RESULTS FROM SEVERAL EXPERIMENTS AT WHITE SANDS MISSILE RANGE AIMED AT ASSESSMENT OF FALLING-SPHERE DENSITY DATA

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SUMMARY

Density measurements utilizing inflatable passive falling spheres were made at White Sands Missile Range. Two different rocket vehicle systems, the Viper balloon dart system and the Super Loki balloon dart system, were used to deploy the sphere at apogee to demonstrate the capabilities of each of these systems in providing high-altitude data. Five sets of density data computed from a total of fourteen flights were compared with density data derived from rocketsonde soundings and the 1966 Standard Atmosphere. A negative density departure from the 1966 Standard Atmosphere was shown to exist between 70 and 80 km. Two sets of density data were derived from each flight, with the exception of the first flight, one utilizing the Sandia drag table the other the University of Minnesota drag table. The difference between the density values using the two tables can be as great as 12%. Density data computed from these flights were compared with density data derived from rocketsonde soundings and the 1966 Standard Atmosphere. These comparisons indicate varying agreement; however, no conclusions can be made because of the limited number of comparisons. One flight compared density differences derived from the radar tracks of two FPS-16 radars tracking the same sphere. These differences were within $\pm$ 1% throughout the vertical profile. Some of the problems encountered in acquiring density data from approximately 40 to 100 km and some of the areas in which the sphere data may be questionable are discussed.

INTRODUCTION

The Atmospheric Sciences Laboratory at White Sands Missile Range provides upper atmospheric data to Range Projects. In support of these missions, surface observations, radiosonde releases, and rocketsonde launches are made to provide a vertical profile of the atmosphere from the surface to 65 km.

Recently, several of these programs, particularly those involved in reentry studies, have specified a requirement for density data up to 100 km. This increased altitude is beyond the capabilities of the usual low cost operational sensors and vehicles; thus, a different technique or method must be developed to meet the new requirements.

The system which demonstrated the most promise as a density measuring tool at altitudes above 65 km is the passive falling sphere being developed by the Air Force Cambridge Research Laboratory (ref. 1). Its advantages as an operational system for use at a missile range are low cost relative to other density measuring systems, basic operational simplicity, and tracking by AN/FPS-16 radars, which are the radars utilized at missile ranges. Two different rocket vehicle systems were available, the Viper and Super Loki (ref. 2) which can deliver the inflatable 1/2-mil Mylar sphere to apogees in excess of 125 km at White Sands Missile Range. The apogee performance of these rocket vehicles is aided by the higher launch elevation of approximately 1200 meters mean sea level (MSL) at the Range. This performance satisfies the apogee altitude of approximately 125 km required to derive density data from 40 to approximately 100 km.

Plans were made to flight test both configurations and establish the upper limits of density data that could be derived from both systems. The advantage in utilizing the smaller Super Loki rocket motor rather than the larger Viper rocket motor was lower cost. It was believed that the Super Loki system could be used when there was no stringent requirement for density data to 100 km, and data between 90 and 95 km would suffice.

Nine Viper and five Super Loki balloon dart systems were employed in determining the operational characteristics and density measuring capabilities of these systems. Two computer programs were provided by the University of Dayton Research Institute (ref. 3) through the U. S. Air Force Cambridge Research Laboratory. The first program contained the drag values derived at the University of Minnesota hereafter termed the Minnesota drag table (ref. 4), a second program contained the sphere drag values from the Tullahoma ballistic range hereafter termed Sandia drag table (ref. 5). It was necessary to derive densities using both programs since there was a difference in the drag coefficients reported by the two investigations resulting in differences in derived densities using the same input data.

FLIGHT TEST PROGRAM

For comparison purposes, each sphere launch (table I), except the second Super Loki and second Viper, was made with a supporting rocketsonde. In most cases, two FPS-16 radars were used with each launch to determine whether radars tracking the same falling sphere would yield similar results. Comparisons were also made between two sphere flights when the time lag between launches did not exceed 48 hours. In all cases when density data were derived, a comparison was made with the seasonal 1966 Standard Atmosphere. These comparisons were made with both sets of drag values, those derived from the Minnesota drag table and those derived from the Sandia drag tables.

Each of the launches from which density data were collected is discussed, beginning with the Viper launches, and following with the Super Loki launches.

Viper 1 was launched 14 January 1969, at 1205 hours MST, followed by a rocketsonde launch at 1310 MST. Two FPS-16 radars were used to track the sphere; however, good radar track data were received from only one of the radars, and one set of density data was derived by using the Minnesota drag table. These data were compared with the 1966 Standard Atmosphere, January 30°N, a mean wintertime density profile derived from eight rigid falling spheres (ref. 6) and the rocketsonde densities (fig. 1). The dominant features exhibited by this sounding when compared with the 1966 Standard Atmosphere are the positive density departures at approximately 90 and 58 km and the negative departure in the 74 km region. This type of oscillatory pattern has been noted by other researchers both in theory and empirical data (ref. 7) and could be attributed to the diurnal effects of the upper atmosphere, or to the data from the Standard Atmosphere. Upon inspection of figure 1 it can be seen that, in the upper portions of the data, the trends or slopes are in agreement, with the positive-to-negative departures crossing near the same altitudes. The sphere data show a large negative departure, whereas the mean density data are negative but to a lesser degree.

The large negative departure between 80 and 70 km may be due to the inaccuracies in the drag coefficient for spheres in the transonic region, since it is very difficult to determine drag values accurately in this region.

The comparison between the sphere and rocketsonde data indicates good agreement from 51 to 48 km, at which point the two sets of data diverge markedly. At approximately 42.5 the sphere collapses and cannot be used to compute densities because it is no longer a sphere. A graph of the density ratio between the sphere and sonde is shown in figure 2, where the density departure becomes as much as 12 percent. This difference becomes somewhat difficult to resolve as the sonde should have an increased accuracy at levels below 50 km. Densities using the program with the Sandia drag tables were not derived because the original data tapes were mistakenly degaussed before this was accomplished.

Viper 2 was launched the following day at 1230 MST, with one FPS-16 radar scheduled to track the falling sphere. The apogee altitude and point of deployment of the inflatable sphere was 147 km. Density data could not be derived at an altitude of 97.5 km, when the resultant accelerations of drag and gravity became greater than -3 m sec^{-2}. At 94 km the first density value was derived because of the limitation of the drag table in the low Reynolds number regime at the higher altitude. After this point, density data were derived to an altitude of 78.5 km, where the radar track data appeared to become erratic down to 66 km. Densities were again able to be computed from 66 to 54 km where the sphere collapsed. Figure 3 is a plot of the density departures derived from the Viper 2 launch and utilizes the Minnesota and Sandia drag tables compared with the 1966 Standard Atmosphere. From 94 to 90 km some variation is shown; from 90 to 80 km, both programs yielded identical results; and below 78 km, data are not available from either program until 66 km, after which point the departure values exceed a density ratio greater than two. The density data throughout the vertical

profile appears questionable because of the high density values, this being particularly true below 66 km. This may have been due to the poor quality of radar data which indicated some type of radar tracking problem between 66 and 78 km.

Although the density data from Viper 2 appear to be questionable, the densities computed by the two different drag tables were compared to determine at what point the derived densities deviated. Figure 4 shows some disagreement at the upper end of the data and then identical results from 90 to 78 km; at 66 km, the two drag tables begin to give different density values, with maximum departures of 12 percent from 58 km to balloon collapse at 54 km.

Flights of Viper 8 and 9 were the next analyzed. These two rounds were launched as part of a special series (ref. 8). This series consisted of nine rocketsonde and two sphere launches over a four-hour period. Viper 8 was launched at 1100 hours Mountain Daylight Time (MDT) on 9 May with a supporting rocketsonde launched at 1300 MDT and Viper 9 was launched the next evening (10 May, 2000 MDT).

The density data from Viper 8 (fig. 5) indicate a negative departure from the 1966 Standard Atmosphere. Two sets of density data were plotted by utilizing the different drag tables. The first density value computed from the Minnesota drag table was at an altitude of 76 km, whereas the first value computed from the Sandia drag table was at 82 km. The differences in altitude of the computed densities are possibly due to the more complete Sandia drag table in the particular flow regime experienced by the sphere which was deployed at a lower altitude (92 km) than normal. When the density departures are compared, it can be seen that from 76 to 72 km, the density departures from the Minnesota data are less negative than those computed from the Sandia data. At 70 km, this trend is reversed and continues downward to 42 km, the difference between the values increasing to 14 percent at 42 km. Figure 6 depicts the density ratio between Minnesota and Sandia drag tables and indicates more clearly the difference in density data derived from each of the tables.

Figure 7 shows the density departure determined from data obtained by two FPS-16 radars tracking the same sphere. The difference in derived densities from both radars does not exceed $\pm$ 1 percent. Figure 8 shows the results of the two sets of density data compared with density data computed from the supporting rocketsonde measurement. The data derived from the Sandia table appear to agree more favorably, although the region from 49 to 44 km exhibits rather large positive departures. The density data using the Minnesota drag values show poorer agreement, the values being less than the rocketsonde measurements throughout the same region of measurement.

Results from the comparison of data from Viper 9 to the 1966 Standard Atmosphere are plotted in figure 9. This profile shows mostly negative departures, the largest departure occurring at 76 km. Figure 10 compares both sets of density data derived from the sphere with the rocketsonde

density data. In this case there is better agreement between the densities derived from the Minnesota drag table, with departures from the sonde data being no greater than 5 percent. As mentioned previously Viper 9 was launched in conjunction with a short-term density variability study. The results of this investigation indicated the average density difference in a vertical layer from 58 to 40 km to be 4 percent over a four-hour period, and the variability between two rocketsondes fired almost simultaneously was less than 1 percent. Therefore, a conclusion may be drawn that the variability due to the instrumentation is small and the density varied approximately 3 percent; however, the variation between the density data derived utilizing the Sandia drag and the rocketsonde densities at the same altitudes is from a minimum of approximately 5 percent to a maximum of 13 percent. Figure 11 provides a comparison of the variation between the day and night soundings, the two systems being compared with each other. The sonde data indicate that daytime densities were greater than nighttime densities, whereas the sphere data show a negative departure at 58 km and then a positive departure at 60 km. The sonde data agree with a previous study made at the White Sands Missile Range which indicated the maximum densities at these altitudes to occur during the daytime (ref. 9).

The set of densities from Super Loki 2 was compared to the seasonal 1966 Standard Atmosphere and the mean densities from the rigid sphere with the results plotted on figure 12. Density values were derived beginning at 91 km because above this altitude the Reynolds numbers were too low. Both sets of density data are plotted and are the same down to 72 km, at which point the two sets begin to deviate. There is a large negative departure throughout most of the profile, the maximum departure being at 74 km.

DISCUSSION

The results from the flights of the Viper and Super Loki balloon dart systems at White Sands Missile Range have demonstrated a capability of increasing the heights of atmospheric measurements from 40 km to an altitude between 90 and 100 km. The available density data from the flights, except that of Viper 2, appear to have reasonable values when compared with the Standard Atmosphere. There are some areas in which additional investigation should be made to improve the density measurements. The amount of density data derived from these flights was small, but this condition was due to several factors which can be minimized in the future.

Of the fourteen sphere launches, nine utilized the Viper system and five, the Super Loki system. Four of the Viper systems achieved a dart apogee of under 60 km; this low performance resulted from a mechanical problem which caused poor dart separation. Once this problem was rectified, the remaining vehicles performed satisfactorily. For each of the Viper launches, two FPS-16 radars were scheduled to track the vehicle. This step was found to be absolutely necessary because in the five Viper launches that reached the required altitude, only one launch received good radar track from the assigned FPS-16 radars. In three of the launches, one good

radar track was received from the two radars, and in the case of Viper 6, both radars lost track near apogee and did not reacquire the sphere until it was down to an altitude of 38 km. It is believed that the problem of radars losing a track on the dart can be reduced once the radar personnel become familiar with the performance of the Viper system.

A similar radar problem was encountered with the Super Loki and perhaps intensified since the acceleration of this dart vehicle is the same as that of the Viper but the radar cross-sectional area of the dart is smaller. The radars were able to track only one of the five Super Loki flights successfully. On the first flight, the target was lost by the radars at 69 km and was not reacquired until it was at about 44 km. On the second flight, a good radar track was obtained with one of two FPS-16 radars scheduled to support this flight. The vehicle achieved an apogee of 129 km, and density data were derived from 91 to 58 km; thus, the Super Loki system proved to be capable of collecting high-altitude density data. On the next flight, the radars did not acquire the target, and on the two remaining flights, the radars acquired the spheres below 60 km. Although these initial results were not completely satisfactory, it is believed that they can be vastly improved with experience.

One of the problems exhibited by the sphere itself was the variation in altitude at which the sphere collapsed; this collapse occurred anywhere between 58 and 42.5 km.

Density values could not be computed at altitudes above 94 km even though the resultant acceleration was greater than -3 m sec^{-2} because no drag numbers were available at Reynolds numbers below 150. This situation proved to be the case with Viper 2 and 9 where the spheres were deployed at approximately 147 and 146 km. The same condition occurred with the Super Loki launch where the sphere was deployed at 129 km, and densities were not computed until the sphere reached an altitude of 91 km.

When the densities derived from the two drag tables were compared, there was no difference above 72 km. From that altitude downward, the differences became greater with an average difference of 12 percent between 40 and 50 km. In most cases, the sphere had collapsed at altitudes above 40 km, but the data could still be used to indicate the difference in densities due to use of the two different drag tables although the absolute density values were incorrect after the sphere collapsed.

One of the dominant characteristics of the sphere density data as compared with the 1966 Standard Atmosphere is the negative density departure between 70 and 80 km. This particular characteristic may be due to the error in determining the drag coefficient under transonic flow conditions.

The agreement was generally unsatisfactory when a comparison was made between the sphere densities derived from the two different drag tables and from the rocketsonde. The Sandia values were a little better for one sounding than those derived from the Minnesota drag table; for the other sounding, the opposite was true.

The lack of agreement in the overlap region could be attributed to errors associated with both systems. In the case of the sphere system, there might be some disagreement due to incorrect drag numbers, not precise enough radar data or some other factor associated with computing densities from passive falling spheres. The rocketsonde could also contribute errors to the density due to temperature and height differences in the rocket and radiosonde soundings or to errors in the observed thermistor temperature (ref. 10). In a recent investigation, M. Kays and P. Avara found that a height difference of 300 meters could bias the density at the upper levels by 4 percent, while a temperature error of $2^{\circ}C$ could result in an error of less than 1/2 percent.

These results are preliminary, and additional launchings would be required to determine the overall performance characteristics of this system. Since these are required data, effort should be put into this program which provides density measurements between 100 and 65 km.

CONCLUDING REMARKS

Some specific areas which require further research are discussed below.

Discrepancies in the density measurements between the falling-sphere and rocketsonde techniques should be investigated. Careful consideration should be given to the accurate determination of the radiosonde height for tie on to rocketsonde by a radar track to eliminate possible bias error in the computed density data. Another possible method of circumventing the problem of errors in computing densities at rocketsonde altitudes is to incorporate a pressure sensor into the rocketsonde. This would eliminate the requirement of a radiosonde pressure measurement for computing densities.

The drag curves from the wind tunnel and ballistic ranges should be studied to determine their validity experimentally. This might be accomplished by varying the ballistic coefficient and deployment altitude of several spheres. These spheres would be deployed almost simultaneously in approximately the same space so that each sphere would experience essentially the same atmosphere. The spheres would be at different Mach and Reynolds numbers at a given altitude, but each sphere should yield similar density values at the same altitudes. Another method of testing the drag curves would be to compare the density derived from the spheres and the rocketsonde and use this overlap region to check other portions of the curve. For example, the present sphere is transonic at an altitude between 70 and 80 km; it might be advantageous to have the sphere become transonic at a level at which density data are available from the rocketsonde. This would enable the drag data to be checked against some other measurement, and possibly an empirical determination could be made of some of the drag values. If this cannot be accomplished, at least it could point to certain areas in the drag curves which might require additional work.

The sphere itself might be more closely examined to determine its sphericity.

More drag data should be made available at the lower Reynolds numbers to compute density data to 100 km.

A study should be made to determine which sphere drag coefficients are valid in the subsonic regime, those values measured by Sandia Corp. or those by the University of Minnesota.

Most important comparison flights with other systems and techniques should be made. This would include such systems as the active falling sphere, Pitot probe, grenades and other systems capable of making high-altitude density measurements. A measurement program of this type could aid in determining the validity of the density measurement and could also point out possible areas where the measuring techniques of the various systems might be improved.

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TABLE I

SUMMARY OF LAUNCH DATA

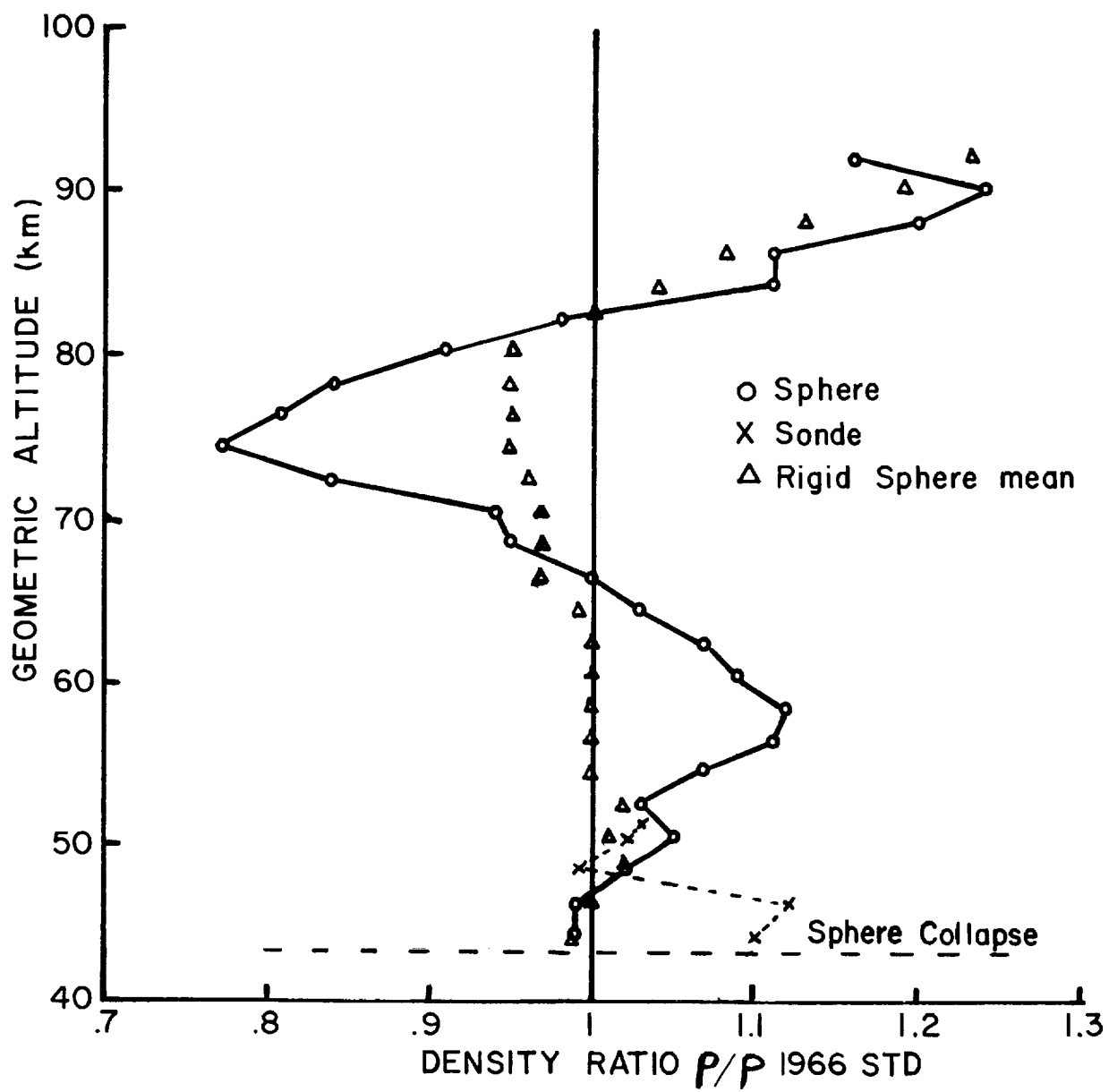| Flight	Date	Launch time, hr	Radars	Apogee altitude, km	Altitude of sphere collapse	Density data, km	Remarks
Viper 1	14 Jan 69	1205	2 FPS-16	147	42.5	94 to 42.5	Good flight
Viper 2	15 Jan 69	1230	1 FPS-16	147	54.0	Data questionable	Good flight
Viper 3	19 Mar 69	1200	2 FPS-16	51	Undetermined	None	Poor dart separation
Viper 4	20 Apr 69	2000	2 FPS-16	43	Undetermined	None	Poor dart separation
Viper 5	25 Apr 69	0930	2 FPS-16	46	Undetermined	None	Poor dart separation
Viper 6	27 Apr 69	2219	2 FPS-16	146 (est.)	Undetermined	None	Radars lost track at 110 sec at 118 km
Viper 7	28 Apr 69	0007	2 FPS-16	18	Undetermined	None	No dart separation
Viper 8	9 May 69	1100	2 FPS-16	94	42.5	83 to 82.5	Low dart apogee
Viper 9	10 May 69	2000	2 FPS-16	145	55.5	92 to 55.5	Good flight
Super Loki 1	24 Jan 69	2000	2 FPS-16	126 (est.)	Undetermined	None	Radars lost track at 55 sec at 69 km
Super Loki 2	27 Jan 69	1500	2 FPS-16	127	58.5	92 to 58.5	Good flight
Super Loki 3	19 Feb 69	1230	1 FPS-16	Unknown	Undetermined	None	No radar acquisition
Super Loki 4	20 Apr 69	2115	2 FPS-16	Unknown	Undetermined	None	No radar acquisition
Super Loki 5	11 May 69	0100	2 FPS-16	126 (est.)	50.0	56 to 50.0	Late radar acquisition at 34.5 sec at 58 km

Figure 1.- Viper 1, 14 Jan 1969, Density Departures from 1966 Standard Atmosphere, January, 30°N.
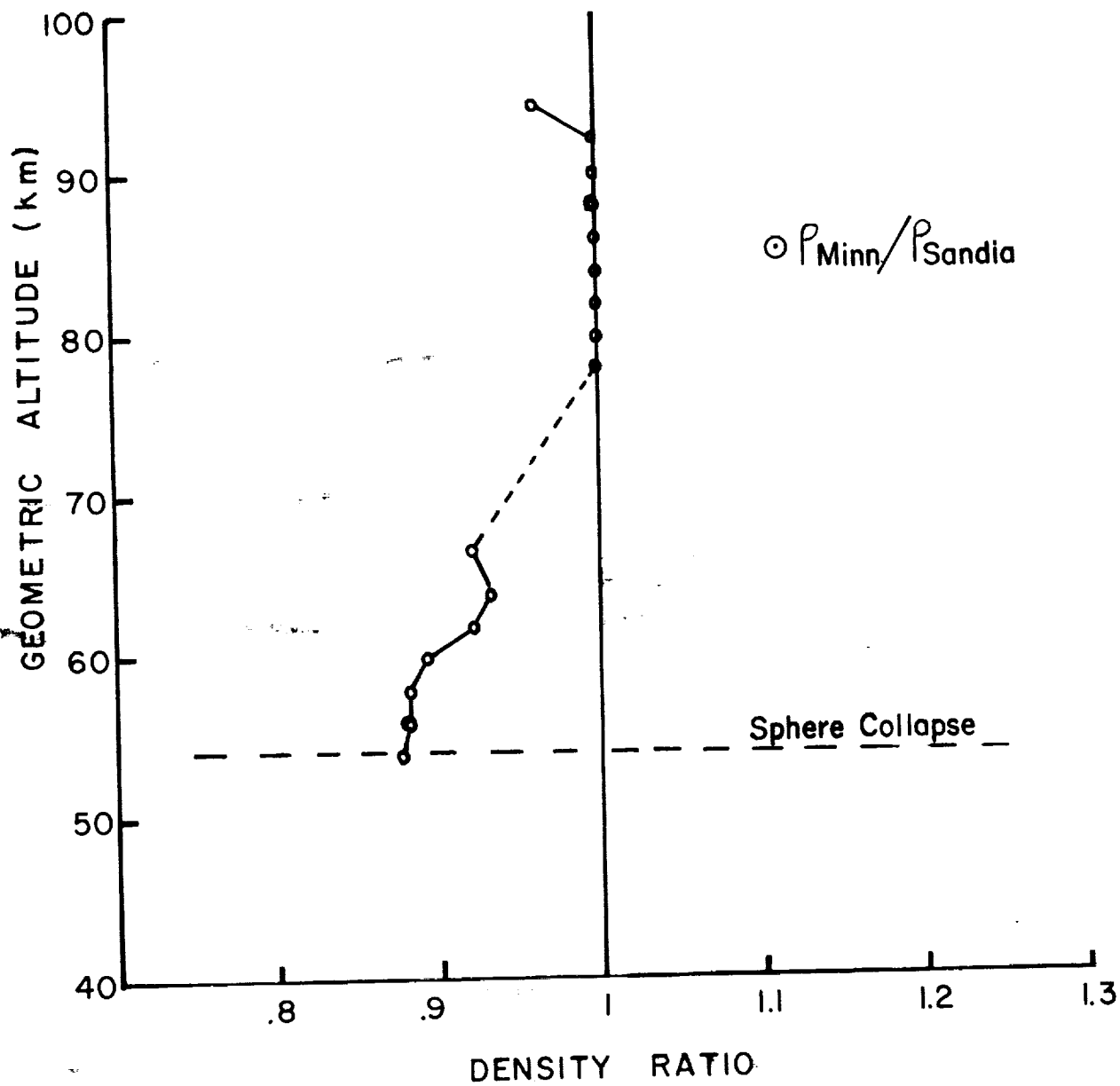
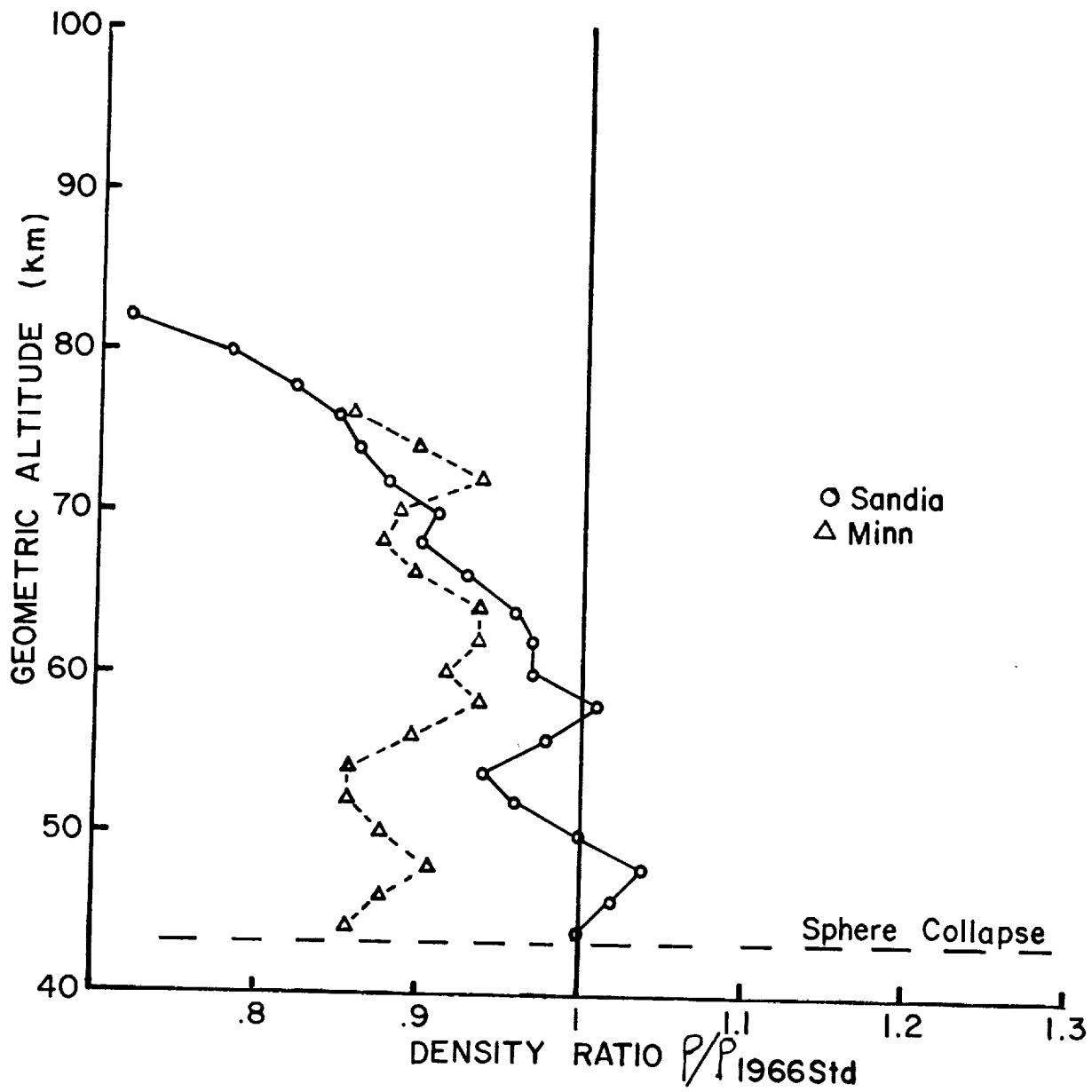Figure 4.- Viper 2, Comparison of Densities Using Different Drag Tables.

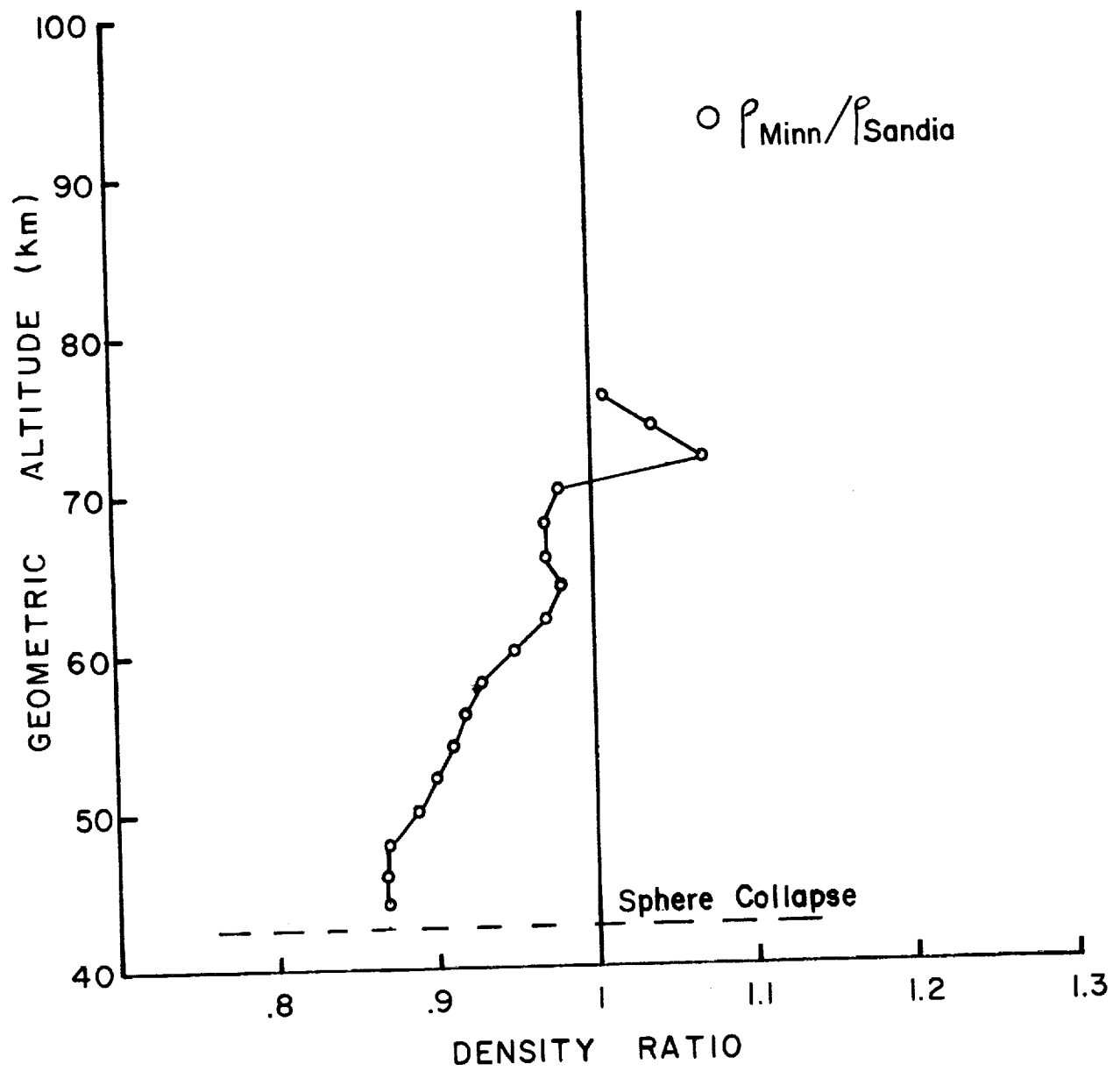Figure 5.- Viper 8, 9 May 1969, Density Departures from 1966 Standard Atmosphere, July, 30°N.

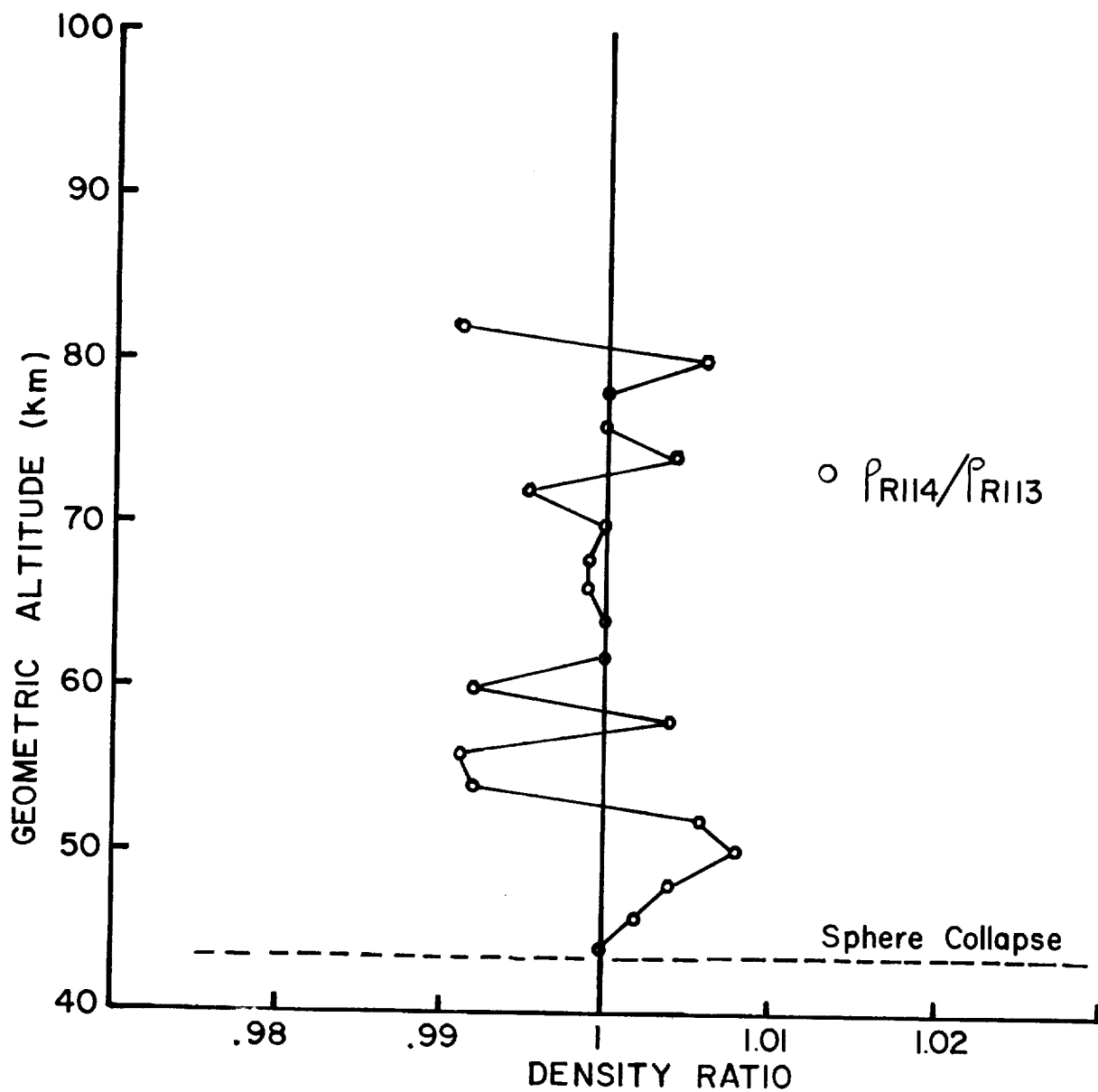Figure 6.- Viper 8, Comparison of Densities Using Different Drag Tables.

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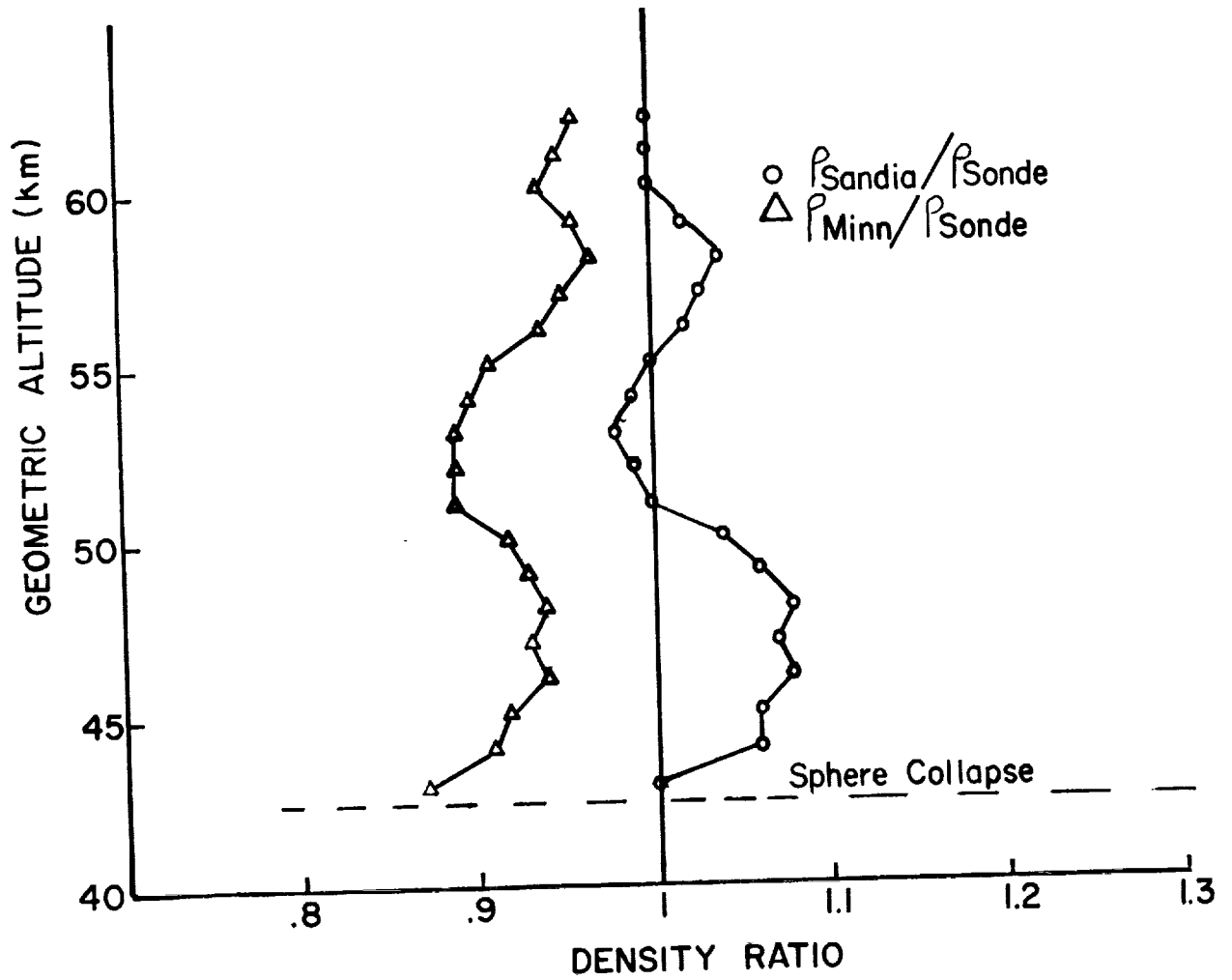Figure 7.- Density Ratio Between 2 FPS-16 Radars Tracking the Same Sphere.
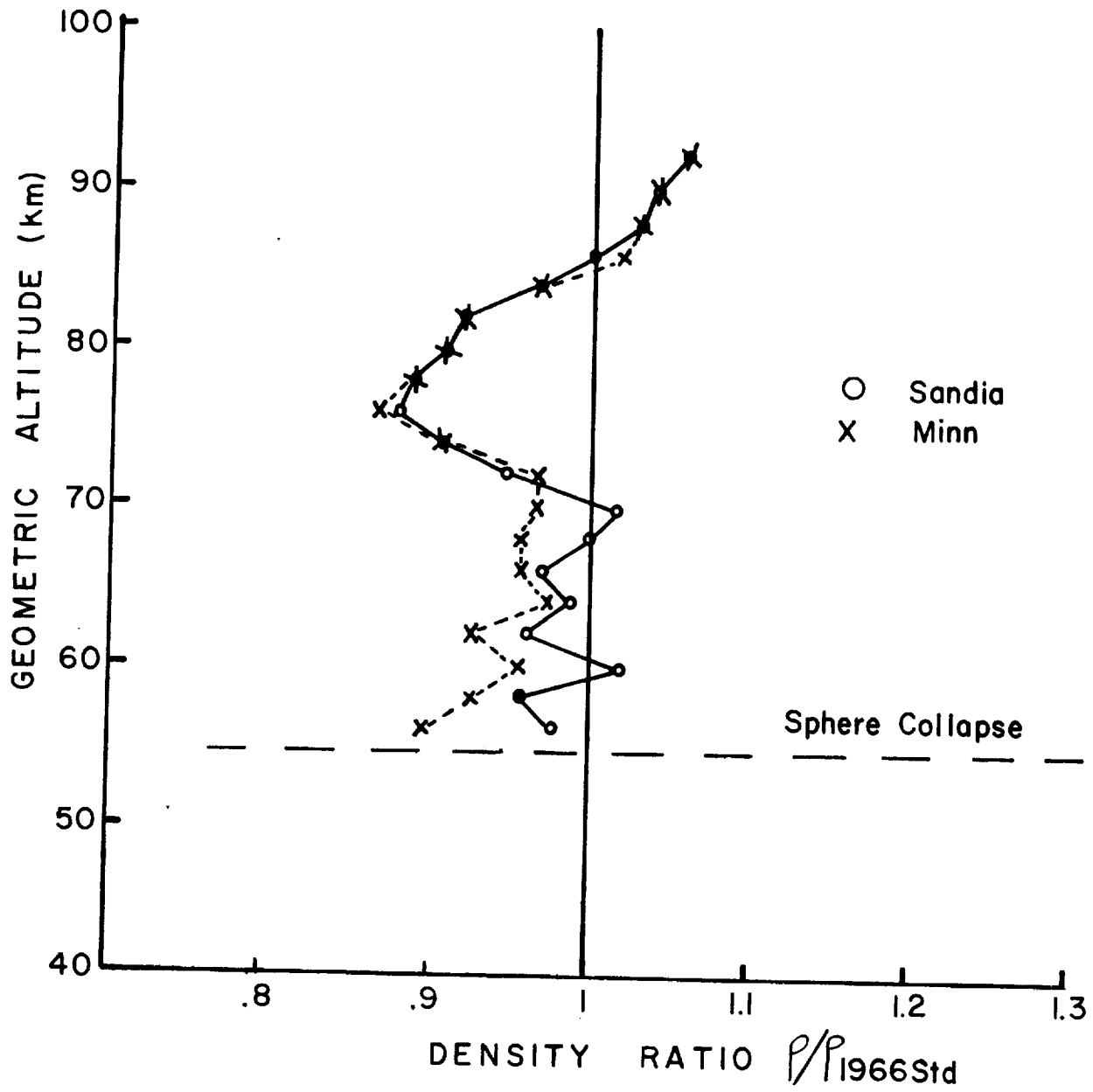
Figure 8.- Viper 8, Comparison of Density Between Sphere and Rocketsonde.

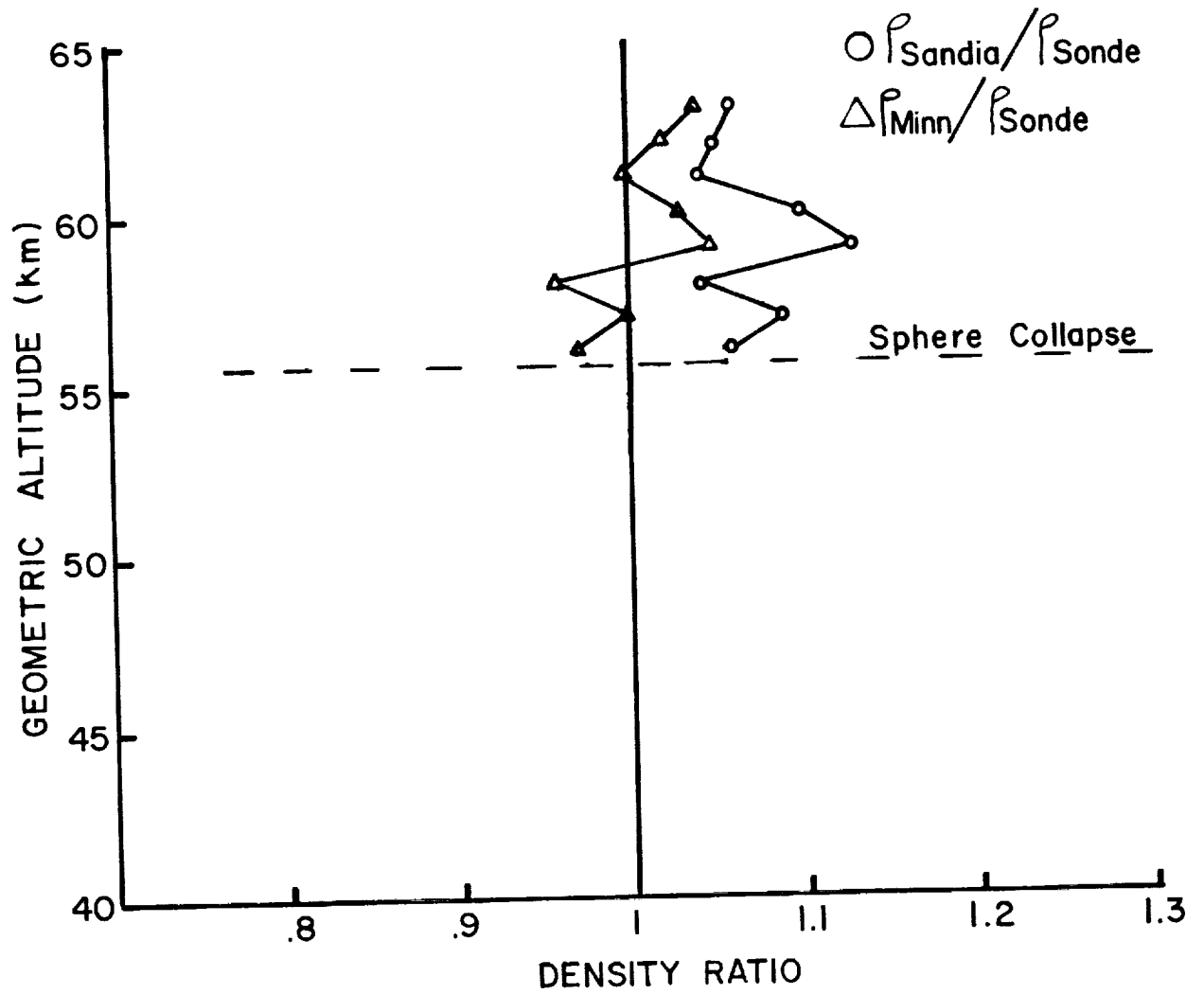Figure 9.- Viper 9, 10 May 1969, Density Departures from 1966 Standard Atmosphere, July, 30°N.

Figure 10.- Viper 9, Comparison of Densities Between Sphere and Rocketsonde.
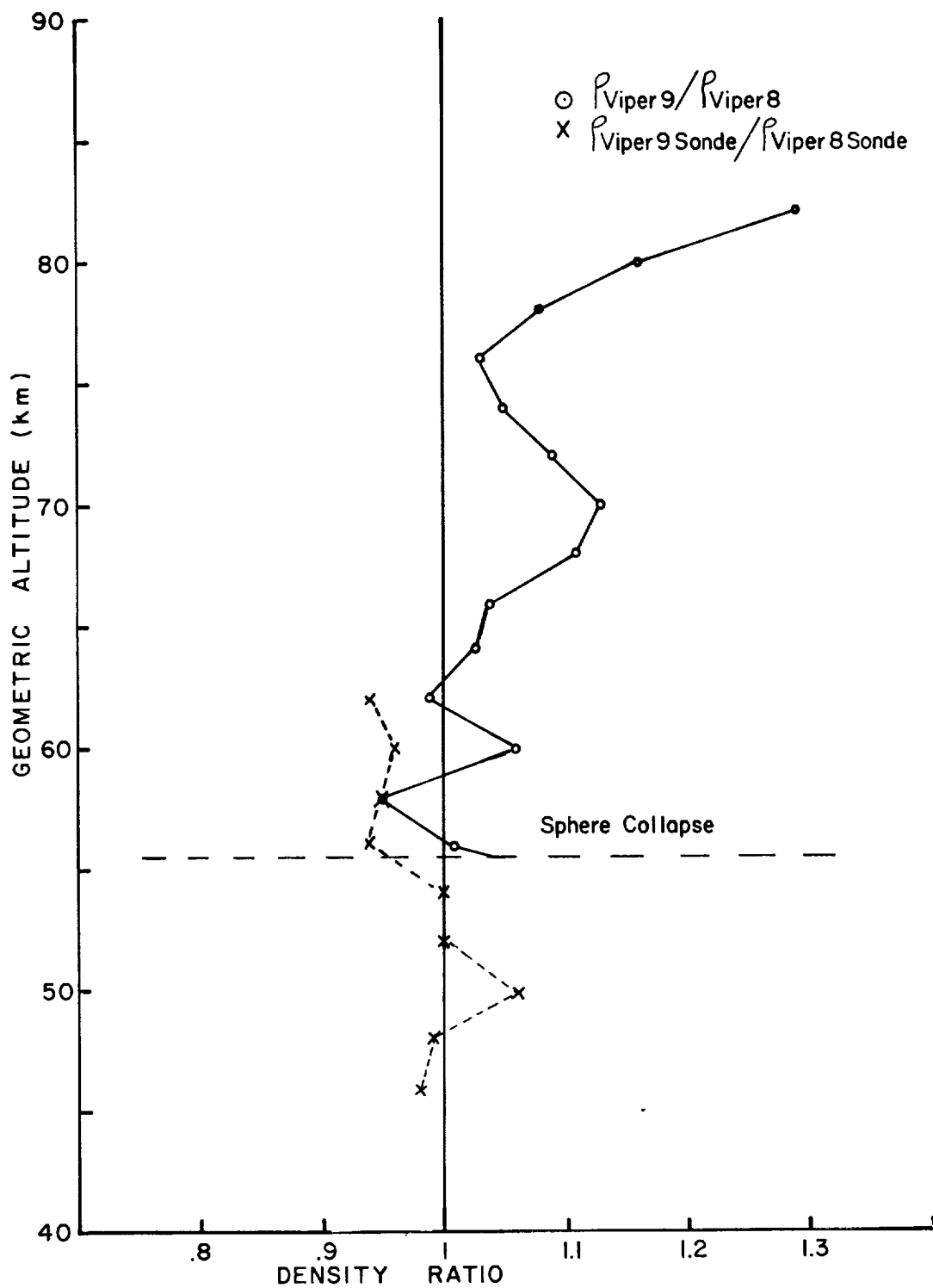
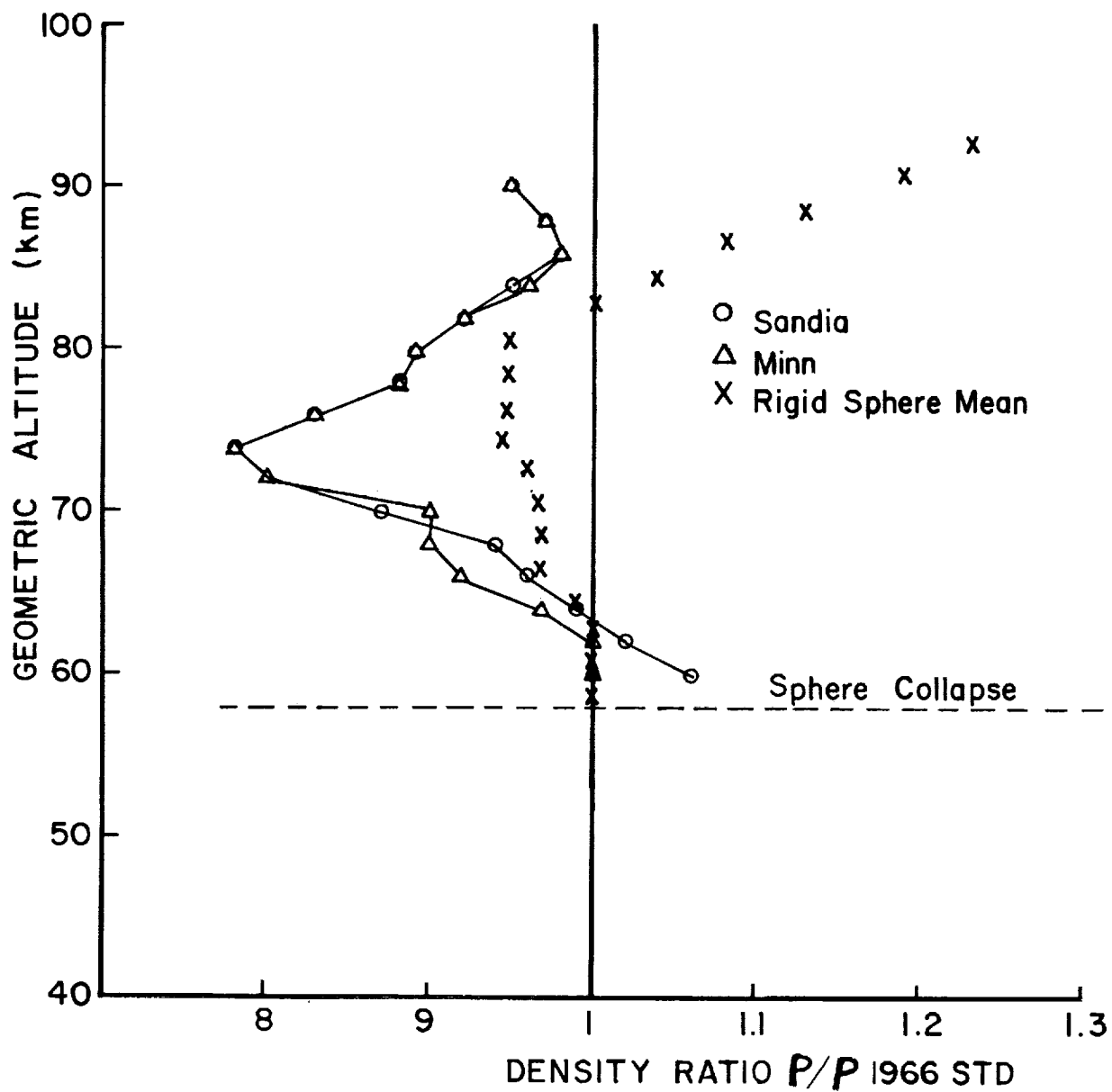Figure 11.- Comparison of Day and Night Density Soundings.

Figure 12.- Super Loki 2, 27 Jan 1969, Density Departures from 1966 Standard Atmosphere, January, 30°N.