ADEQUACY OF THE PASSIVE INFLATED FALLING SPHERE TECHNIQUE

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SUMMARY/INTRODUCTION

The radar-tracked, inflated, falling sphere is an economical technique for obtaining high-altitude density data at any launch site possessing a high-powered radar. The technique as utilized by many experimenters has provided a large amount of grossly adequate density and temperature data in the stratosphere, mesosphere, and lower thermosphere. In addition, winds are very accurately measured to 70-km altitude.

There are several sources of error inherent in the technique, and a general agreement on their magnitudes has yet to be reached. However, recent experiments and studies have been undertaken specifically to ascertain errors. This paper describes those carried out by The University of Michigan's High Altitude Engineering Laboratory.

In particular the following areas were examined: detection of sphere deflation, consequences of premature deflation, radar tracking errors, drag coefficients, and methods of data reduction.

DETECTING THE MAGNITUDE OF ERRORS

Error Sources

In discussing the detecting of errors we shall limit ourselves to discussion of density which is the primary atmospheric parameter measured. Temperatures derived from the densities are sometimes a key to understanding and in those cases will be mentioned, but errors arising from the inference of a temperature profile from a density profile are not discussed here. Neither are wind errors considered.

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While it is always impossible to state with certainty that a list of experimental error sources is truly exhaustive, we here make the attempt. Known possible error sources are:

1. Incorrect value of sphere mass

2. Incorrect value of sphere frontal area

3. Incorrect radar position data

4. Incorrect drag coefficient as a function of Mach and Reynolds numbers

5. Incorrect Mach number determination

6. Incorrect Reynolds number determination

7. Vertical wind component

Some of the listed sources could be further broken down. Sphere mass error might be due to a mistake in weighing, or loss of a component after launch: Mylar envelope, metal capsule, or isopentane. Sphere frontal area error might arise from incorrect measurement, asphericity, or collapse (partial or complete). Radar data always exhibit some degree of scatter. Smoothing is required to yield the velocity and acceleration. The smoothing technique therefore influences the amount of error. Drag coefficients are based on experimental data in which scatter is evident. Surface roughness is not accounted for. Peculiar instability in the boundary layer may be the result of rotation or varying attack angle. In some regimes such as the transonic region there are insufficient measurements.

Analyzing an Unusual Sounding

Shortly after noon (1330 EST) on 7 August 1965 a sphere payload was launched at Wallops Island, Virginia. The ratio of the derived downleg densities to the U. S. Standard Atmosphere, 1962, is shown in figure 1. This sounding exhibits a remarkable wave-like structure of three cycles between 30 and 60-km with peak-to-peak amplitudes of 24, 36, and 24%, and wavelength of 10-km. The sounding was sufficiently unusual that the question immediately arose as to whether the result was an atmospheric effect or some error. The remainder of this paper is devoted to discussing the error contributions which will enable a conclusive answer to that question.

ERRORS DETERMINED TO BE NEGLIGIBLE

Discussion

For errors to be called negligible, they must be negligible with respect to other errors or with respect to the desired measurement accuracy, preferably to both. If they are negligible only with respect to other errors, future improvements in other parts of the system might cause them to be important.

Three of the seven error sources are presently negligible because other errors are more important. They must be kept in mind because recent improvements show promise of drastically reducing other sources which for years have been considered most detrimental.

The three negligible sources are:

Incorrect value of sphere frontal area

Incorrect Mach number determination

Incorrect Reynolds number determination.

Frontal Area

1. The frontal area of each sphere is measured on 7 diameters before packaging. The measurement is made while internal pressure of 20 mb gage is maintained in the sphere. The asphericity must be less than 1% along any 2 diameters. The 7 diameters are averaged and used for the experimental value of frontal area.

Therefore the maximum area error is 1.4% between any two given aspects. In this worst possible case (5 diameters = x, 2 diameters = 1.01x) the average frontal area varies 0.4% from the calculated frontal area. However, in over 80% of the spheres the maximum diameter variation was less than one-half that allowed.

The average error from frontal area measurement is much less than 0.2%. The maximum possible is 0.4%. We have chosen to neglect this error.

2. The area is subject to change if the physical integrity of the sphere is not maintained. We shall describe below how this event is rapid rather than gradual and introduces no error more than 1 km above the abrupt termination.

3. The area is subject to change caused by the capsule weighing 8 g, at -4 g maximum acceleration attempting to deform the sphere. At the nominal internal pressure of 15 mb, the deformation is unmeasurably small. Pressure will be equalizing and skin tension greatly reduced prior to collapse. However, this can only occur in a region with minimum deceleration hence the deforming force is also greatly reduced. Deformation occurs only in the final few hundred meters which data are normally disregarded because of radar smoothing requirements. This source is negligible.

4. The total error due to incorrect frontal area from all sources is believed to be much less than 0.2% on the average and never to exceed 0.4%. It is therefore neglected.

Mach Number and Reynolds Number Determination

Assume that the drag coefficient is known with absolute precision as a function of Mach and Reynolds numbers. Any other error in the entire technique will cause some error in density and temperature. This error will then cause an error in the determination of Mach number and Reynolds number and hence an erroneous drag coefficient will have been chosen.

Fortunately, drag coefficient is only a weak function of Mach and Reynolds number except in the transonic region. Tracking data is processed with an iteration of Mach and Reynolds numbers by assuming the temperature and density in the layer above. Mach and Reynolds numbers are calculated. The drag coefficient is obtained and the density and temperature calculated. Mach and Reynolds numbers are recalculated and a new drag coefficient chosen. A new density and temperature are calculated. The process continues until arbitrarily small corrections are made. This convergence is rapid.

In one region, transonic, the drag coefficient is not such a weak function of Mach number and when processing this region occasional failure to converge has been noted. This happens only when processing unusually poor data, as in the case of an uninflated sphere. In these rather rare instances the process does not diverge, but appears to converge so slowly that the computation is halted for economy's sake.

The error in the final data due to erroneous determination of the Mach and Reynolds numbers is a function of all other errors. It is presently one-to-two orders of magnitude less than the drag coefficient error and may be termed negligible.

IMPORTANT ERROR SOURCES

Four sources of error remain to be reckoned with: incorrect mass, incorrect radar data, incorrect drag coefficient, and vertical wind. Vertical wind will be treated in the next section.

Sphere Mass

The 66-cm sphere weighs about 50 g: 34 g of Mylar, 8 g of aluminum capsule, and 8 g of isopentane. The mass is determined by weighing the deflated, evacuated envelope in a chemical balance and recorded to 1/1000 g. Considerable care is exercised and personal error in this operation has never been considered an error source in the system.

The only other way for a mass error to enter is for the mass to change after weighing, after rocket launch, or after ejection. First we consider the Mylar. If any portion of the Mylar is lost the sphere has no ability to be inflated and if already inflated will collapse under the slightest aerodynamic force. A collapsed or noninflated sphere is useless for density determination. Therefore loss of Mylar is impossible as an error source. Next consider loss of the capsule. This is impossible without a loss of pressure integrity of the sphere and is equally impossible as a mass error source.

Loss of isopentane is the remaining possibility. If the capsule should leak after the sphere is weighed and the liquid (or gas, B.P. 28°C) should permeate the Mylar and escape, a mass error would be introduced. We have tested capsules by oven baking and then weighing daily for weeks, and by storage for five years and have yet to detect a leak. We conclude that such a leak is improbable. Each flight capsule is subjected to a bake test and then weighed daily for one week before being packaged in a flight sphere.

If the capsule should leak after launch and prior to ejection the isopentane would have insufficient time to permeate the Mylar and escape, hence no loss of mass. It would, however, tend to inflate the packaged, unejected sphere at the low ambient pressure and probably cause a sphere failure at ejection. Thus, if the sphere was seen to be properly inflated by the radar, then no mass loss of this type could have occurred.

There remains only one possibility for incorrect mass—loss of isopentane after ejection in a very slow, noncatastrophic manner as if issuing from a pinhole leak. There are three ways this might occur:

1. After pressure test the air is evacuated from the sphere through a

hole which is subsequently taped shut. It is impossible to pressure test this tape for leakage on a flight sphere. Many simulation tests of flight-ready spheres have been conducted and in one case there was such a leak, therefore, it is a definite possibility.

2. After pressure test, the pressurizing hose is removed and the hole taped, similar to (1). Although no leaks have been detected, the same considerations apply.

3. When packaging the evacuated sphere for flight it is folded and squeezed severely to fit inside the sabot. Although accomplished as carefully as possible, a fold-point might become a pinhole. Testing has been limited. Numerous ejection tests in vacuum chambers are useless to prove this point as the high velocity of ejection causes the sphere to rupture upon striking the side of the chamber, even when caught in a net. This occurrence is likewise possible.

However, if pinhole leakage occurred at time of ejection the isopentane would continue to leak during flight and the sphere would lose pressure as well as mass. In this case the sphere will deflate at some altitude considerably above the design deflation altitude. The 66-cm spheres are designed for internal pressure of approximately 15 mb and should deflate at approximately 28.5-km.

If deflation occurs at the design altitude there is no error attributable to incorrect sphere mass. If deflation occurs above the design altitude the logic outlined demands a substantial mass correction. The leak is assumed a sonic jet and the mass change for a 66-cm sphere is given by:

$$\frac{m}{m_{70}} = e^{-\alpha} \qquad \alpha = \frac{t - 70}{t_d - 70} \ln \frac{15}{p_d}$$

where:

m_{70} is mass of gas at 70 sec (ejection)
t is time (sec)
p is ambient pressure (mb)
sub d is at deflation.

The calculation of mass loss at a given altitude as a function of deflation altitude for the 66-cm sphere is shown in figure 2. In figure 3 is given the percent change of sphere mass at any altitude as a function of deflation altitude. If not corrected, this percent change may be thought of as a density error. Figure 4 shows the effect of mass correction for early deflation on NASA 10.265.

The correction of sphere mass for premature deflation is sufficiently important that it is incumbent upon the experimenter to determine the altitude of deflation carefully on each flight. We have found this to be an obvious procedure, although it was once disputed.

The deflation altitude is found by first reducing the data to as low an altitude as possible, neglecting where deflation may or may not occur. Then the fall rate, or vertical velocity is plotted on a semilogarithmic graph. Figure 5 is an example of such a plot. The solid lines represent the standard deviation in fall rate of 12 soundings at Kwajalein Island. Fall rate never departs from this pattern until deflation when it suddenly decreases. It is elementary to note the normal deflation of one sphere (NASA 10.253) and the abnormal 40-km deflation of the other (NASA 10.265).

If the fall rate plot is not sufficiently convincing, the plot of densities should be made. Figure 6 shows the density data from the same two flights. A 30 to 40% density increase in 1-km cannot occur and indicates deflation.

The radar AGC records confirm deflation rather than indicate it. On many occasions the AGC record has a remarkable change of character at deflation, it is often subtle, but always detectable on the FPQ-6. The two flights under discussion are excellent examples of both extremes and are shown in figure 7. The deflation of 10.265 is sufficiently obvious that it may be utilized to pinpoint the exact time and therefore altitude of deflation. Deflation of 10.253 is not immediately obvious but a definite change of character in the signal is there. If several more feet of the record could be shown it would be even easier to verify, since the high frequencies persist to the end of the record and no high frequencies are present in the noise earlier in the flight. Pinpointing deflation time of 10.253 would be hazardous. It may be added that normal and premature deflations have no correlation with AGC signal characteristics.

Summarizing the sphere mass error discussion: There is no error attributable to sphere mass when deflation occurs at design altitude. There is a substantial correction to mass required when premature deflation occurs. Whether this correction is exact depends upon the logical arguments given. No other logical argument has been heard. Since the correction is large, based on ideal flow through an orifice, and since the character of a leak is indeterminate it is important to pay careful attention to sphere sealing and packing as well as an accurate determination of the deflation altitude. This determination is simple and precise.

Radar Tracking Data

1. Discussion

Radar position data has long been credited with contributing a major share of error in the sphere technique. In order to determine the magnitude of the error many computer simulations have been made but sufficiently elaborate radar error functions cannot be supplied. Therefore, these studies proved to be inconclusive.

Recent flights have been made which promise to end the speculation, all involving use of the AN/FPQ-6 radar at Wallops Island, Va. This radar has on the order of 20 db more return signal than the standard AN/FPS-16 radar due to higher gain in transmission and antenna, a smaller angular error specification, and a direct reading range-rate output which is superior to our best computed effort at range differentiation. All told, the performance of the AN/FPQ-6 was such as to be expected to yield the highest quality sphere data yet obtained.

The importance of this high quality data was not in improving the knowledge of the upper-atmosphere over Wallops Island, but in serving as a standard for comparing other radar performance, particularly the AN/FPS-16, and for determining the overall precision of our reduction techniques.

2. Techniques Compared

It has been long recognized that the highest quality data in a passive sphere technique is obtained when the sphere is ejected on the upleg. Since radars are fundamentally a range-measuring device their range data are vastly superior to their angle data. The upleg drag acceleration can then be computed almost wholly by double-differentiation of the range data because the sphere is flying directly away from the radar and angle measurement is of small import.

The FPQ-6 with range-rate output used in conjunction with upleg ejection was expected to and did, provide excellent data to an exceptional altitude and at the same time offered the opportunity to compare three data reduction techniques. The results of sphere 10.253 are shown in figure 8.

The "Ascent-$\mathring{R}$ data" plot from 91 to 120-km are densities obtained by differentiating the range-rate data as explained by Peterson, _et_ _al_. [1965]. This density data represent the best possible as only a single differentiation of the data is required and the angular components of velocity are small.

The "Ascent-R, α, ε data" plot from 95 to 110-km was obtained by our usual upleg technique of singly and doubly differentiating the range-data to provide velocity and acceleration. Again, single differentiation of the angle data is required but angular components of velocity are small.

The "Descent-R, α, ε data" plot from 100-km down to 30-km are densities obtained from our usual descent technique in which single and double differentiation of the range, azimuth, and elevation data is required at each level at which a density calculation is made.

Agreement of the three techniques is outstanding. The significant results are that all three techniques are practical, that an upper altitude limit for each technique is established with good confidence, and that this radar can provide a standard for comparing other radars and methods.

We conclude from this comparison that considering radar tracking errors alone the limits are 93-km for descent, 108-km for ascent range data, and although no comparison can be made, perhaps 120-km for ascent range-rate based on the lack of scatter. The average difference between ascent techniques from 94-to 108-km is 3.1%.

3. Radars Compared

To compare radars we use the technique comparison above which indicated FPQ-6 ascent range-rate data was an excellent standard. Figure 9 compares FPQ-6 ascent range-rate data with FPS-16 ascent and descent data. The FPS-16 radar involved was equipped with parametric amplifiers. (FPS-16 has no range-rate output.) The flight is 10.254 at Wallops Island, Va. The FPS-16 ascent data show considerable scatter beginning at 104-km. Between 97-km and 104-km the average difference is 5% (from FPQ-6 range-rate data). Descent data is obviously yielding an intolerable error above 93-km, while scatter at 88-km and 81-km looks suspicious. Unfortunately, the FPQ-6 on descent was tracking an uninflated second sphere and no descent comparison below 93-km is possible.

In figure 10 is shown a descent comparison of the two radars tracking sphere 14.386 downwards. The FPQ-6 shows scatter above 94-km almost exactly as predicted by the technique comparison. The FPS-16 shows intolerable scatter above 80-km, which also is consistent with figure 9. The agreement below 80-km looks poor to the eye but the average difference is only 2.8%.

Another comparison is available on our unusual wave-like sounding 10.154. With the FPQ-6, ascent range data is good to about 110 km, descent data to 98-km. The maximum altitude on the FPS-16 is 102-km for ascent and 82-km for descent. The FPS-16 was not equipped with parametric amplifiers at the time of this flight. The descent data comparison is truly phenomonal as the plotted points below 80-km cannot be distinguished at most altitudes. The average difference below 80-km is only 1%.

4. Summary

The comparisons of radar performance and data processing techniques have yielded conclusive results:

a. The fine atmospheric structure shown by the falling sphere technique cannot be dismissed as a problem associated with radar tracking error. This is proved conclusively by the two independent tracks of 10.154 which copy every structural detail. If the small excursions are not atmospheric, they are due to some other error source.

b. The performance of the radar or radar-sphere combination is considerably variable. Compare 1.0% on sphere 10.154 with 2.8% on sphere 14.386.

c. The maximum altitude of satisfactory radar performance with a 66-cm sphere is approximately:

Technique	Max. Alt.
FPQ-6 Ascent (range-rate)	120-km
FPQ-6 Ascent (range, angles)	108-km
FPQ-6 Descent (range, angles)	94-km
FPS-16 Ascent (range, angles)	102-km
FPS-16 Descent (range, angles)	80-km

d. Density errors due to radar tracking errors below 80-km may average on the order of 2% with the FPS-16 and 1% with the FPQ-6. Above 80-km the technique must be carefully chosen to ensure validity. If the tabular values in (c) are observed the error should not exceed an average of 3%.

Drag Coefficient

The knowledge of drag coefficient (C_D) as a function of Mach and Reynolds numbers is essential to relate the experiment results to the ambient atmosphere. The falling-sphere technique yields the product of C_D and density as primary data, hence errors in C_D cause inverse proportionate errors in density.

Aerodynamic drag theory can predict the drag coefficient in certain Mach and Reynolds number regimes with precision but these regimes are limited. Virtually all the drag coefficients required must be experimentally determined. Because experimental data were badly lacking in some regimes required for passive sphere data experimental wind tunnel measurements were conducted [Heinrich, 1965]. These experimental data were soon utilized by most if not all passive sphere experimenters.

All inflated spheres are designed for a minimum mass-to-area ratio, therefore when falling through the atmosphere they quickly lose velocity, pass through the transonic region, and reach a terminal velocity of less than Mach 0.39 at about 58-km altitude for a 66-cm sphere. The spheres continue their flight at smaller Mach numbers thereafter. This Mach number is of interest because the referenced investigator, Heinrich, presented a curve and table for $M \leq 0.39$ implying no Mach number dependence below that number. This curve and tabular values did not agree in slope with his wind tunnel results at higher Mach numbers. Using these data we consistently derived extraordinarily high stratopause temperatures. The temperatures were the result of using the $M \leq .39$ curve as it was exclusively used below 58-km.

In 1968, another series of experiments was conducted in a ballistic range [Goin, 1968]. These results exhibited much the same trends as the Heinrich's $M \leq .39$ curve but were about 10% lower in the Reynolds number range of interest $(2,000 < Re < 20,000)$. Figure 11 presents the results of Goin, Heinrich, Heinrich's $M \leq 0.39$ curve, and some other experimental results of Wieselsberger and Lunnon. Goin's data closely match Wieselsberger's and Lunnon's, while they do not confirm Heinrich's data at higher Mach numbers, even in trend.

We were concerned about the seeming discrepancy at $M \leq .39$ until, checking, no experimental basis for the Heinrich curve was found.

Passive-tracked-sphere experimentalists should use the Goin data. Otherwise, density results will be about 10% low at Mach numbers below $M = .39$. For 66-cm spheres the temperatures will also be erroneous as the curve is entered at a Reynolds number where the slope is incorrect as well.

In the case of 1-meter spheres, the curve is entered at a Reynolds number some 50% higher in a region where the slope is approximately correct. This causes minor effect on temperatures but a large density error will still be encountered.

Further experiments to obtain suitable drag coefficients in the transonic and some supersonic regions are indicated. The small scatter of Goin's ballistic range data (total excursion less than ±1%) affords basis for optimism that the drag coefficients can be measured reliably along the entire trajectory to an accuracy approaching 1% excepting the region very close to Mach 1.0.

Summary

Three major error sources have been discussed. Mass error is nonexistent on properly deflating spheres, but an appreciable correction, implying unknown error, is required in the case of premature deflation. Radar tracking errors were shown to be intolerable above a limiting altitude which depends on radar type and sphere technique. Below this limit, average errors of 1% to 3% were inherent with the AN/FPQ-6 and AN/FPS-16 respectively. Drag coefficient errors of under 2% were found in the subsonic regime which spans a major portion of each flight when using Goin's data. A major error occurring from use of Heinrich's $M \leq .39$ curve is noted which is unusually important because $M \leq .39$ covers 30 to 40% of the altitude range.

ANALYSIS OF THE UNUSUAL SOUNDING

Error Magnitudes

Figure 1 demonstrated sphere densities from 10.154 which were unusual in having oscillations of 24%, 36%, and 24% peak-to-peak with 10-km vertical wavelength, lying between 30 and 60-km.

The question was apparent: could this wave-like oscillation be erroneous? In the previous discussion all known error sources were examined. Three were found to be negligible. Three more were found to be significant: mass loss, drag coefficient, and radar track. In 10.154 deflation was at the normal altitude and mass loss is ruled out as the source of any error. In the regime below 60-km, drag coefficients are known quite well; interpolation for Mach number between Goin's measurements should add less than 1% and the Goin measurements are on the order of 1%. Radar tracking by two radars was in extraordinary agreement, implying an average error of approximately 1% due to the radar track-errors. These three errors are not necessarily random so the three are added to give a conservative total error of 3%. Therefore the oscillations cannot be due to any error source we have discussed.

Vertical Winds

From our previous analysis it is evident that the wave-like oscillation of density on sounding 10.154 must be atmospheric. The most convincing conformation would be another sounding. Fortunately, the unusual sounding was the first of a series, and was followed by another about nine hours later. Figure 12 shows the density results of both, 10.154 and 10.169. While the wave-like oscillation is of smaller amplitude and shifted somewhat in the vertical scale, 10.169 confirms that the effect was atmospheric and had persisted for hours. It too, viewed alone, would be termed unusual.

In the falling-sphere technique, it is impossible to distinguish density effects from vertical winds. The vertical wind was customarily assumed to be negligible, and for years most theorists felt that the vertical component would attain a maximum of several centimeters per second. The possibility of vertical motion induced by gravity waves should also be considered. Vertical winds as high as 25 m/s have been estimated from noctilucent cloud observations above 80-km [Witt, 1962]. Short period gravity waves may induce relatively large vertical velocity [C. O. Hines, private communication, 1967]. In analyzing the unusual sounding we found a vertical wind component of 3 m/s would have been sufficient to cause the oscillation presumed to be density. The falling-sphere technique appears to be an excellent detector of a gravity wave, though by its nature must fail to distinguish vertical wind from density. In a strong wave, such as encountered in 10.154 any portion of the density oscillation which was in fact a vertical wind would cause erroneously large temperature oscillations.

CONCLUSIONS

The passively-tracked, inflated, falling-sphere technique is adequate for making routine high-altitude soundings with economy and accuracy, but is limited to sites having a powerful radar. Evaluation of the sphere deflation altitude and the correction of sphere mass is crucial to deriving the correct atmospheric density. Descent density data obtained by tracking a 66-cm inflatable sphere with a AN/FPS-16 radar equipped with parametric amplifiers is questionable above an altitude of 80-km. New drag coefficient data as measured by Goin should be used to derive the proper atmospheric density profile. The inflatable, passive sphere appears to be an excellent detector of a gravity wave, though by its nature must fail to distinguish vertical wind from density.

REFERENCES

Goin, Kennith L.; and Lawrence, W. R.: Subsonic Drag of Spheres at Reynolds Numbers From 200 to 10,000. AIAA J. (Tech. Notes), vol. 6, no. 5, May 1968, pp. 961-962.

Heinrich, H. G.; Niccum, R. J.; Haak, E. L.; Jamison, L. R.; and George, R. L.: Modification of the Robin Meteorological Balloon. Volume II - Drag Evaluations. AFCRL-65-734(II), U.S. Air Force, Sept. 30, 1965. (Available from DDC as AD629775.)

Lunnon, R. G.: Fluid Resistance to Moving Spheres. Proc. Roy. Soc. (London), ser. A, vol. 118, Apr. 2, 1928, pp. 680-694.

Peterson, J. W.; Hansen, W. H.; McWatters, K. D.; and Bonfanti, G.: Falling Sphere Measurements Over Kwajalein. J. Geophys. Res., vol. 70, no. 18, Sept. 15, 1965, pp. 4477-4489.

Wieselsberger, C.: Further Investigations of the Laws of Fluid Resistance. Phys. Z., vol. 23, May 15, 1922, pp. 219-224.

Witt, G.: Height, Structure and Displacements of Noctilucent Clouds. Tellus, vol. 14, no. 1, Feb. 1962, pp. 1-18.

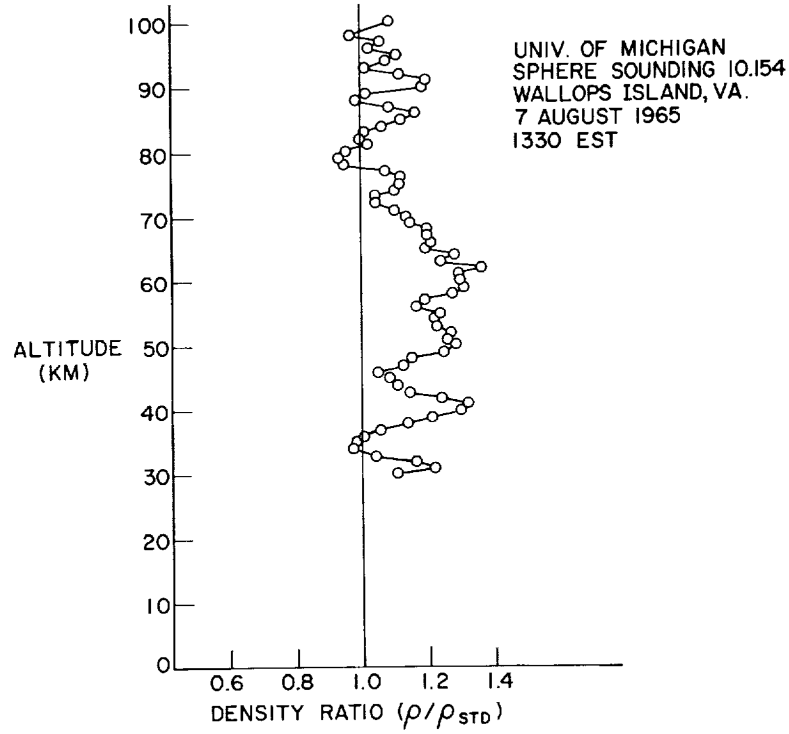

Figure 1.- A very unusual sounding.

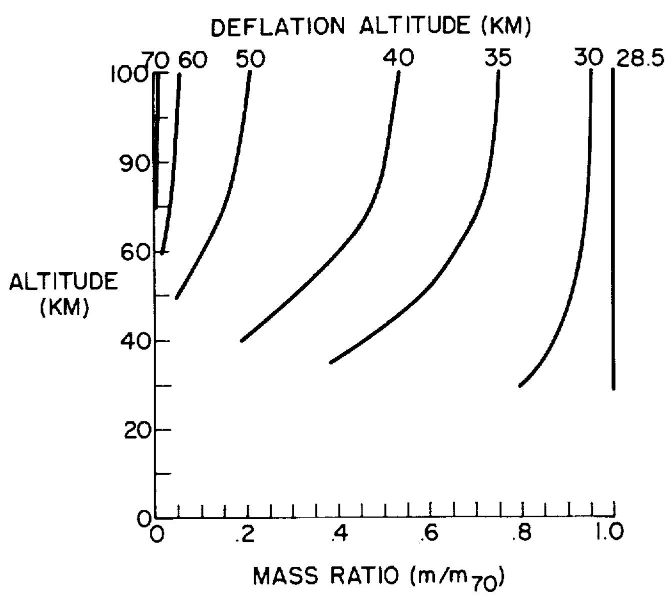

Figure 2.- Ratio of mass of gas in sphere at any altitude to mass of gas in sphere at ejection (70 sec) as a function of deflation altitude.

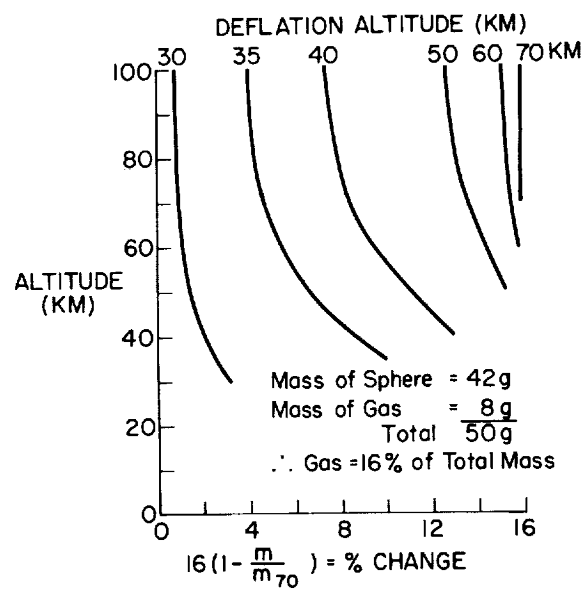

Figure 3.- Percent change in sphere mass caused by a leak.

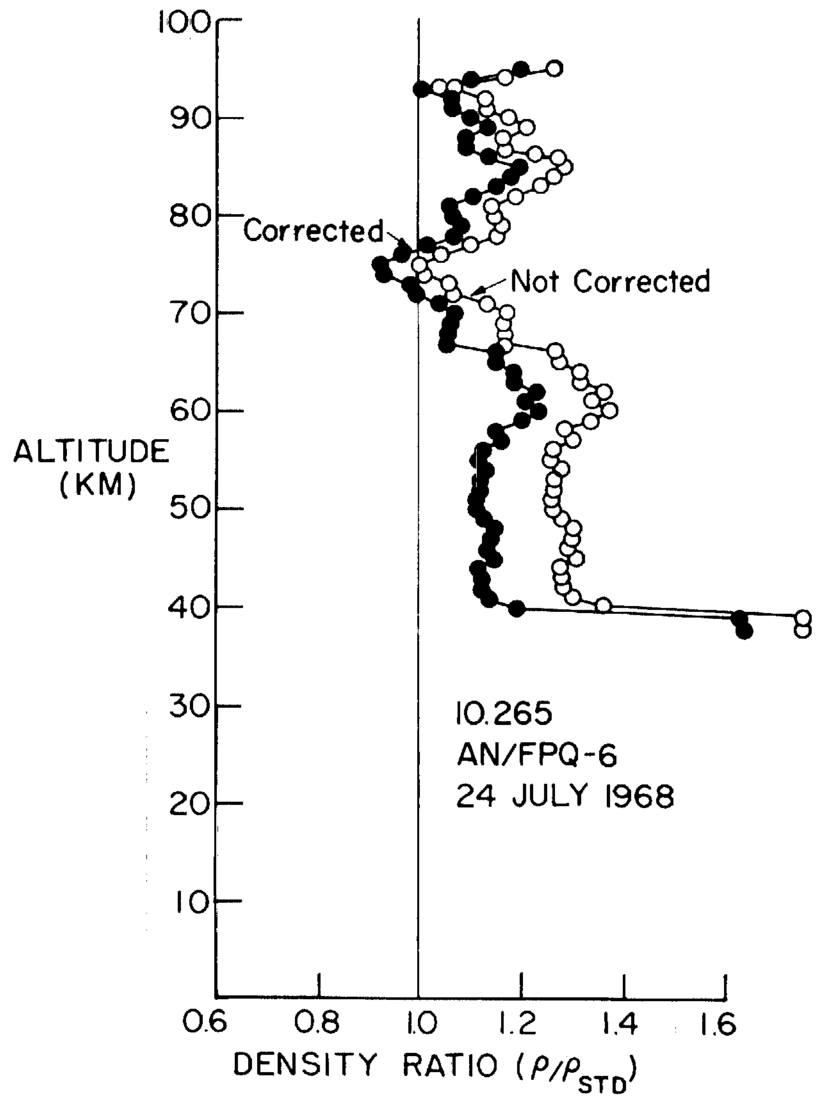

Figure 4.- Effect of mass correction on density in the case of an early deflation.

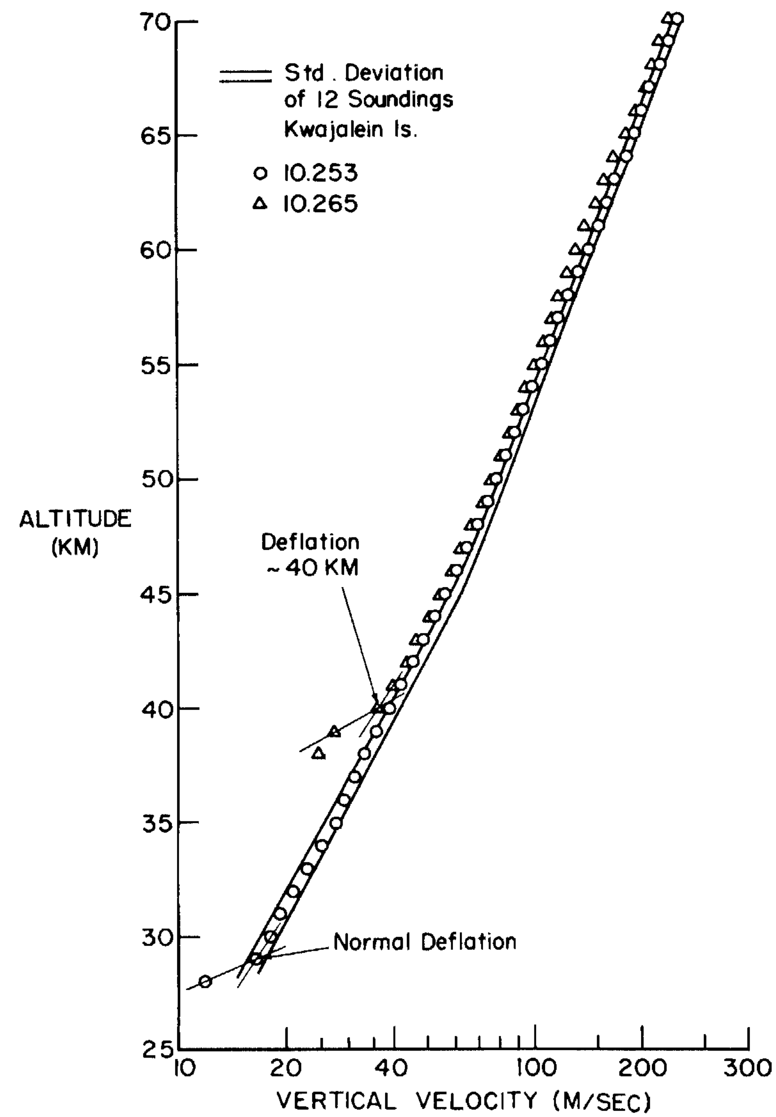

Figure 5.- Fall rate indicates sphere deflation.

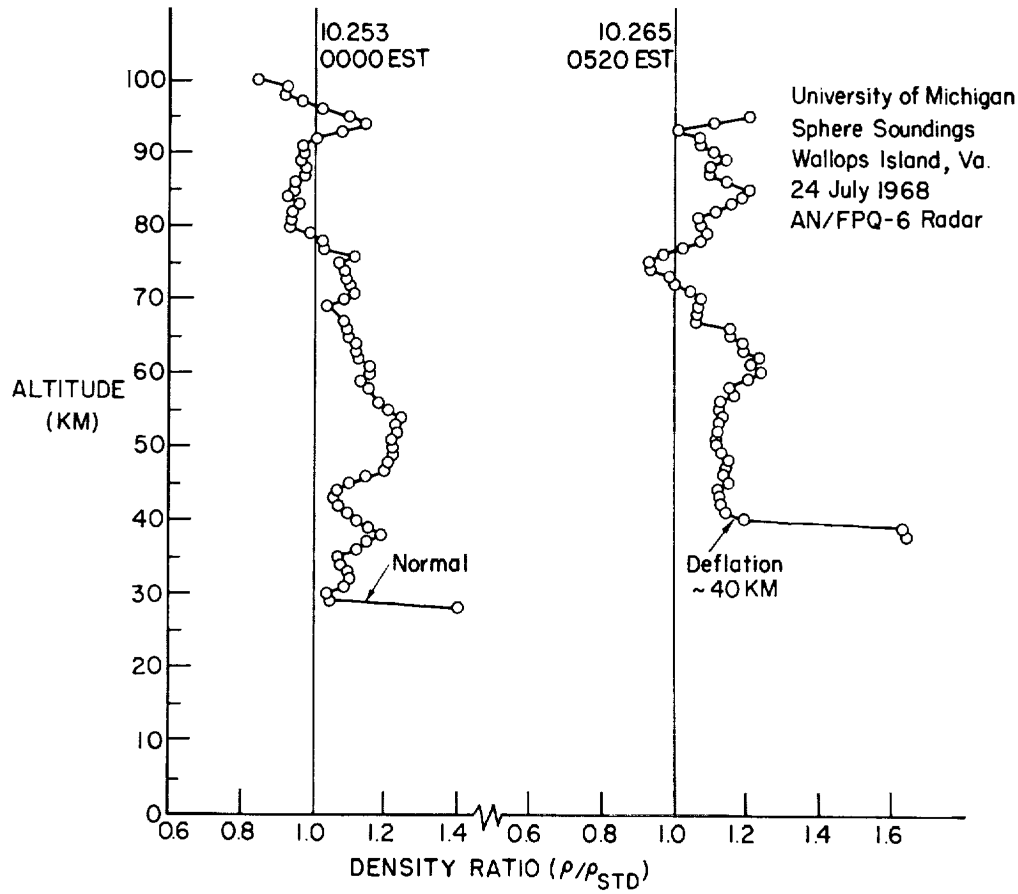

Figure 6.- Density ratio indicates sphere deflation.

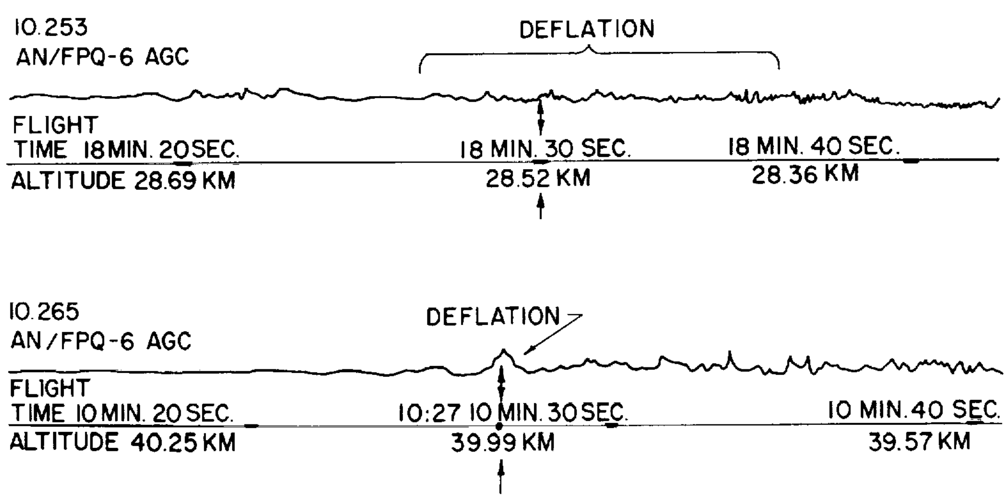

Figure 7.- Deflation observed on AGC records.

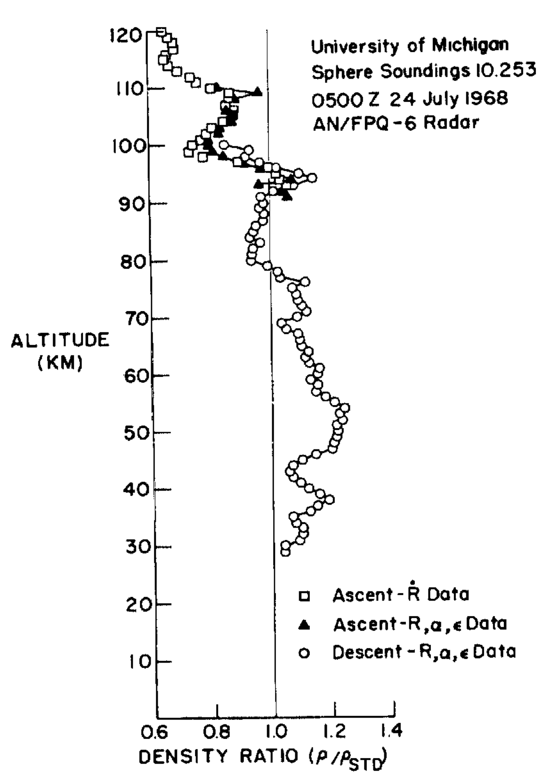

Figure 8.- Three sphere data techniques.

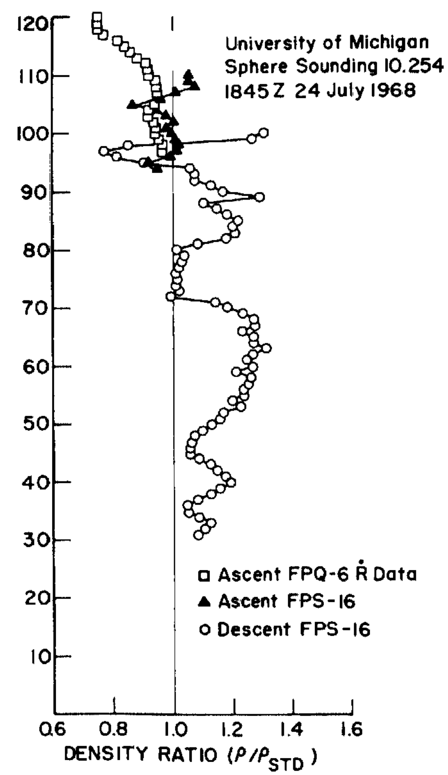

Figure 9.- Comparison of AN/FPQ-6 with AN/FPS-16 in July 1968.

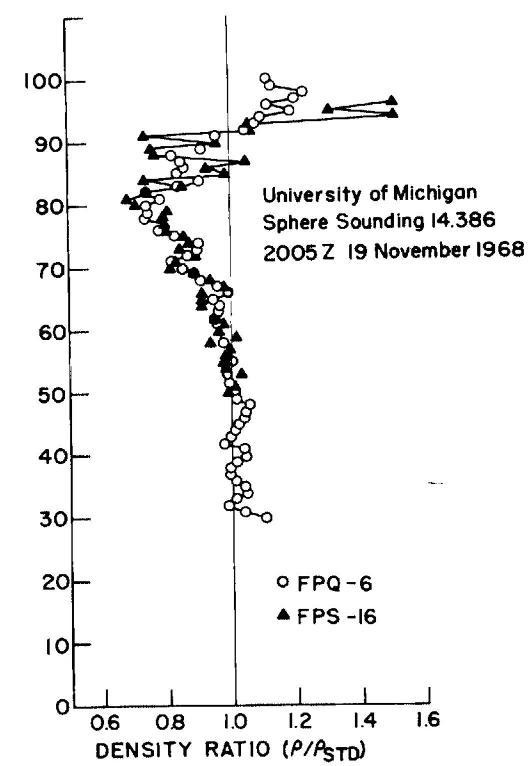

Figure 10.- Comparison of AN/FPQ-6 with AN/FPS-16 in November 1968.

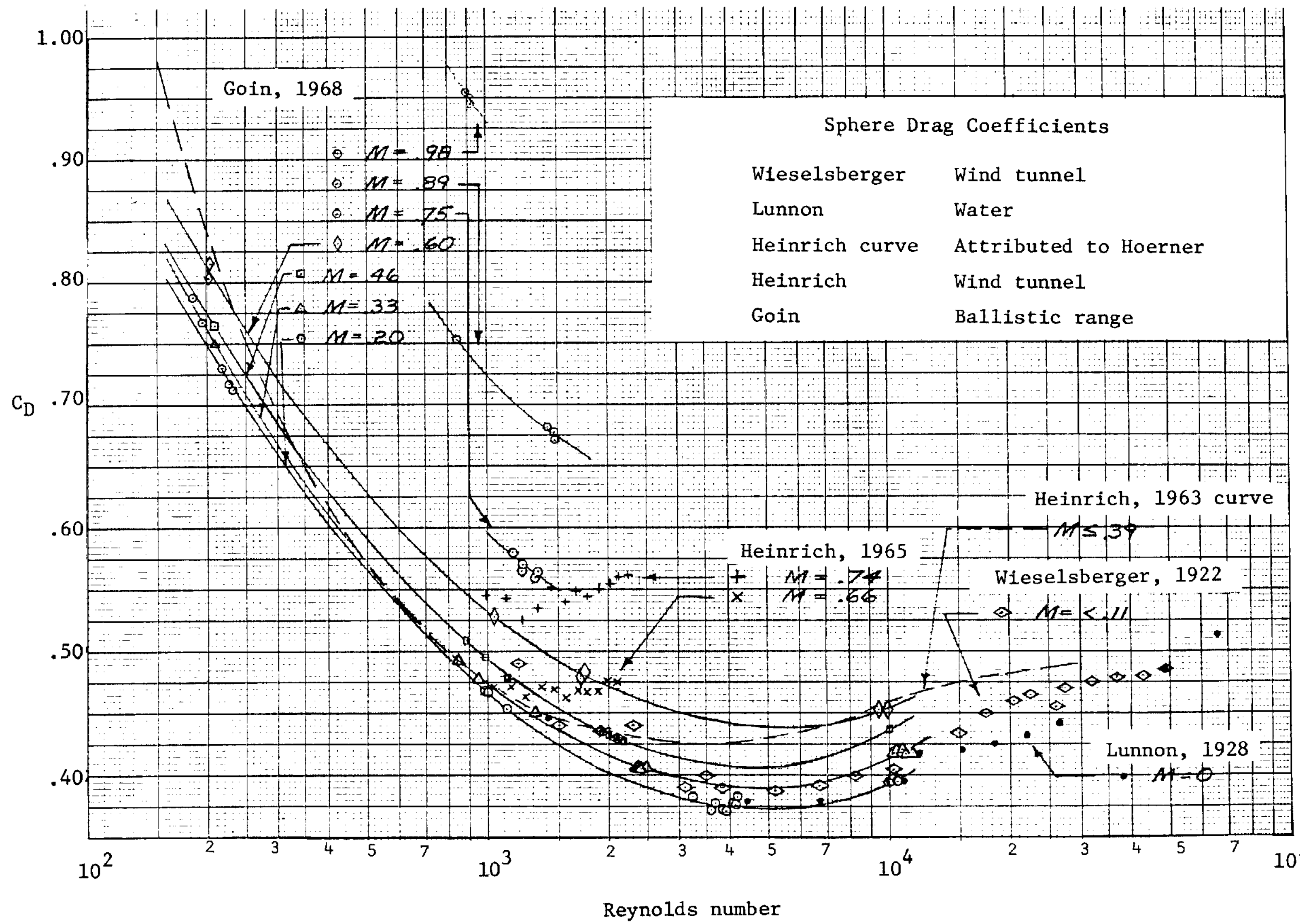

Figure 11.- Sphere drag coefficients.

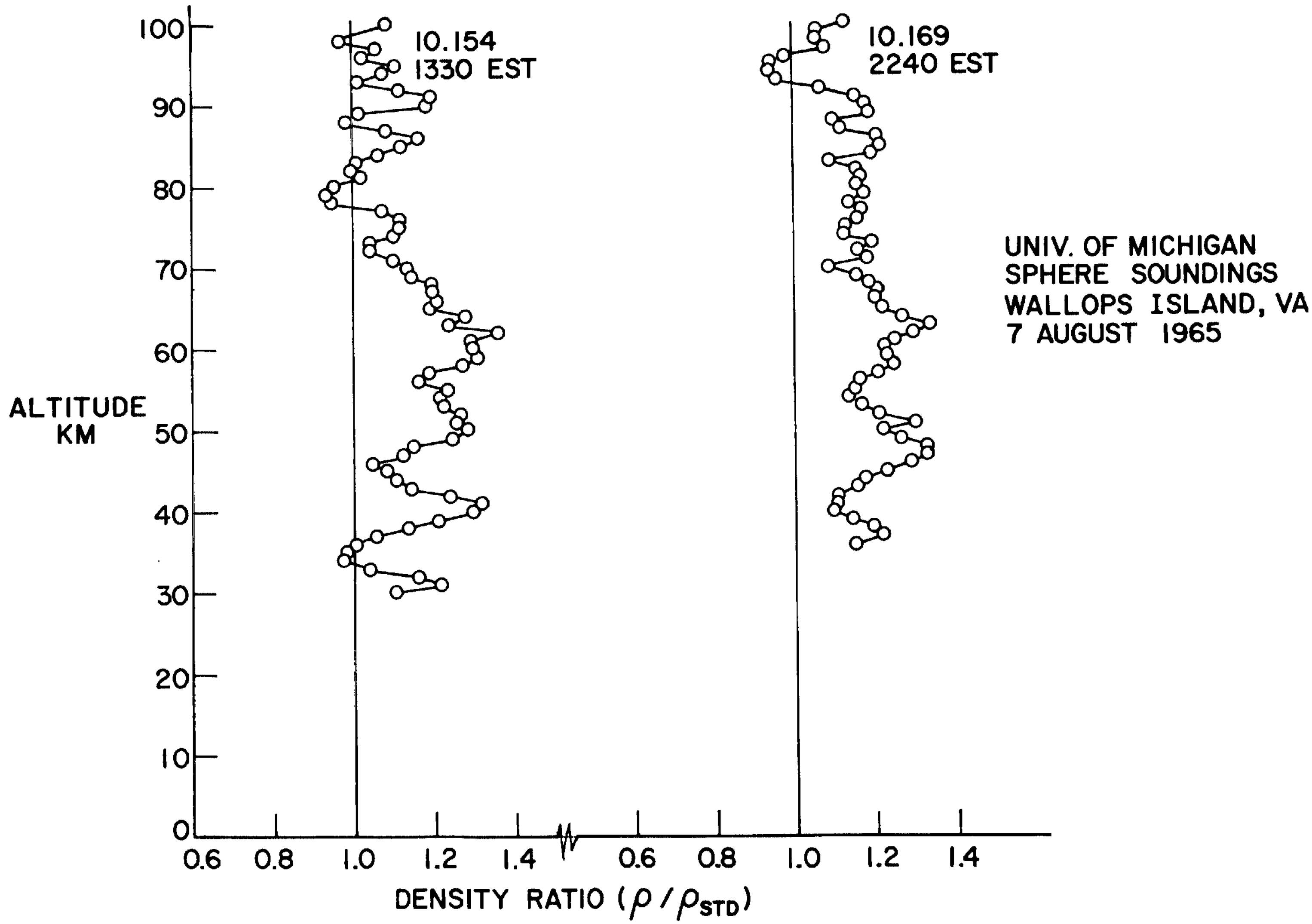

Figure 12.- The unusual sounding and another 9 hours later.