose cover is pulled by a one - meter long cable at apogee ejection. A 1 - 1/2 meter square plastic pillow ejects first and inflates to provide some protection from a "dirty" pyrotechnic separation charge, prevalent in early ARCAS, which ejected sparks for a brief interval as the nose cone was pushed off and its cover removed.

The aforementioned ARCAS-ROBINs were flown in 1961 - 1962 at Eglin Air Force Base, Holloman Air Force Base, and Wallops Island. It was eventually recognized, but not before standardization took place and additional quantities had been ordered for operational use, that the reliability of the ROBIN to inflate into a rigid sphere deteriorated as the time between fabrication and flight increased. In addition, collapse of the "good" balloon, which was designed for 30 mb pressure or approximately an altitude of 30 km, occurred at an average altitude of nearly 40 km. Many chamber tests indicated a 30-km collapse was possible but not consistently so.

Efforts to eliminate these problems continued in the mid - 60's (Table 1). Due to the need for higher altitude data, the efforts were directed toward the boosted ARCAS configurations. These latter nosecones, incidentally, require different ballasting than for the ARCAS alone due to aerodynamic stability changes at the higher Mach Numbers attained. These efforts were characterized by lack of continuity due to funding variations, vehicle problems, and contractual difficulties including a contractor who went out of business during a contract thereby losing a year in the process of officially transferring the contract to a successor.

It was felt that damage to the balloon by hot sparks in the separation event noticed in some chamber tests caused at least the early deflation problems. Therefore, some work was done on improving protection during the ejection sequence. A longer cable (5 to 20 meters), with and without a canister containing the balloon, was tested in chambers without significant improvements. In this period, the rocket separation charge was improved and post - explosive particles were minimized.

In addition to mechanical protection, the aforementioned canister as well as some reduced packing volume nosecones were tried in the belief that entrapped air in the balloon had a detrimental effect. Since mylar is microscopically porous, low density packing and long storage could allow gradual leakage of air into the balloon resulting in catastrophic inflation at altitude. In addition, a few empty capsules with no balloon inflation in some tests indicated that isopentane from a leaking capsule could enter the balloon and then leak out through the balloon skin.

The capsule for the ARCAS-ROBIN is perhaps its weakest element. The strip of neoprene under the cap aged to a sticky condition and, coupled with an easily deformable cap, caused capsule malfunction. A few experiments with other capsule ideas associated with other inflatants such as a glass vial were not attractive. An externally mounted bottle for helium injection followed by release after the filling sequence proved to be a larger and more sophisticated problem than anticipated or funded. Certain other inflatants with a few showing mixed improvements were utilized. Ammonia and ammonia water improved the superpressure characteristics over a larger altitude range. However, the complexity of encapsulating ammonia and its solvent effect on metallized mylar were negative factors.

Details on ARCAS - ROBIN theoretical studies and experiments on inflatants, capsules, packing, etc. may be found in final reports on the contracts indicated in Table 1. Some of these reports are in limited and unofficial supply. The net improvements on the original ARCAS configuration were small. Because the basic ARCAS technique does not provide a simple and positive way of controlling the capsule function and because a boosted dart vehicle appeared to offer various advantages, a few ROBIN configurations were designed and tested in 1963 utilizing the LOKI - Dart. At the end of the short program, several successful flights were made (ref. 4). In 1967, this design was incorporated into the VIPER - Dart with encouraging results (ref. 5).

The long cylindrical dart requires that the one - meter sphere be folded differently and more densely packed. Hence, entrapped air or inwardly leaking air is minimized. The payload is held in long half - cylinder staves within the dart body (fig. 3). The separation sequences consist of a pyrotechnic charge in the dart tail exerting pressure on a piston which pushes the staves and payload forward breaking shear pins in the nose ogive. As the staves exit the forward end of the dart, they are free to fall apart and allow the ROBIN payload to deploy. The motion of the piston is utilized for capsule activation, an additional bonus in the use of a dart system.

The dart capsule (fig. 4, Upper), longer and more slender than the ARCAS capsule, is positioned at the aft end of the dart with only one thickness of balloon material between it and the padded piston. A slide - fit cap on the end of the completely sealed capsule body contains a sharp "hypodermic" needle positioned so that first motion of the piston pushes the cap further on the body and punctures the end of the body. The cap is held on by friction from a piece of rubber and the isopentane flows out through the needle. This capsule, being a completely sealed metal body before activation, is less likely to have leakage or aging problems.

A corner reflector was used early in the general ROBIN development due to its high radar reflectivity ($\sim 25\ m^2$), thought necessary should a lesser tracking radar (e.g., SCR 584, Mod 2) be utilized. Subsequent analysis of ROBIN data obtained by these radars indicated unacceptable meteorological data accuracies. Since FPS-16 or more precise radars are available at most missile ranges and since it was found that metallized one-meter spheres can be tracked by these radars, the use of a corner reflector is not obligatory. It was retained in most of the AFCRL development flights (and Air Weather Service operational flights) however, for several reasons. The radar AGC display or recording shows a W-form of perturbation indicating a corner passage as the ROBIN slowly rotates. At collapse of the balloon and internal reflector, this signal characteristic drastically changes thus providing a simple method of determining the end point of atmospheric thermodynamic data. This method of locating the collapse altitude has correlated well with other methods that are mentioned under "Data Reduction".

An additional advantage of providing a stronger target for any tracking radar is to approach the optimum signal-to-noise ratio in order to attain the minimum target position errors.

Aerodynamic Drag

As indicated by equation (1) the drag coefficient of a falling sphere must be known in order to evaluate atmospheric density (or for some applications vice versa). The descending ROBIN, weighing 110 to 120 grams, falls from 130 - 140 km to 30 km over a wide range of flow conditions, including transitional, slip flow, and continuum flow (fig. 5). Because of error considerations, computations during part of the acceleration portion of the flight are not attempted. Hence, most of the useful part of the high-altitude flight is from a Mach Number of 3.0 downward and a Reynolds Number of 10^2 upward.

During the early development of the ARCAS - ROBIN, however, where the balloon fell from 65 km, only subsonic flow, principally in the continuum flow regime, is experienced. At that time, little information was available on subsonic compressibility effects on drag coefficients of a sphere at Reynolds Number of 5×10^2 to 10^4. Neither was it possible to find many test facilities capable of performing tests at these conditions. A small wind tunnel at the University of Minnesota, under the direction of Dr. Helmut G. Heinrich, was located and tests made (Table I) as a subcontract under one of the G. T. Schjeldahl hardware contracts. Instrumentation difficulties led to some repeated tests as well as extension of the range of tests into supersonic conditions when the higher altitude systems were begun. These again were made as a subcontractor under the Litton hardware contract (ref. 6) and reported in reference 7. The drag coefficients reported therein have been used in the "March 1965 ROBIN Computer Program" from that date through the present.

Figure 6 illustrates the range of vertical acceleration experienced by the falling sphere released at an altitude of 139 km. Indicated along the curve are the Mach and Reynolds Numbers experienced during flight. Other release altitudes will result in different acceleration levels at these Mach and Reynolds Numbers. Thus it is felt that drag coefficients obtained in static wind tunnel tests, particularly for the high Mach Number - low Reynolds Number conditions, do not represent the accelerated flow condition. Ballistic range data would be more representative if a range of acceleration conditions could be matched to the aerodynamic parameters.

There have been some recent tests made in a ballistic range at subsonic velocities at the Air Force Arnold Engineering Development Center for Sandia Corporation. These newer drag coefficients in the incompressible case ($M < 0.3$) agree better with classical experiments although even this statement seems to be somewhat in disagreement depending on exactly which reproduction of classic data is utilized. Figure 7, upper section, shows the drag coefficients as measured by Heinrich and used in the "March 1965 Program". These drag coefficients were derived from plots and cross plots of the experimental wind tunnel data which consisted of many duplicated test points. However, interpolation through a Mach 1.0 between test points at $M = 0.9$ and $M = 1.2$ required some subjective reasoning. Hence, this area is subject to greater uncertainties than other sections of the table. Figure 7, lower section, is a composite made up of the aforementioned subsonic ballistic range data and the Heinrich supersonic wind tunnel data. This experimental combination of drag coefficients has been used recently and shows in some cases improved agreement between ROBIN and rocketsonde densities at the 50-km level (see Meteorological Data).

Because proper sphere drag is a prime necessity in the system, it is felt that this parameter should be isolated and made the subject of a basic and major aerodynamic program. The Air Force Arnold Engineering Development Center recently indicated not only their capability of duplicating these aerodynamic flow conditions but their scientific interest in the problem and the availability of their personnel and facilities for these purposes.

An Air Force plan to fund AEDC in a substantial amount for a two year program beginning in FY70 was not approved. Several techniques and facilities would have been used with the hope of analyzing the whole problem and duplicating the correct flow conditions by different techniques.

Data Reduction

The tasks outlined at the beginning of the ROBIN effort in this category were simply stated as: given the radar space - time coordinate history of a falling sphere, determine (1) the technique of obtaining atmospheric wind, density, temperature, and pressure utilizing modern digital computers, (2) the errors associated with these parameters, and (3) the potential of using a graphical or desk type of reduction. The third task was quickly resolved as a solution capable of producing only gross numbers much to the disappointment of meteorological personnel.

The other two tasks, not independent of each other, have and are still requiring considerable time and effort. One aspect of the philosophy adopted in the data reduction area was to establish a computer program using equations, smoothing techniques, drag coefficients, formats, etc., which would represent the best knowledge and information at a given time and to leave it untouched. In this fashion, all ROBIN flights would be reduced in the same manner and subject to the same errors or uncertainties. When several reasons accumulated such as new smoothing intervals or drag coefficients, then a new program was introduced into the field.

Thus references 8 and 9 define the first field programs used until reference 10 introduced the "March 1965 ROBIN Computer Program". This program is in use today at most of the U.S. missile test ranges although a few minor details have been changed or added.

In general the development of the ROBIN computer program has required considerable effort in the classic task of eliminating "noise" from the raw data without removing real detail and conversely not introducing "noise" by inadvertent mathematical operations.

Without any discussion of the background and decisions leading up to the adoption of the current program, an abbreviated description of its operation will describe its highlights (ref. 11). The simple equation presented earlier in this paper is considerably amplified since (1) the sphere is moving in three - dimensional space with winds present, (2) buoyancy, apparent mass and a moving reference point on earth must be considered, and (3) there are "noise" and bias errors in the radar coordinates. In general, the raw radar data are smoothed in order to obtain sphere velocities and accelerations followed by the use of equations of motion, hydrostatic and gas law relationships to obtain the atmospheric parameters in the one - pass digital computer program.

Following sphere deployment, usually at apogee, the horizontal and vertical velocities are obtained first by the least squares fitting of straight lines to 31 one - half-second space points and assigning the slope as the velocity at the midpoint. The horizontal and vertical accelerations are determined by the least squares fitting of straight lines to 7 one-second velocity points and assigning the slope as the acceleration at the midpoint. Sufficient points are dropped and added to obtain velocities and accelerations every one second immediately preceeding the balance of computations described below. In addition the values of density and W_Z from the previously computed (higher altitude) point are brought in as first approximations.

Figure 8 is a simplified flow chart showing the meteorological parameter computations. W_X and W_Y are computed, then W_Z is computed,and a convergence check of W_Z is made. If a 1% convergence value is not obtained, the small loop indicated is traversed using the computed W_Z. When convergence is indicated, the value of V (the balloon velocity with respect to the air) is computed; then using the drag coefficient from the previous higher point as an approximation, the first calculation of density is made. The hydrostatic equation is then used to calculate pressure and the gas law to calculate temperature. Because Mach and Reynolds Numbers serve to define the aerodynamic flow conditions of the sphere and, hence, its drag coefficient, these numbers are calculated using the velocity, density, and temperature. A drag coefficient table is entered and a drag coefficient obtained. A check of density probably indicates no convergence with the previous higher altitude density and a loop back to the start of the chart is indicated. Calculated values, rather than previous point values, are used in progressing down the chart again and at the density step, the drag coefficient previously obtained from the table is used. When density convergence with the previous computed density is indicated, the final values of density, pressure, temperature, and wind parameters are printed out for this particular altitude. It should be noted that the balloon horizontal displacement per unit time, X or Y, is not taken to be the wind velocity as with most wind sensors in current use. Instead, the equations indicated are used wherein the terms after the minus signs represent the lag of the balloon in responding to wind changes.

Figure 9 is a flow chart similar to figure 8, but depicting the operations required at the first or highest altitude point where the main thermodynamic program commences. It can be seen that a temperature estimate is required which is carried through and printed in the output format for only this point. In addition, the pressure here is calculated by the use of the gas law. For missile launch sites such as Patrick Air Force Base, Eglin Air Force Base, and Point Mugu, the initial temperature guess is based on a 30°N latitude average summer - winter atmosphere (ref. 12). The program at present does not begin until acceleration reaches - g/3 in order that the magnitude of various terms is sufficient to prevent excessive errors. Hence, the ROBIN sphere must be ejected at an altitude well above the altitude at which measurements are desired. In the case of the VIPER - Dart - ROBIN, for example, a flight having a 128-km ejection altitude provided data from 91 km downward.

With the collapse of the balloon from a rigid spherical shape to a nondescript shape, the thermodynamic parameters may no longer be deduced, although the winds may be calculated by using somewhat simplified equations. The determination of ROBIN balloon collapse is made within the computer program by a "lambda check" in which parameters of balloon motion, which in turn may be associated with density lapse rate, are calculated internally throughout the fall. When the limits of the lambda terms are exceeded, the following type of line is printed:

Lambda = <0.00005 or >0.0002   Balloon has collapsed.

The program then optionally continues its complete computations or shifts to a calculation of wind terms only.

Another method of determining balloon collapse, most applicable for quick field use, is to time the sphere through fixed altitude layers. Table II, based on many successful flights, shows the time corridor for a rigid, 115 - 120-gram, 1-meter-diameter ROBIN to fall through 3-km-altitude layers after ejection well above 73 km altitude. A collapsed sphere requires a longer time to fall than indicated in Table II.

A third method of determining sphere quality involves the observation of the strength of radar signal return, the character of the return in which the corner - reflector pattern in a rigid sphere may be seen, and the level of the range and angle error signals.

Error analyses of the current ROBIN system were made during the development of the "March 65" data reduction program. However, these were done while only ARCAS - ROBIN data were available and hence the errors shown apply only to data from 70 km downward. Table III indicates the RMS errors for the various parameters when a precision radar (AN/FPS-16) is utilized for tracking a rigid sphere at 0.1 second to 0.5 second sampling rate. In addition, at the start of the computations, where the initial temperature estimate might be in error by 10%, a corresponding 2.5% density error would occur which would decrease very rapidly with decreases in altitude. If a radar of lesser accuracy, such as the AN/MPS-19 radar, is used (standard angle errors of approximately 1.5 mils instead of 0.1 mils), errors occur of the magnitudes shown in Table IV.

Reference 13 presents a technique for error estimation which was used to approximate the errors associated with using the "March 65" computer program at higher than program design altitudes. Table V indicates the degradation experienced in applying this program above 70 km.

Obviously the use of the "March 65" computer program with ROBIN flights in the 100-km to 70-km region is undesirable. During the past year, efforts have been directed to improving and optimizing the program for reduction of data for a complete sounding from 100 km to 30 km. Another paper at this symposium will describe the types of changes that will be made to minimize the errors and describe the program which will be introduced into the field within the next few months. It is planned to modify some of the drag coefficients, in the new program, as previously discussed knowing that future changes may again be needed if a significant aerodynamic program were initiated. The new program will be distributed to those NASA, Army, Navy, and Air Force agencies currently in possession of the "March 65" computer program.

METEOROLOGICAL DATA

More complete coverage of the ROBIN and examples of measured data may be found in references 5, 8, 10, 14, 15, and 16. Reduced data from approximately 300 research and development flights as well as several hundred operational flights by the Air Force 6th Weather Wing have been forwarded to the Air Force Climatic Center and the U.S. Meteorological Rocket Network for storage and dissemination. Research and development flights with the VIPER - Dart - ROBIN system have supported most of the recent SATURN - APOLLO launches.

Figures 10 through 15 present examples of meteorological data obtained during the VIPER - Dart development. Figure 16 shows the complete density profile from the surface to 90 km provided by rawinsonde, rocketsonde, and ROBIN for the APOLLO 11 flight. Figure 17 indicates the effect of using the previously mentioned experimental drag coefficient table. The resulting density profile agrees more closely with the rocketsonde density in the 40 - 60 km levels. However, the temperature profile departs further from the rocketsonde temperature over this altitude range.

CONCLUSIONS AND RECOMMENDATIONS

The intent in this section is to summarize the AFCRL view of the ROBIN falling - sphere system as well as point out problem areas and suggest the direction of further study, development, or test. The comments are given also as recommendations should the general program suggested in the NASA study under Contract NASI - 7911 be implemented in the coming years. Not all of the following remarks have been fully discussed in the body of this report due to varying degrees of complexity beyond the scope of this summary paper. By perusal of the various references listed as well as by means of a round table discussion with others present here, these points can be more fully analyzed.

1. The feasibility of measuring atmospheric winds, density, temperature, and pressure from 100 km to 30 km by means of a passive radar - tracked falling sphere has been established. Subjective analysis indicates reasonable values of the measured parameters.

2. Error analyses made to date for data gathered between 65 and 30 km indicate errors of 3 to 0.5 m/sec in wind magnitude, 3% in density, 10 to 4% in temperature and 6 to 3% in pressure.

3. In spite of these quoted figures, comparison with rocket-sondes flown within one hour sometimes indicated differences in the order of 20% in density while at times better agreement is found.

4. A data reduction computer program developed satisfactorily for the 65 - 30 km range of altitudes after further analysis, which will be presented at this Symposium, seems to show that the degree and thickness of the smoothing interval is critical as the altitude, and hence, fall velocity, becomes sufficiently large. To some degree, the character of the wind profile needs to be known in order to minimize the error in the wind.

5. It is possible that an optimum density program may not provide an optimum temperature output and vice versa.

6. Consideration of errors and the computation procedure indicates that a constant percent error in the drag coefficient or density is required if one wishes to minimize temperature error.

7. The above two statements indicate the need to more rigidly define the exact parameters to be measured in a synoptic meteorological network. Density is probably the principle parameter desired by the aerospace community although some meteorologists may prefer temperatures for their analyses of the atmosphere.

8. Vertical winds are assigned as a zero - value in the computations. Various experimenters indicate this is not the case and have published values which are significant only at the lowest altitudes where the sphere velocity is small.

9. Some analyses with a few 65-km ROBIN flights were made by assuming that the small perturbations in density were caused by vertical winds. The maximum vertical winds detected by this method were $\pm$ 5 m/sec (but more typically, $\pm$ 3 m/sec) with wavelengths in the order to 2 km. A 3-m/sec error in vertical sphere velocity represents a 6 - 1/2% error in vertical velocity or 13% density error at 40 km. This reduces to less than a 2% density error at 75 km.

10. To some extent the above two statements might lead to consideration of the tradeoffs in using either (a) a single system for winds and density from 100 km down to nearly 30 km or (b) two systems or a compound system for separation of measurements into optimum altitude levels. A rocketsonde might be ejected at 60 km or two spheres of differing mass area ratios might be utilized from a two-stage dart.

11. In a similar vein, it was found that the measurement of winds above 70 km with the ROBIN, as will be reported in another paper here, requires special attention. It is possible that chaff or a slower falling target than the ROBIN will be required to sense horizontal winds to the accuracy desired.

12. The requirements for horizontal winds needs to be more precisely defined before further effort be expended in developing a final system. Not only does the accuracy in wind magnitude need defining, but the wavelengths of wind perturbations that must be sensed should be indicated as an aid in establishing design goals in hardware and computer techniques.

13. The input from the tracking radar scientific community has been tedious and only by a gradual item by item approach have certain, but possibly not all, of the radar characteristics been investigated. On one program it was found that the servo bandwidths were better set at a different position for minimal target position error than recommended to the technicians by their official training instructions. Other as yet unknown peculiarities should be isolated and an expert assigned to any overall new development.

14. Analysis of error recordings indicated that FPS-16 radars at Eglin, at least when tracking the standard 65-km ROBIN, has RMS errors of less than $\pm$ 0. 2 mil in elevation and azimuth angles, not unlike their

handbook values. From other programs it is known that individual FPS-16 radars vary appreciably in their noise characteristics and the quotation of a single error figure for one type of radar is misleading. A decrease in signal-to-noise ratio whether caused by a weaker target, greater slant range, more background noise, or an "untuned" radar can increase the tracking error.

15. Enhancement of radar return without use of a corner reflector is desirable for simplification in fabrication and packaging.

16. If a new radar concept is pursued as suggested in the recent aforementioned NASA conceptual study report for a 1980 rocket system, its design approach should include not only the minimization of tracking error but also the shaping of its "noise" character to optimize data reduction techniques.

17. Drag coefficient values used in ROBIN soundings are uncertain as judged at least by (a) rocketsonde data in the lower altitude portions and (b) by data peculiarities in the transonic region around 75 km.

18. Drag coefficients for the most part obtained by static wind tunnel tests are used in the ROBIN and other falling sphere systems. Vertical accelerations during the measurement phase descending from 100 km pass from negative values through zero to as much as + 3 g's at 80 km and then decrease to insignificant values at 30 km. Similarly, lateral accelerations are present. Static drag coefficients do not, to varying degrees, represent proper values under accelerated flow conditions. Hence, some attempt should be made in the future work to utilize ballistic ranges where Mach and Reynolds Numbers and acceleration levels may be simulated.

19. Consideration of apparent mass indicates this term is negligible above 20 km and it is felt does not adequately attack the accelerated flow condition.

20. The state of knowledge of the aerodynamic parameters accuracies is perhaps the weakest point in the ROBIN system. If a world meteorological rocket network of a scale initimated in the aforementioned study were pursued and implemented, a world standard atmosphere would most assuredly follow from the large amount of data gathered. To have this standard based on questionable sphere drag coefficients would be folly indeed. Hence, it is strongly recommended by this author that a significant program be established and managed by a Government aeronautical agency for this very basic research problem for application to either current or future falling - sphere systems.

21. The feasibility of using the ROBIN in several types of rockets, subject to accelerations of over 100 g's, has been demonstrated. The vehicle would seem to be the least of all problems in the system. Some further reduction in cost over the already reasonably priced VIPER - Dart might be attained by further efforts along the line of the Super LOKI motor in a new dart configuration or possibly other vehicles under development (Canada - Army, Astrobee, etc.). Gun probe personnel have indicated a nearly hopeless hardware task with this approach and it is assumed that this is a final conclusion.

22. The ROBIN hardware development has demonstrated that thin plastic spheres can be ejected at high altitudes and inflated by means of vaporization of various liquids. In-depth studies and tests some years ago indicated for example that sublining solids were too slow in action for this application. There may be today newer chemicals, solids, or liquids, that might offer promise leading to simplification of encapsulation and release of the chemical and reduce further the mass-area ratio of the sphere.

23. Evaluations of the internal sphere gas temperature for hardware considerations as well as the skin temperature for aerodynamic considerations have been attempted but without assurance by the theorists that their methods are rigorous.

24. A significant reduction in the sphere's mass - area ratio would of course reduce the range of aerodynamic flow conditions and possibly improve sensing ability through simplification of the required measured parameters. Reference 1 indicates that in a wind shear of .02/ sec , a 5 m/sec wind error would result if the fall velocity were 45 m/sec and the horizontal acceleration terms were completely ignored. While such a velocity is unattainable at high altitudes, it indicates a limit in simplification.

25. Consideration of better ejection and deployment techniques is suggested wherein lower dynamic loads would be imposed thereby allowing light gauge (and weight) materials. Attempts to use 1/4 and 1/3 mil with ARCAS - ROBIN indicated a decrease in reliability.

26. Similarly, newer materials should be considered with improved strength and weight characteristics. While perhaps heavier than desirable, a scrim - plastic combination might permit simple and relatively uncontrolled pressurization techniques. In addition, a larger superpressure than the 30-mb design in the ROBIN would assure spherical conditions down to less than 30 km.

27. While there is disagreement with other experimenters concerning this matter, the usual collapse altitude of the ROBIN at 40 km

rather than 30 km is felt to be another as yet unresolved problem. Temperature balance is felt to be a part of the problem. The University of Michigan uses metallized spheres and publishes density data to 30 km. However, Air Force experiments with metallized spheres has shown little correlation with collapse altitudes. Quantity of inflatant and temperature - pressure characteristics need refinement particularly if new chemicals are considered.

28. It was hoped that a report could be made here on the successful deployment of a ram - air inflated sphere from a rocket. Two were attempted; one was not tracked and the other track indicated the descent of a heavy object. The idea, originally conceived and demonstrated at sea level by the AFCRL Starute contractor, Goodyear Aerospace Corporation, is worthy of further pursuit. The elimination of chemicals, capsules, etc. should simplify the total hardware picture.

29. Consideration of body shapes other than a sphere, possibly using the ram - air inflation principle, might be attractive due to potentially larger and less varying drag coefficients during their fall. The remaining aerodynamic characteristics (C_m , C_L) would possibly lead to other design problems which would have to be solved for all flow conditions.

30. Before the final framework of aerodynamic test requirements are established for a sphere (or other body), all hardware improvements should at least be checked and verified.

31. If a flexible development program is possible, there are payoffs in intermixing flights of spheres of various sizes and weights with laboratory or wind tunnel tests. For example, a peculiar hook in the current drag coefficient table was found after the reduction of flight data using early wind tunnel data indicated a hook existed in the density profile. More detailed wind tunnel tests uncovered a peculiar drag coefficient variation thereby smoothing the calculated density profile.

32. Comparative flight tests between spheres of various masses and sizes and with other sensors during day and night can be productive in evaluation of errors and consistency. Only a small amount of this comparison testing has been accomplished. Comparisons of ROBIN densities with rocketsonde densities have in general shown inconsistent disagreements.

33. In summation, it is believed that FPS-16 radars, available at missile ranges in this country, contribute less to the total density error in falling-sphere data than the uncertainties in the drag coefficients now utilized. Additional efforts with sphere hardware are also required to improve reliability and low-altitude performance.

REFERENCES

1. Lally, V.E., and Leviton, R., Accuracy of Wind Determination from the Track of a Falling Object, Air Force Surveys in Geophysics No. 93, (ASTIA No. AD 46858) Geophysics Research Directorate AFCRC, Mar. 1958

2. Peterson, J.W., Schulte, H.F., and Schaefer, E.J., A Simplified Falling-Sphere Method for Upper-Air Density, AFCRL-TR-59-263, University of Michigan Research Institute, May 1959.

3. Leviton, R., and Wright, J.B., Accuracy of Density from the ROBIN Falling Sphere, AFCRL, GRD Research Note No. 73, (ASTIA No. AD 274213), Dec. 1961

4. Watson, C.W., JUDI-ROBIN Balloon Dart Sounding Vehicle, AFCRL Report No. 64-471, (ASTIA No. AD 607074), Rocket Power, Inc., May 1964

5. Bollermann, B., and Walker, R.L., Design, Development and Flight Test of the VIPER Dart ROBIN Meteorological Rocket System, AFCRL Report No. 68-0418 (ASTIA No. AD 675608), Space Data Corporation, Jun. 1968

6. Smalley, J.H., and Flink, L.R., Modification of the ROBIN Meteorological Balloon, Vol 1, Design and Test, AFCRL Report No. 65-734, (ASTIA No. AD 629774), Applied Science Division, Litton Systems, Inc., Sept. 1965

7. Heinrich, H.G., Haak, E.L., and Niccum, R.J., Modification of the ROBIN Meteorological Balloon, Vol. II, Drag Evaluations, AFCRL Report No. 65-734 II, (ASTIA No. AD 629775), University of Minnesota, Sept. 1965

8. Engler, N.A., Development of Methods to Determine Winds, Density, Pressure and Temperature from the ROBIN Falling Balloon, (ASTIA No. AD 630200), University of Dayton Research Institute, (Contract No. AF 19(604)-7450), Oct. 1962.

9. Brockman, W.E., Computer Programs in Fortran and Balgol for Determining Winds, Density, Pressure, and Temperature from the ROBIN Falling Balloon, University of Dayton Research Institute, (Contract No. AF 19(604)-7450), Jan. 1963

10. Engler, N.A., Development of Methods to Determine Winds, Density, Pressure, and Temperature from the ROBIN Falling Balloon, University of Dayton Research Institute Final Report, Contract No. AF 19(604)-7450, AFCRL Report No. 65-448, May 1965

11. Wright, J.B., and Leviton, R., The ROBIN Falling Sphere, COSPAR Technical Manual, Falling Sphere Method for Upper Air Density, Temperature and Wind, Feb. 1967

12. Court, A., Kantor, A. J., Cole, A. E., Supplemental Atmospheres, Research Note, AFCRL 62-899, Sept. 1962

13. Luers, J.K., Estimation of Errors in Density and Temperature Measured by the High Altitude ROBIN Sphere, Proceedings of the Third National Conference on Aerospace Meteorology, May 1968

14. Engler, N.A., and Wright, J.B., Wind Sensing Capability of the ROBIN, AFCRL Report No. 62-273 (II), AFSG No. 140, Proceedings of the National Symposium on Winds for Aerospace Vehicle Design, Vol II, Mar. 1962

15. Lenhard, R.W., Jr., and Wright, J.B., Mesospheric Winds from 23 Successive Hourly Soundings, AFCRL Research Report No. 63-836 (ASTIA No. AD 417441), Jul. 1963

16. Engler, N.A., High Altitude ROBIN Flights, AFCRL Report No. 67-0433, (ASTIA No. AD 675810), University of Dayton Research Institute, May 1967

TABLE I - HISTORY OF AFCRL ROBIN CONTRACTUAL EFFORTS

Year	Drag Coefficients	ARCAS-type Hardware	Dart-type Hardware	Data, Programs, etc.	Year
1958		G.T.Schjeldahl Co. Contract AF19(604)-4569			1958
1959					1959
1960	U. of Minnesota Contract AF19(604)-6653	G.T.Schjeldahl Co. Contract AF19(604)-6653			1960
1961	U. of Minnesota Contract AF19(604)-8034	G.T.Schjeldahl Co. Contract AF19(604)8034			1961
1962			Rocket Power, Inc. Contract AF19(628)-1624	U. of Dayton Research Institute Contract AF19(604)-7450 Ref. 8, 9, 10	1962
1963	U. of Minnesota Contract AF 19(628)-2945 Ref. 7	(General Mills) Litton Systems Contract AF19(628)-2945 Ref. 6	Rocket Power, Inc. Contract AF19(628)-2805 Ref. 4		1963
1964					1964
1965				U. of Dayton Research Institute Contract AF19(628)-4796 Ref. 16	1965
1966		(G.C.A., Viron) G.T.Schjeldahl Co. Contract AF19(628)-5538	Space Data Corp. Contract AF19(628)-5911 Ref. 5		1966
1967					1967
1968			Space Data Corp. Contract F19628-68-C-0393	U. of Dayton Research Institute Contract F19628-67-C-0102 Ref. 17	1968
1969					1969

TABLE II

ROBIN DESCENT TIMES

Altitude Layer From, km	Altitude Layer To, km	Time Seconds	Altitude Layer From, Feet	Altitude Layer To, Feet
73.2	70.1	12 - 15	240,000	230,000
70.1	67.1	13 - 16	230,000	220,000
67.1	64.0	14 - 17	220,000	210,000
64.0	61.0	16 - 19	210,000	200,000
61.0	57.9	19 - 24	200,000	190,000
57.9	54.9	23 - 28	190,000	180,000
54.9	51.8	29 - 32	180,000	170,000
51.8	48.8	35 - 40	170,000	160,000
48.8	45.7	43 - 49	160,000	150,000
45.7	42.7	53 - 60	150,000	140,000
42.7	39.6	65 - 75	140,000	130,000
39.6	36.6	Approx. 89	130,000	120,000
36.6	33.5	Approx. 113	120,000	110 000
33.5	30.5	Approx. 145	110,000	100,000

TABLE III

RMS ERRORS FOR ROBIN DATA USING THE AN/FPS-16 RADAR AND THE "MARCH 65" DATA REDUCTION PROGRAM

Meteorological Parameter	Altitude Bands 70 - 60, km	Altitude Bands 60 - 50, km	Altitude Bands 50 - 30, km
Altitude, km	$\pm$ 10	$\pm$ 10	$\pm$ 10
Magnitude of wind vector, m/sec	$\pm$ 3	$\pm$ 1.5	$\pm$ 0.5
Density, %	$\pm$ 3	$\pm$ 3	$\pm$ 3
Pressure, %	$\pm$ 6	$\pm$ 3	$\pm$ 3
Temperature, %	$\pm$ 10	$\pm$ 3	$\pm$ 4

TABLE IV

RMS ERRORS FOR ROBIN DATA USING THE AN/MPS-19 RADAR AND THE "MARCH 65" DATA REDUCTION PROGRAM

Meteorological Parameter	Altitude Bands		
	70 - 60 km	60 - 50 km	50 - 30 km
Altitude, km	$\pm$ 50	$\pm$ 50	$\pm$ 50
Magnitude of wind vector, m/sec	$\pm$ 15	$\pm$ 10	$\pm$ 5
Density, %	$\pm$ 6	$\pm$ 6	$\pm$ 10
Pressure, %	$\pm$ 10	$\pm$ 8	$\pm$ 10
Temperature, %	$\pm$ 12	$\pm$ 8	$\pm$ 10

TABLE V

APPROXIMATE ERRORS FOR ROBIN USING THE AN/FPS-16 RADAR AND THE "MARCH 65" DATA REDUCTION PROGRAM

Meteorological Parameter	Altitude		
	90 km	80 km	70 km
Wind			
RMS Noise Error, m/sec	20	5	4
Bias Error, m/sec	3	3	2
Sinusoidal Wind Field Bias Error, % of Amplitude Measured			
4 km Sinusoidal Wind	1	5	20
10 km Sinusoidal Wind	16	40	80
Density			
Random Error, %	5	3	4
Bias Error, %	14	2	0

Figure 1.- ROBIN (ML-568/AM) spherical balloon.

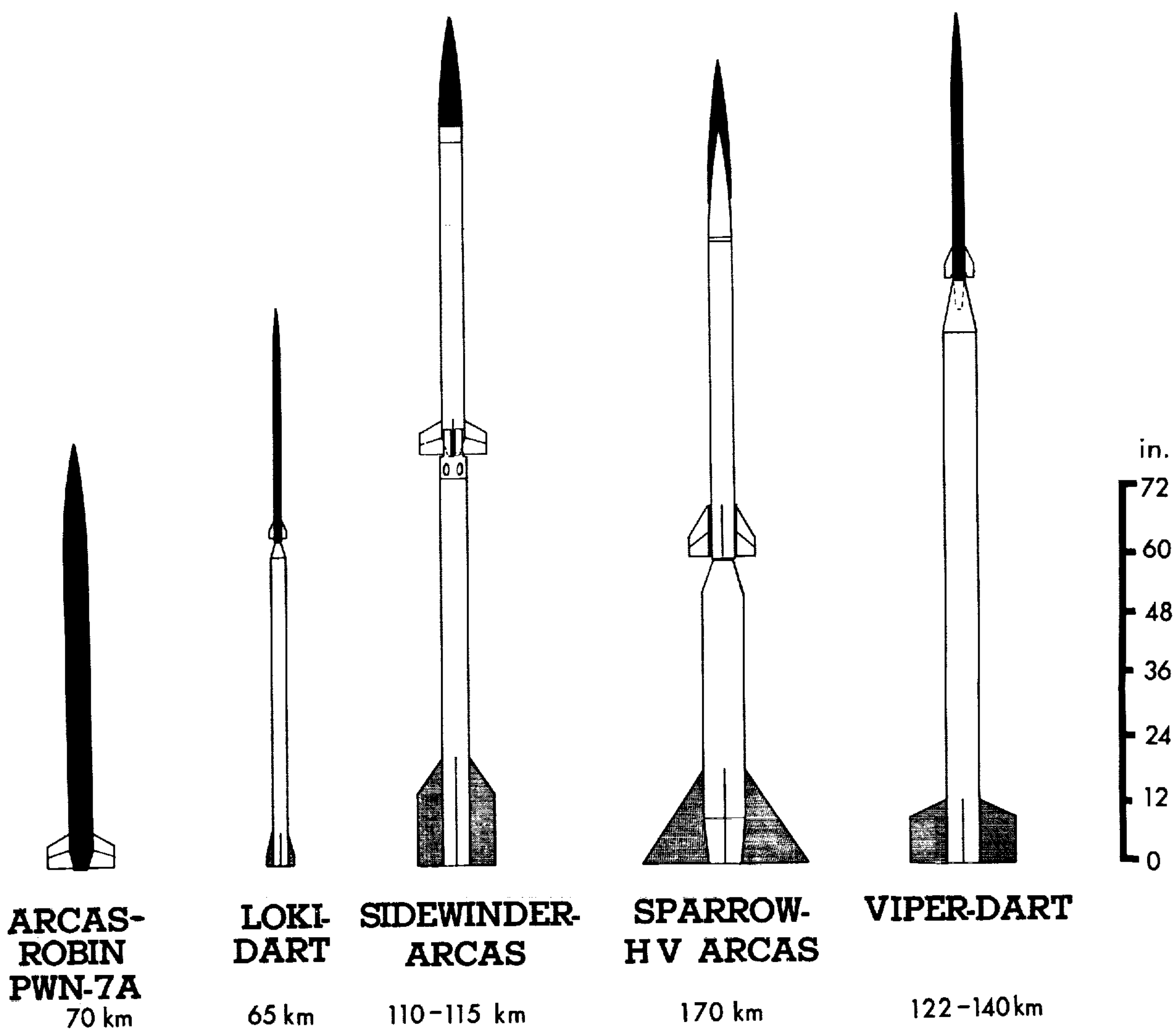


Figure 2.- Meteorological rockets utilizing ROBIN.

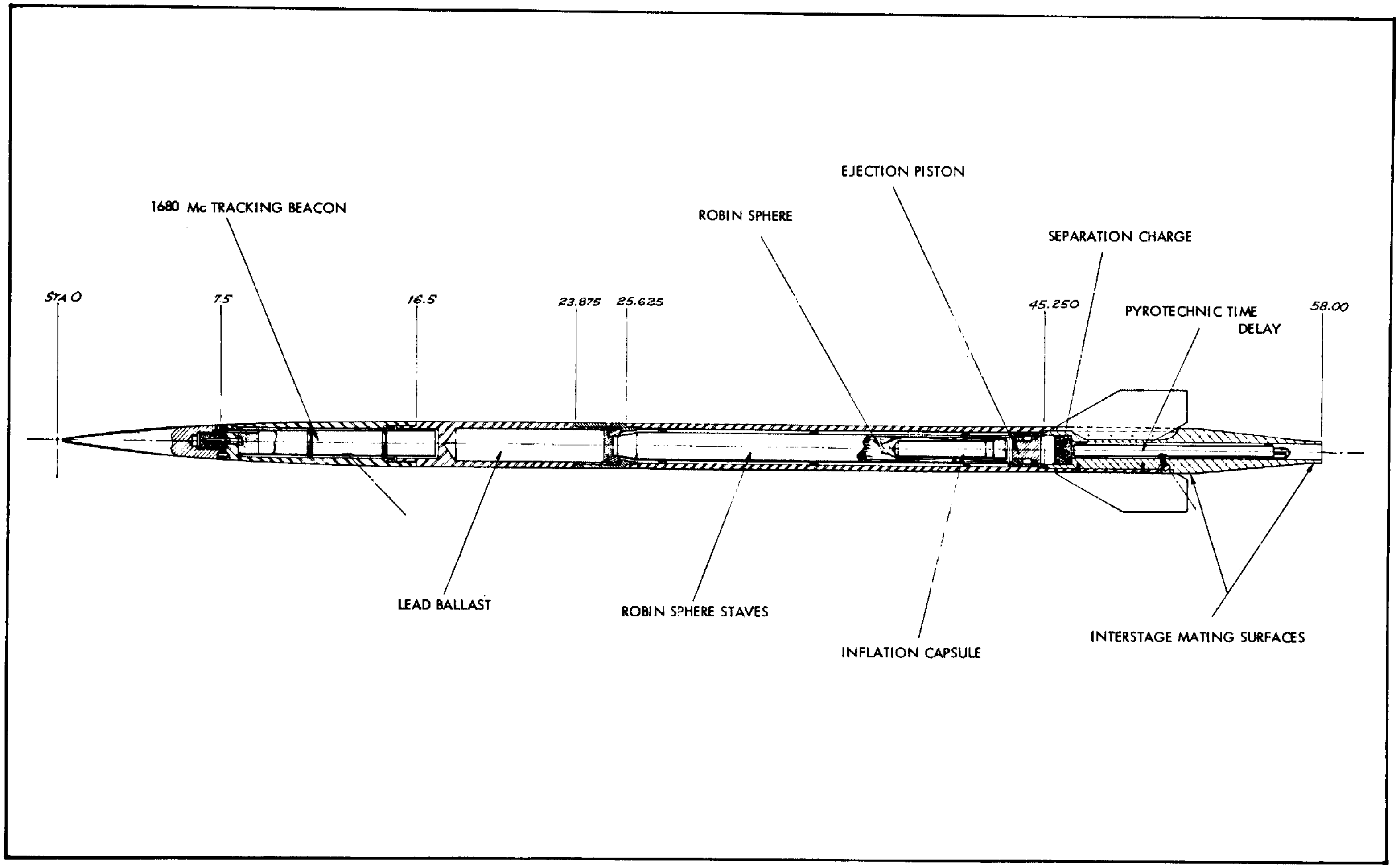


Figure 3.- VIPER-Dart-ROBIN cross section.

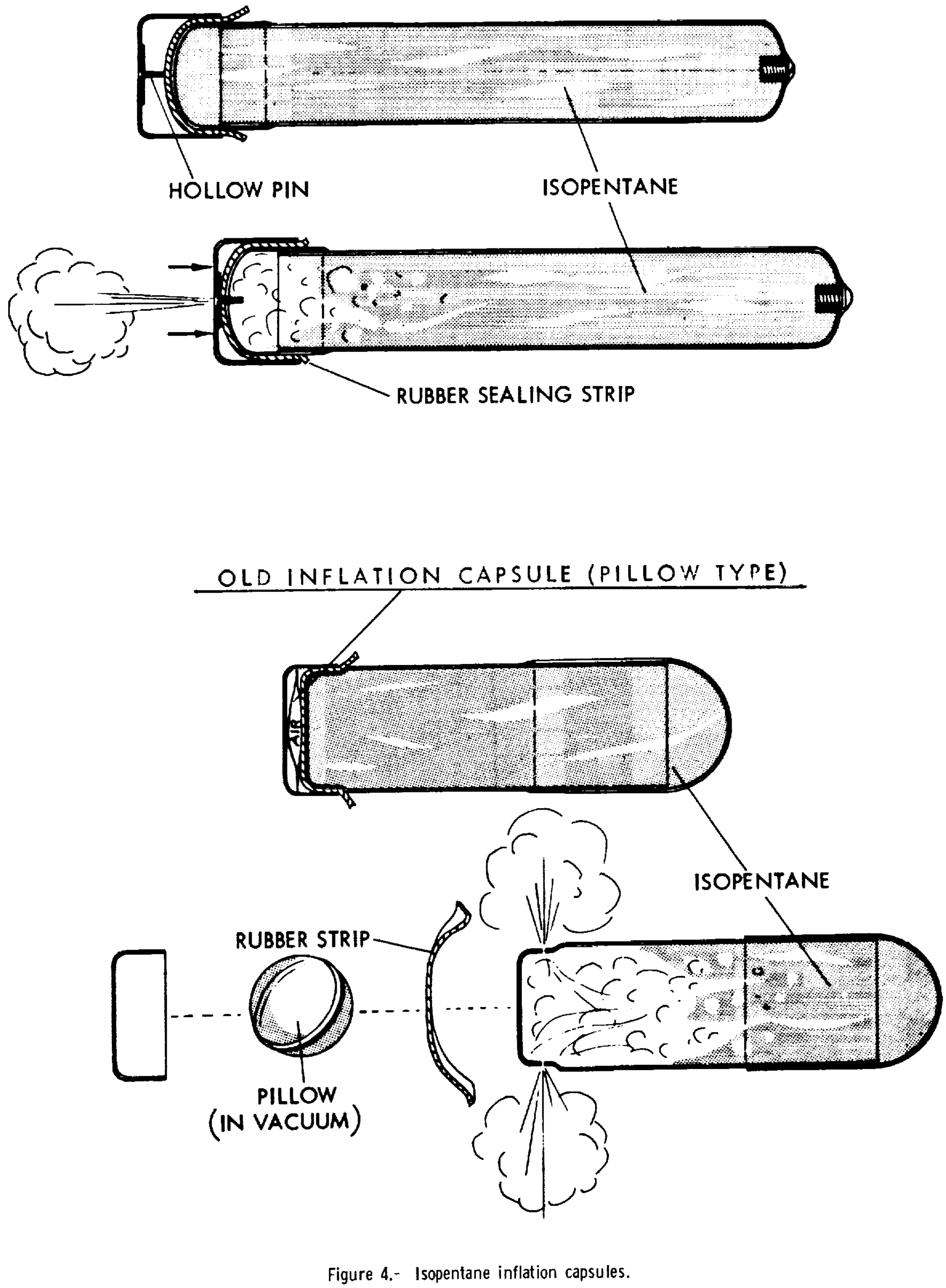


Figure 4.- Isopentane inflation capsules.

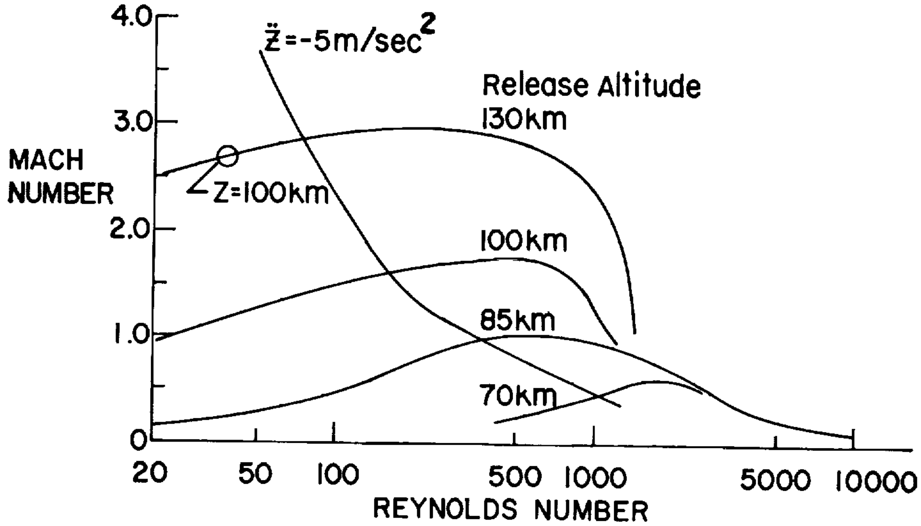


Figure 5.- ROBIN falling-sphere aerodynamic flow conditions.

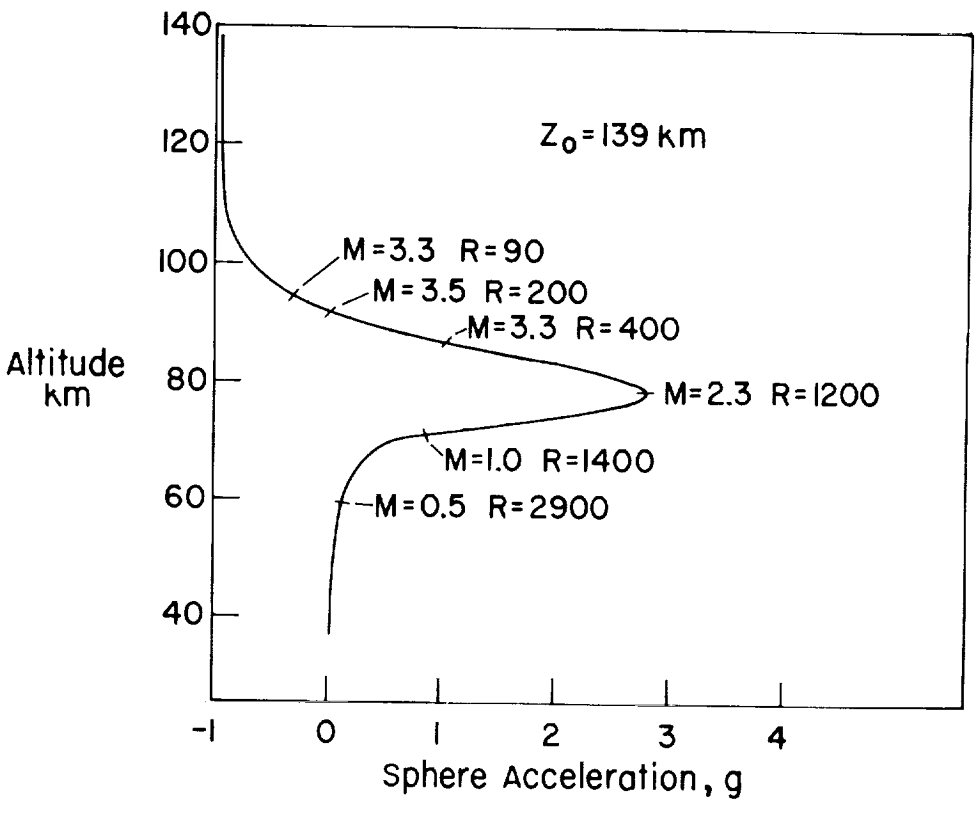
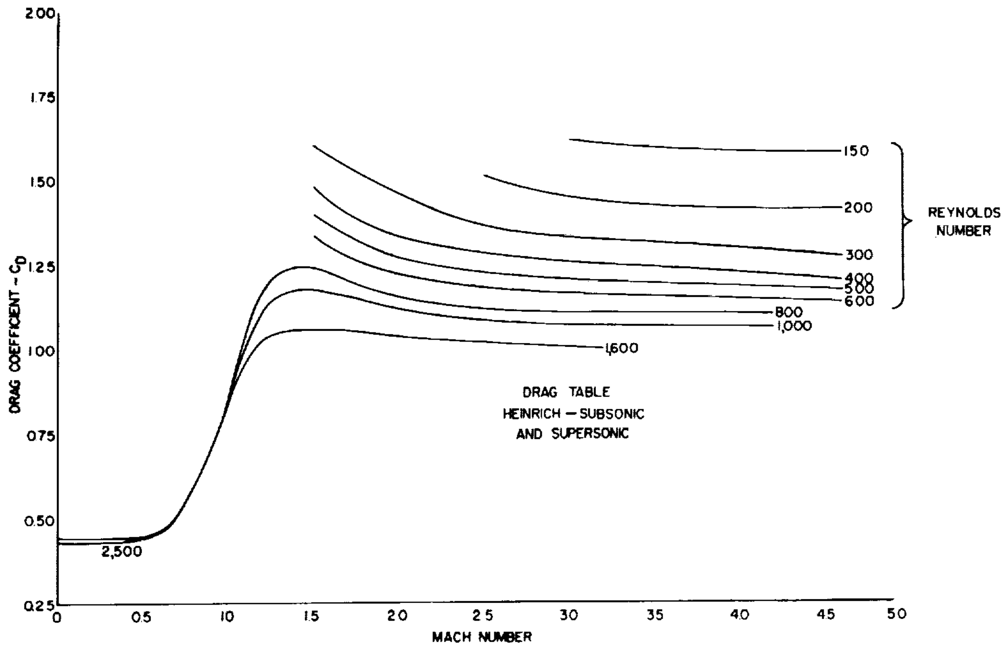
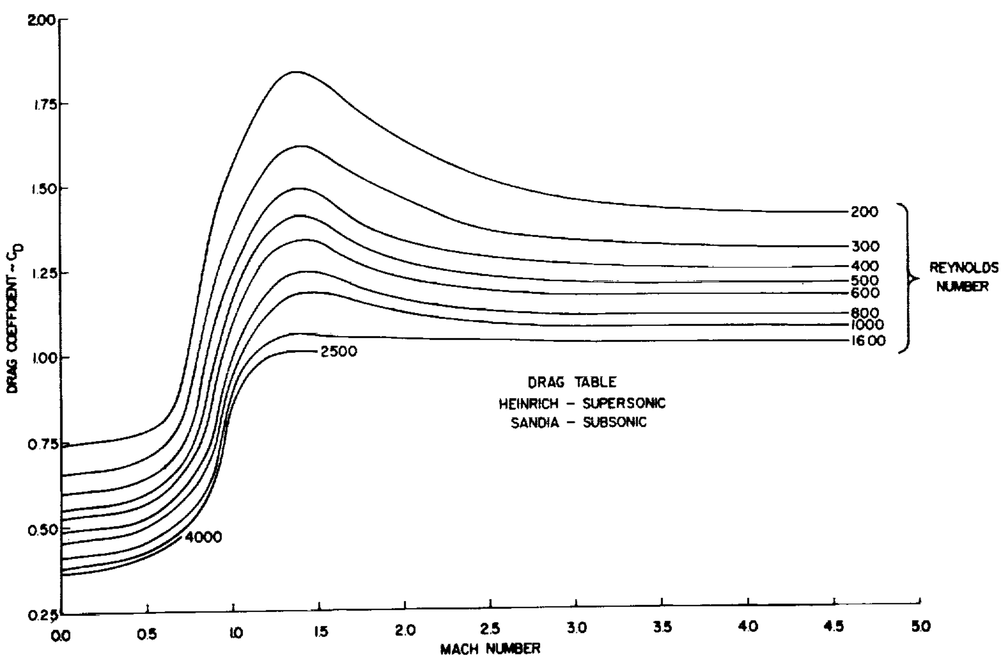


Figure 6.- ROBIN flight profile.



(a) Utilized in "March 65" Computer Program.



(b) Experimental.

Figure 7.- Drag coefficients of a sphere.

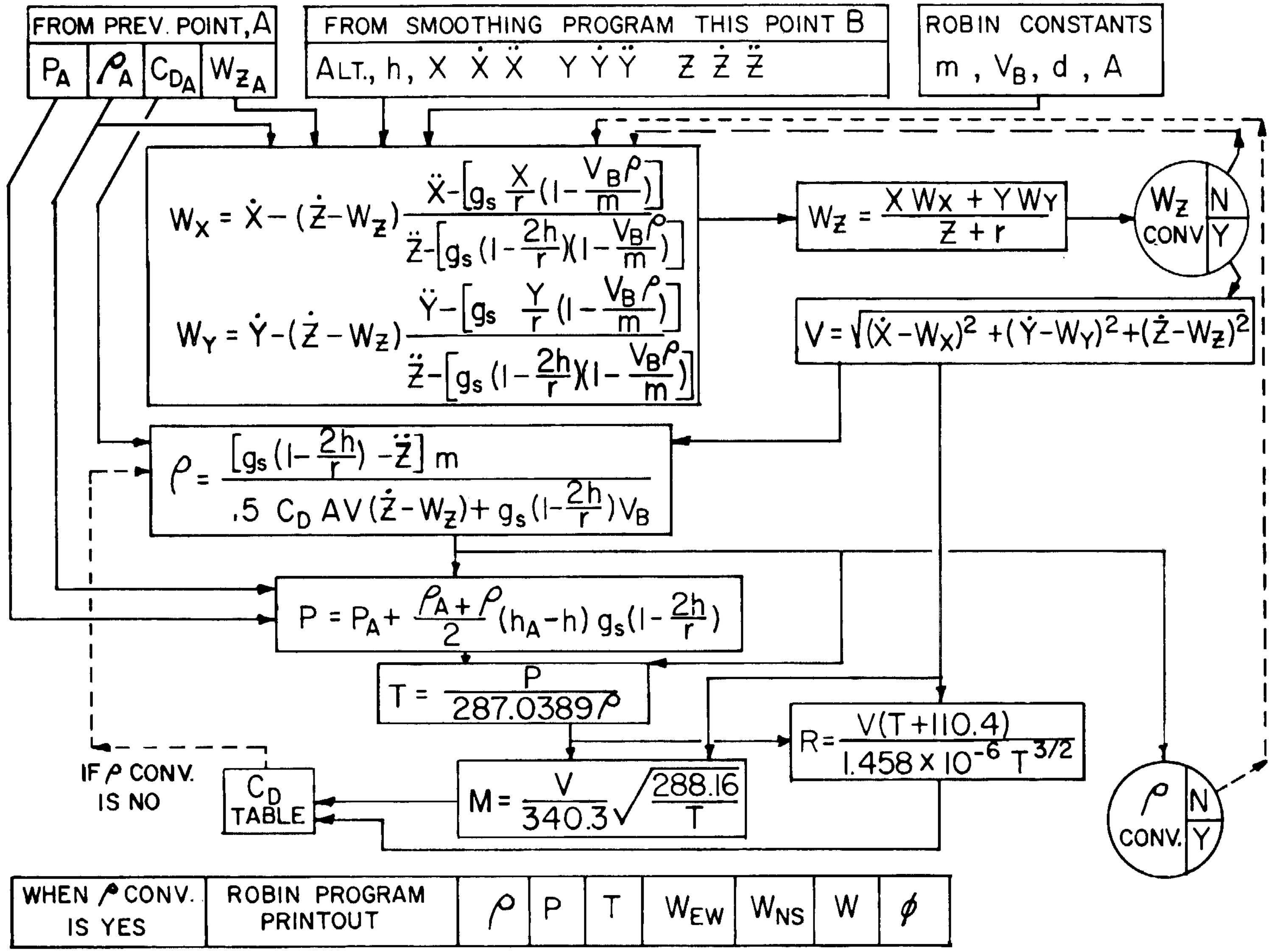


Figure 8.- ROBIN computer program, typical point.

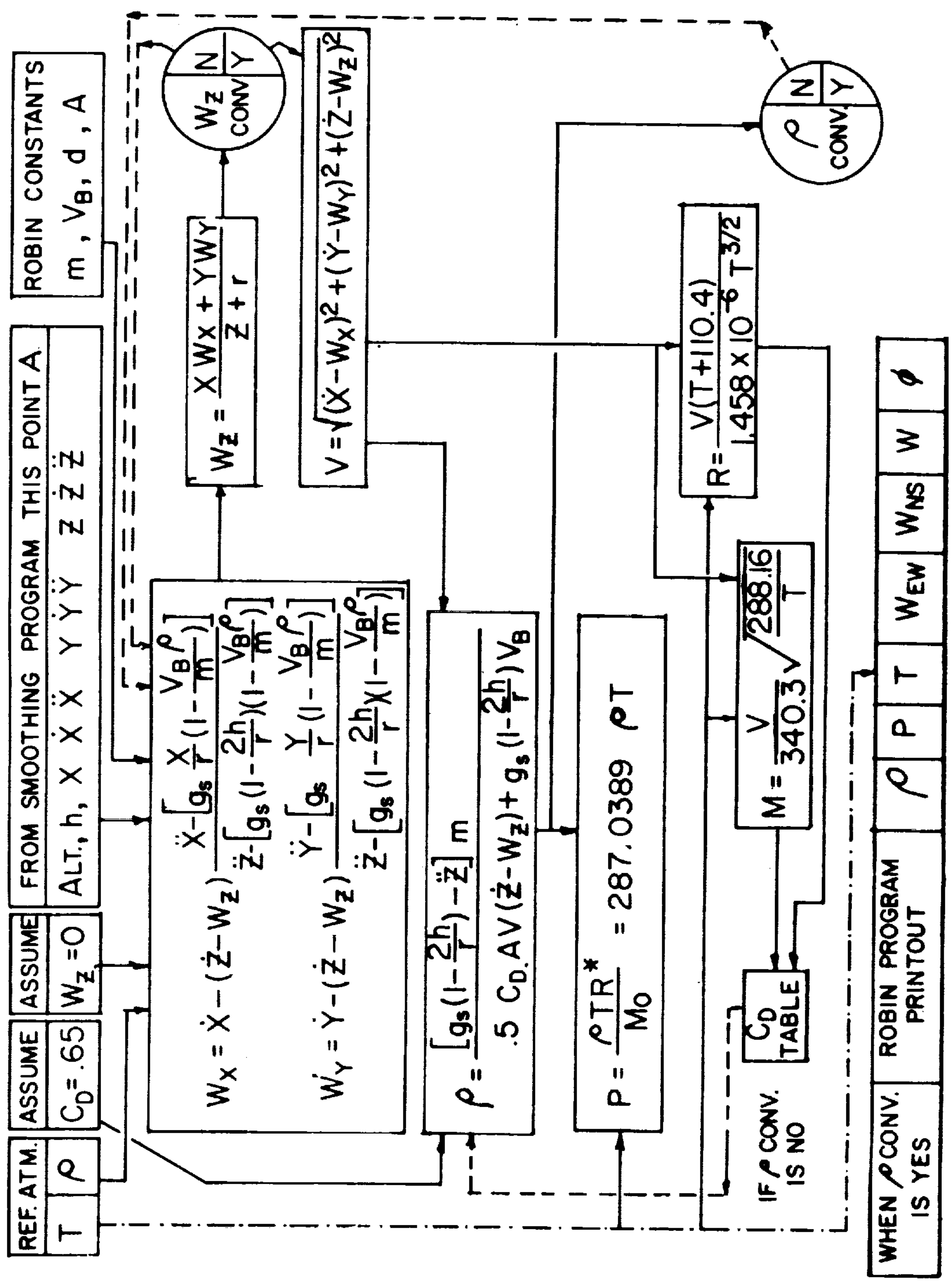


Figure 9.- ROBIN computer program, first point.

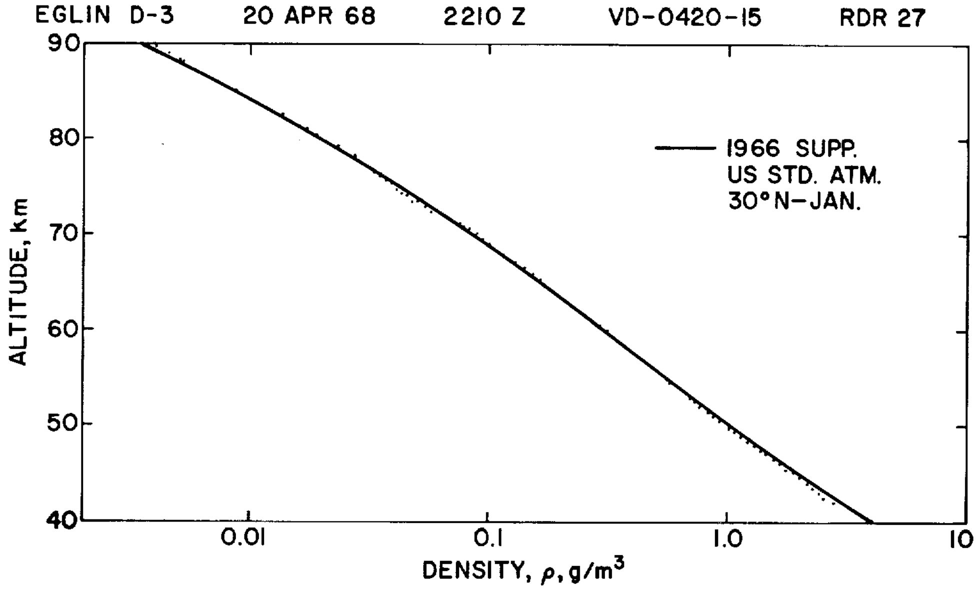


Figure 10.- Density profile from a ROBIN flight.

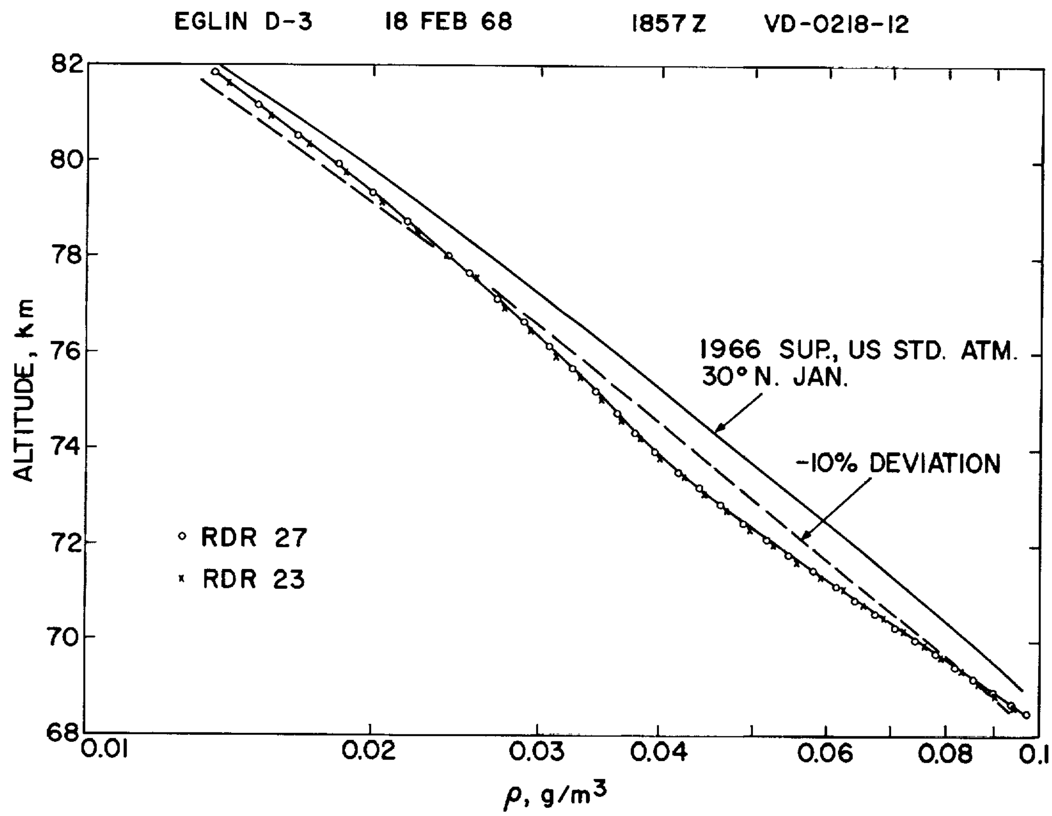


Figure 11.- Section of a density profile from a ROBIN flight.

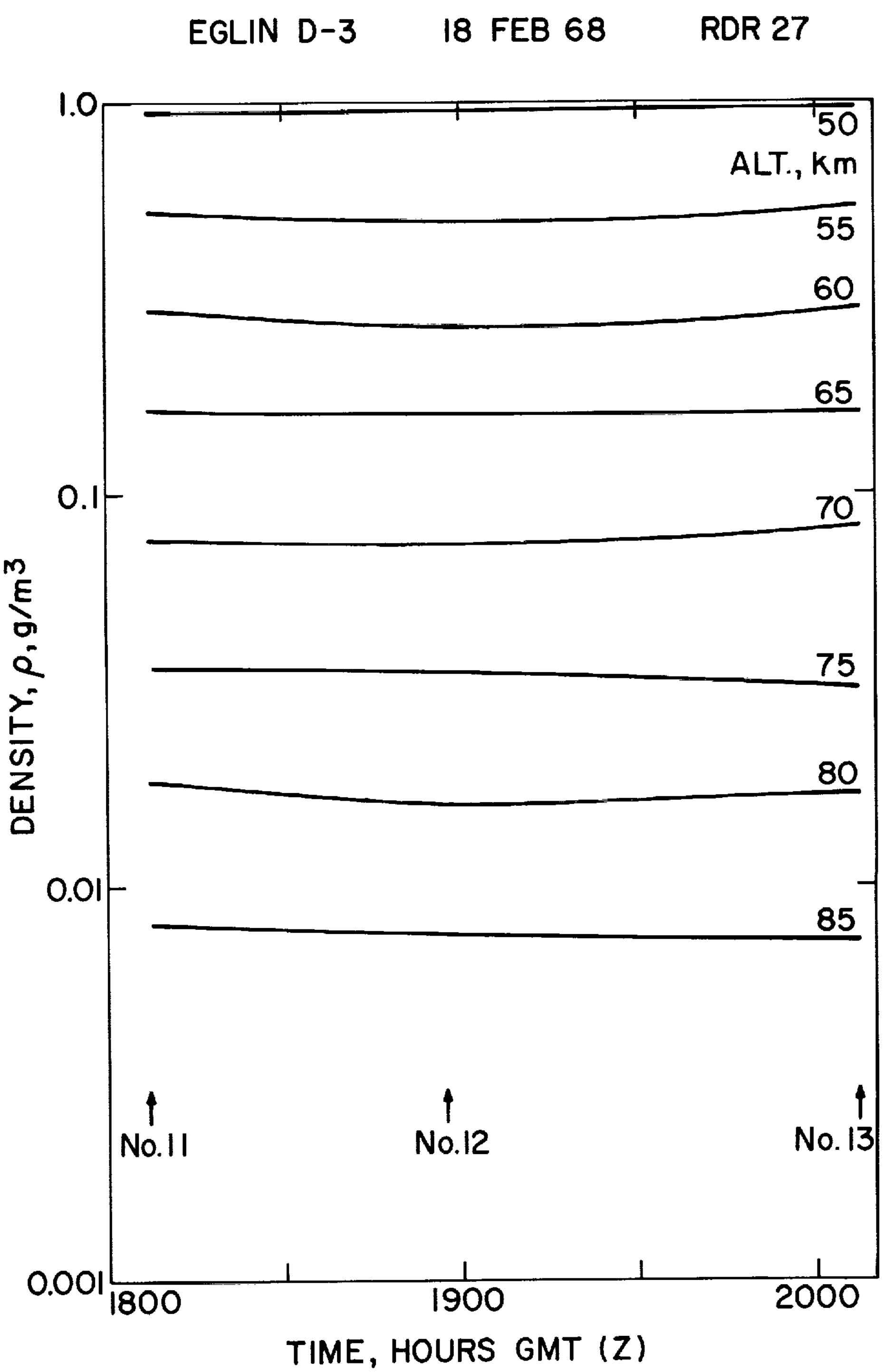


Figure 12.- Constant level densities from three ROBIN flights.

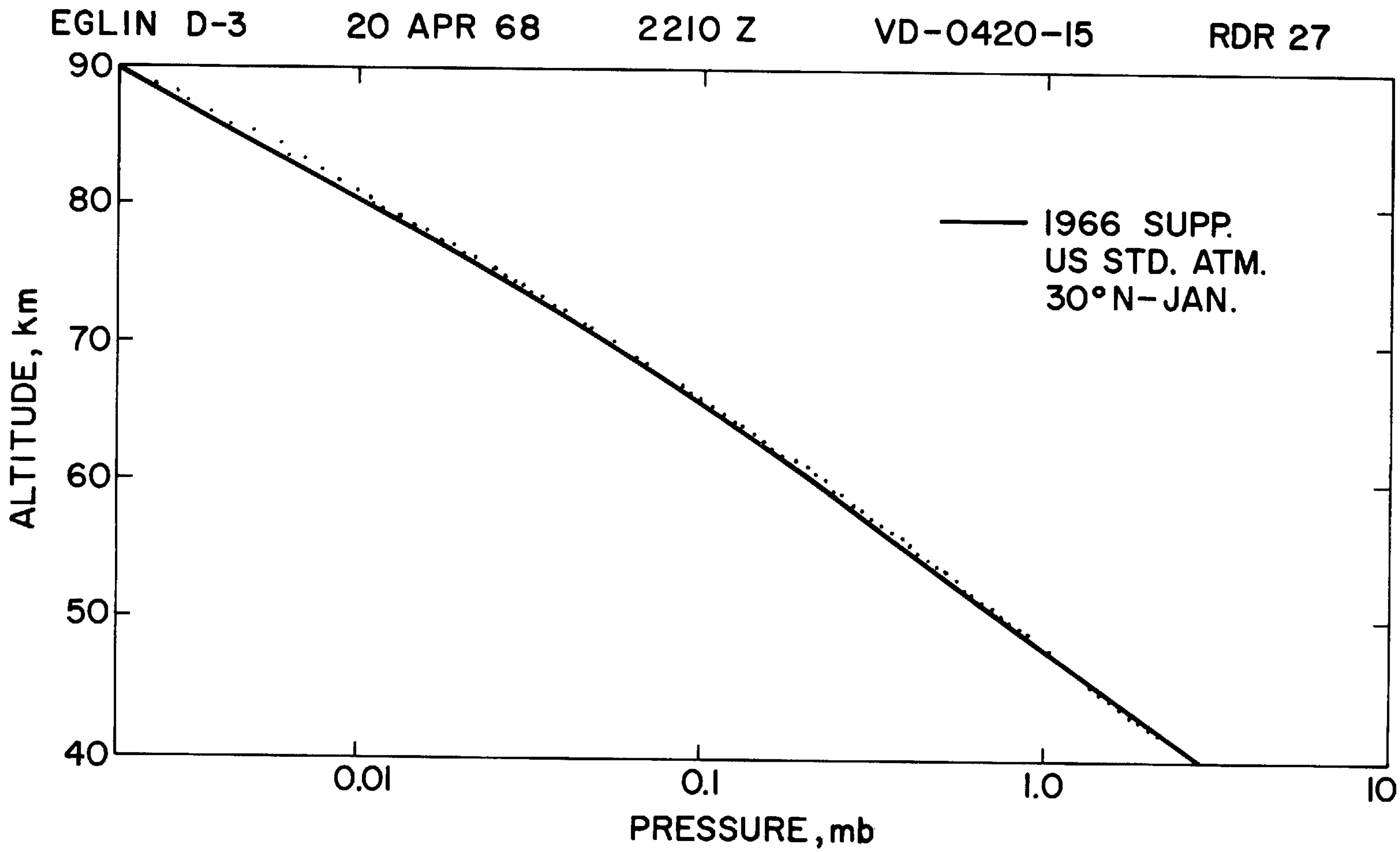


Figure 13.- Pressure profile from a ROBIN flight.

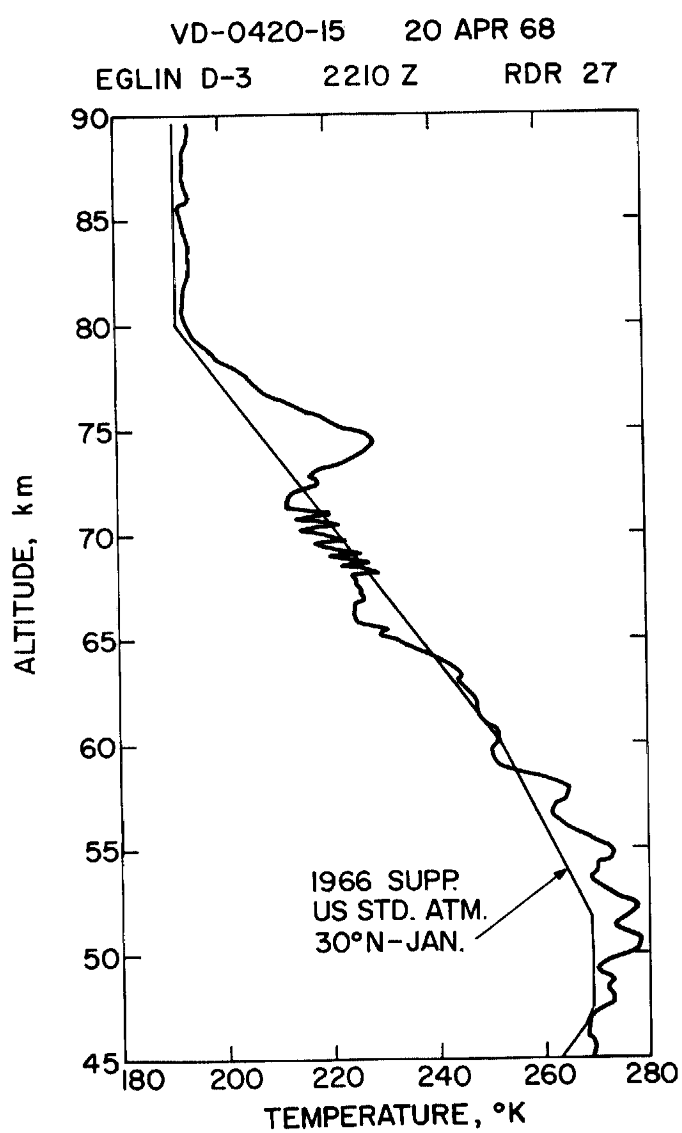


Figure 14.- Temperature profile from a ROBIN flight.

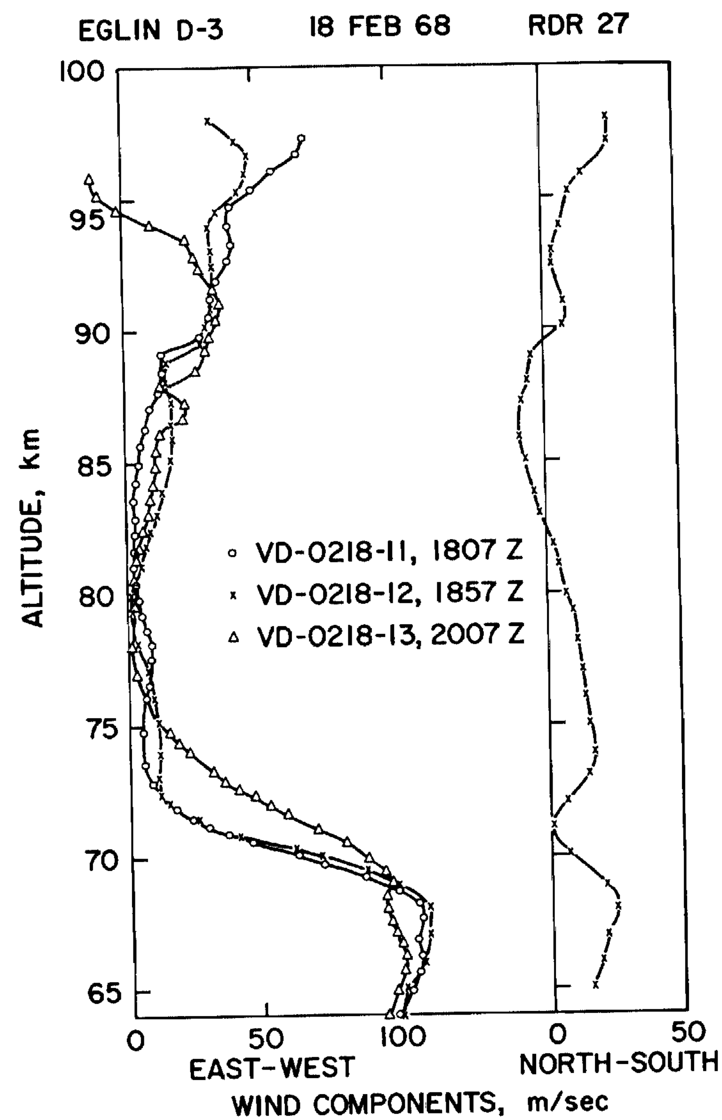


Figure 15.- Wind components from three ROBIN flights.

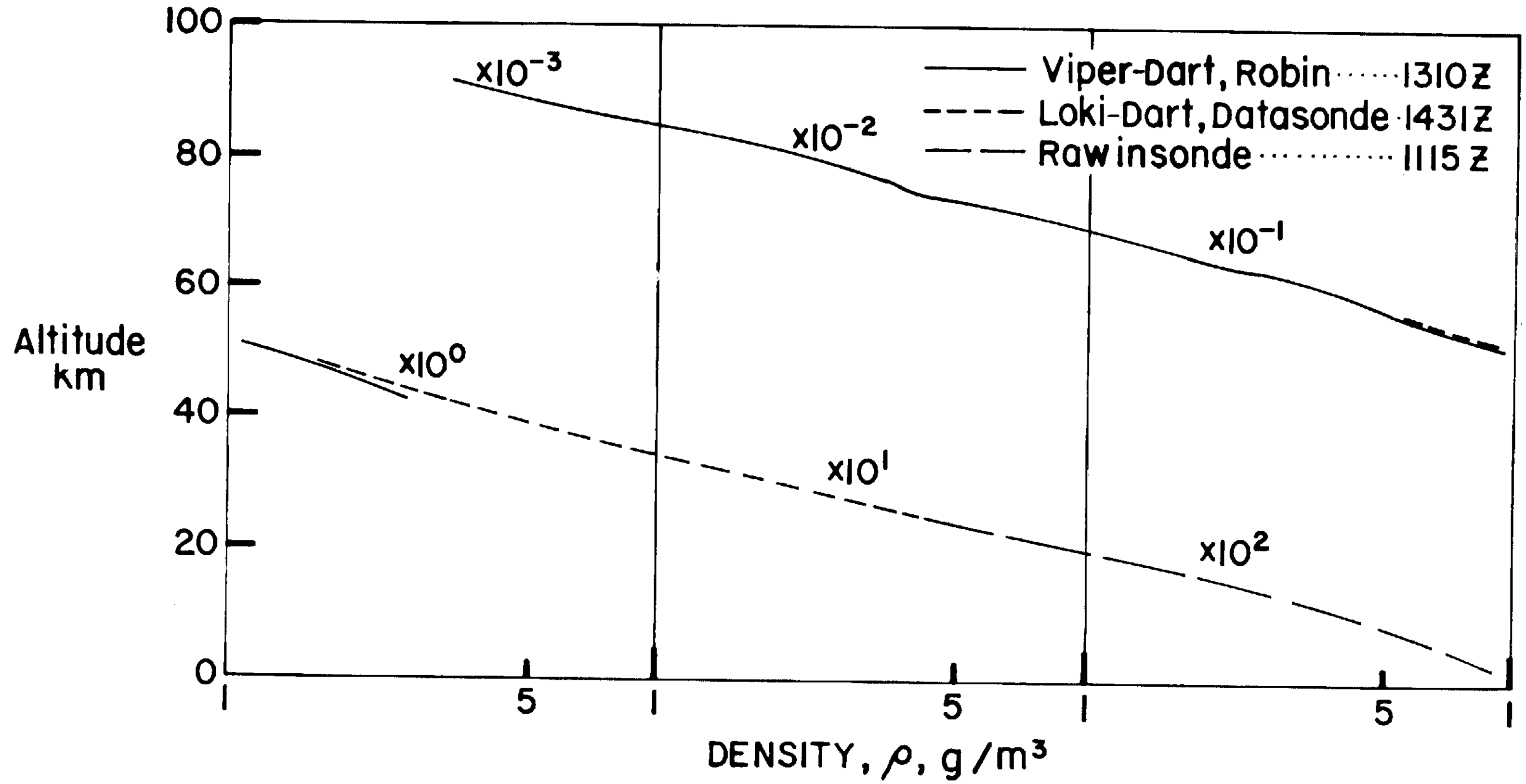


Figure 16.- Density profile, Apollo 11 launch support, ETR, Cape Kennedy, Fla., 14 July 1969.

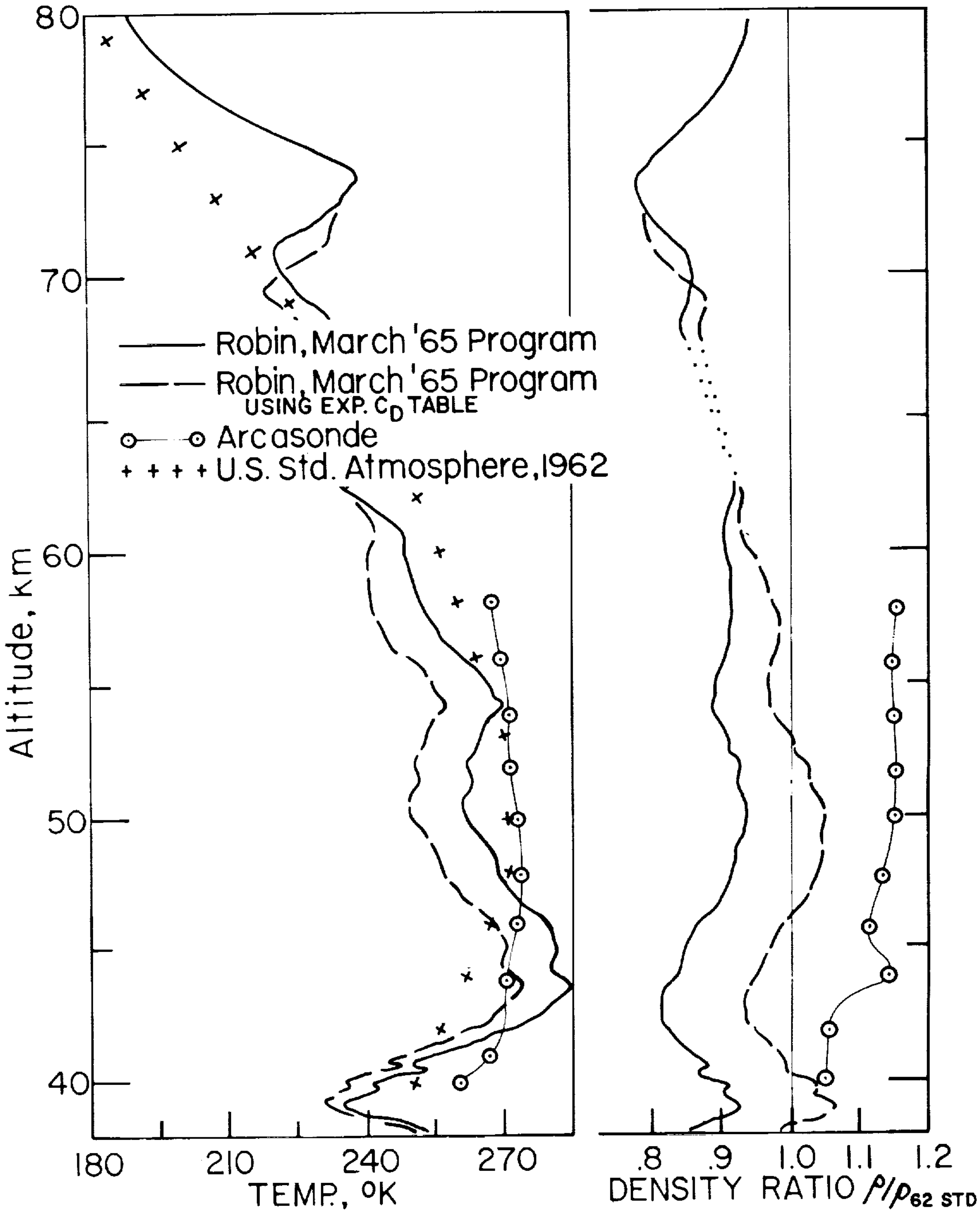


Figure 17.- Effect of using experimental drag coefficients on measured density and temperature, ETR, Cape Kennedy, Fla., 20 Dec. 1968.