SOME PROPERTIES OF DATA FROM FALLING SPHERE SOUNDINGS

By R. S. Quiroz

Upper Air Branch, NMC, Weather Bureau, ESSA

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SUMMARY

Proper use of reduced data from falling sphere soundings requires a detailed knowledge of the many factors affecting their accuracy. Criteria for judging the reliability of ROBIN sphere data (wind and density) are reviewed, and the effect of the data smoothing interval on the suppression of radar tracking error and the retention of real atmospheric detail is briefly considered. The height range of valid temperatures is described in relation to the prevailing pressure scale height and the climatological temperature regime. ROBIN soundings considered valid by stated criteria are presented which illustrate their fidelity to large-scale atmospheric variations. Also shown are rare examples of soundings satisfying the above criteria which indicated physically improbable variations. Special data comparisons include Arcasonde and ROBIN temperatures from Ascension Island, which indicate fair agreement near the stratopause; and densities based on thermistor and sphere data. The latter reveal a systematic difference of about 8%; various explanations are considered, but none is found to account for the full difference. The article concludes with a brief review of past uses of sphere data, together with remarks on persisting problems relevant to all sphere measurements.

INTRODUCTION

Perhaps no method for sounding the upper atmosphere with rockets has required so much study as the falling sphere technique. Much of the commentary has concerned the ROBIN sphere (Engler, ref. 1; Luers, ref. 2), but some of the problems of interest apply to other spheres as well (Jones and Peterson, ref. 3; Salah, ref. 4; Faucher et al., ref. 5; Peterson, ref. 6; Champion and Faire, ref. 7). Nearly 700 ROBIN soundings have been obtained, including a research series of 188 observations in 1960-62 (Lenhard and Kantor, ref. 9) and shorter research series in 1965 and 1966. More than 100 soundings have been taken with other spheres, and these have a proportionally greater value because of the higher altitudes reached. Densities from ROBIN soundings have been obtained generally in the height range 40-70 km, and winds to lower altitudes. Modifications required in the 1965 data reduction program in order to achieve ROBIN measurements above 70 km have been described by Engler (ref.8) and Luers (ref. 2). Figure 1 indicates in greater detail, according to the author's count, the quantity of data obtained.

This discussion of the data is from the standpoint of the user. In order to ascertain the usability of sphere data in such tasks as the construction of synoptic maps or the analysis of small scales of motion, some review of the data accuracies is needed. It is stressed that odd features encountered in various soundings have been more a matter for explanation than alarm. A few soundings, however, have nearly defied explanation. The discussion of accuracies will therefore be followed by examples of unusual soundings which could be shown to be valid and some which remained suspect. The latter are rare, but they have required special probing by the user in order to judge their acceptability.

THE VALIDITY OF ROBIN WINDS AND DENSITIES

Our experience with ROBIN data indicates that with rare exceptions, the winds and densities are broadly representative of the ambient conditions. The rare exceptions might include conditions of very large vertical motions (neglected in the drag equation for density), or appreciable error in the drag coefficient, or unusual balloon behavior perhaps undetected by Engler's Lambda check (see below) (Jones and Peterson, ref. 3). With regard to small-scale variations of the wind and density, the fidelity of representation must depend greatly (as with any observational method) on the smoothing performed on the original data points.

Criteria for Acceptability

All soundings considered in this article meet the stated criteria for valid data (Engler, ref. 1). These are, as we have understood them:

(1) Densities are within the stated accuracies, to be cited below, for that portion of a sounding satisfying the Lambda check. (Mathematical symbols are listed in the appendix.) Lambda is a measure of the vertical density gradient ($\lambda \approx \rho^{-1} d\rho/dz$), and the check assumes that reliable densities are obtained if Lambda, in practice approximated from the vertical acceleration data, falls within a defined neighborhood of the standard atmosphere value. Any unusual perturbation in the vertical sphere motion is assumed to be due probably to collapse or drastic change in shape of the balloon or perhaps to some unusual aerodynamic behavior. With non-spherical balloons, the C_D and cross-sectional area would not be known and the density could not be ascertained.

(2) When the Lambda check indicates collapse below 50 km,

the densities are considered highly reliable. However, if the Lambda check fails above 50 km, the density data are considered unreliable, in accordance with the inference that the balloon was never fully inflated (Lenhard and Kantor, ref. 9).

(3) Winds are considered broadly reliable at all times after the balloon has accelerated to values of $\ddot{z}$ greater than -3 m sec^{-2}. For a non-rigid balloon, however, the response to the wind is not presently ascertainable from theory (ref. 9), and different error estimates apply (see below).

(4) Temperatures are considered broadly reliable at two scale-heights or roughly 15 km, below the starting altitude (see special section on temperature, below).

Smoothing Interval

The ROBIN data in the University of Dayton printout are given for every second above 50 km and for every 2 seconds below 50 km, but what do these represent? Starting from 0.1-sec. radar positional data, 5 values are averaged to get 0.5-sec. positions. Next, 31 of the 0.5-sec. positions are fitted by one-degree polynomial least squares to give 15-sec. values for velocity (from the slope of the curve). The velocities are recomputed at one-second intervals above 50 and 2-second intervals below 50 km, by dropping and adding data points at top and bottom; and then accelerations are determined by least squares fit to 7 of the velocities. This results in accelerations valid for 22-sec. intervals above 50 km and 28-second intervals below 50 km. For densities, which are proportional to the accelerations, the same time intervals apply. To make this review as self-contained as possible, the pertinent equations for solving for the wind and thermodynamic data have been stated in an appendix.

Thus the velocities are effectively determined over a time interval of 1/4-minute and the accelerations and densities over nearly 1/2-minute. For typical fall rates of the ROBIN one-meter balloon, a time interval of 1/4-minute corresponds to a descent of 2-4 km above 60 km and less than a kilometer below about 50 km. Engler (ref. 1) indicates that the horizontal distance of the balloons had oscillations of period exceeding 1/4-minute, which he regarded as real. His analysis of the effect of varying the number of 1/2-second radar positions used for the basic smoothing interval shows that differences up to several m sec^{-1} are possible in the amplitude of the oscillations, according to the data fit used (Fig. 2). More recently, Boer and Mahoney (ref. 10) have analyzed a research series of ROBIN soundings for March 6, 1965 (White Sands), smoothing over a constant-height interval rather than a constant-time interval. Various thicknesses were tried, from 100 to 500 meters; these are substantially narrower layers than the effective smoothing interval at the higher altitudes of Engler's data. For these layers, Boer and Mahoney found that if the acceleration term, $\ddot{z}\dot{x}/(\ddot{z}-g)$, was included in the wind computations, the correlation between wind profiles based on data from two radars (FPS-16) tracking the same balloon was greatly reduced.

The reduction in one sounding (No. 933, 1500 MST) was so dramatic that it occurred to us to correlate the wind profiles based on the Engler data, which also include the acceleration or "response" correction, but involve a smoothing interval of 22 sec. For the actual fall rates of this sounding, this amounts to a layer thickness ranging from 1.8 km to 3.4 km at 60 km. Figure 3 shows the wind profiles (u component), which are indeed in very close agreement. The correlation between them, on removal of the basic trend, is 0.93[1] in contrast to an extremely low correlation, 0.09, calculated by Boer and Mahoney.

Thus, insofar as it rises above the radar noise level, Engler's smoothing appears more realistic. At altitudes of 45-60 km, Lettau (ref. 11) appears to have made effective use of the White Sands Engler-reduced data in tracking small-scale structure which he interprets as evidence of internal gravity waves. At high altitudes Engler's smoothing interval, however, becomes quite gross (effectively, 4-5 km above 70 km), and consideration should be given to a shorter time interval which would exclude tracking error and yet permit the resolution of small-scale wave structure. Not only would the time interval be critical, but the choice of polynomial fitted to the high-altitude data, whether cubic or linear, for example (Luers, ref. 2), would also be important. Indeed, it appears that various tradeoffs would be necessary to minimize the error in both wind and density, while suppressing radar error.

Mention should be made of small-scale oscillations in the ROBIN density profiles. Unfortunately, there were very few valid thermodynamic data from the White Sands series. Figure 4 is a plot of the two profiles based on radar tracking of the same balloon (sounding no. 933). The curves are in excellent agreement. The indicated oscillations in both curves are of small amplitude, making a more detailed comparison difficult, but the oscillations are clearly in phase and with scarcely detectable divergence. Like the wind profiles, these data indicate that for the smoothing interval used by Engler, there is no apparent distortion from radar error.

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[1]Correlation is meaningful in first decimal digit only, owing to subjectivity in determining the trend and choice of sampling frequency in the profiles.

Accuracy Estimates

Finally, we need to have in mind the overall error estimates in the ROBIN data, as given by Engler (ref. 1). These are, for an FPS-16 or similar radar and the curve-fit (31-7) commonly used:

TABLE I. ROBIN error estimates[a]

		RMS Error		
		Above 60 km	50-60	Below 50
WIND	Rigid balloon	6 knots	2.5	1
	Non-rigid	10	7	5
DENSITY	Rigid balloon	3.5%	3%	3.5%
PRESSURE	Rigid balloon	3%	3%	2.5%
TEMPERATURE	Rigid balloon	10%	3%[b]	4%[b]

TEMPERATURES FROM SPHERE SOUNDINGS IN GENERAL

The temperature error requires special discussion. As is well known, a relationship based on the hydrostatic equation is used for deriving the temperature when no thermodynamic data other than a density profile are available (eq. 3, Appendix). An initial guess of the temperature T_o, is required at the starting altitude, i.e. the top altitude with density data. The error in temperature is thus a function of two factors, (1) the departure of the initial temperature from the true temperature, and (2) the error in the density throughout the layer of integration.

For an error-free density profile, it is evident that nearly ambient temperatures are not achieved until the ratio ρ_o/ρ becomes negligibly small. This happens typically at an altitude roughly two scale heights, or about 16 km, below the starting altitude. The reduction of the ratio ρ_o/ρ with increasing height separation is shown in Table II. For example, for a height separation of 2 scale heights $\rho_o/\rho = 0.135$, and the temperature error ranges from 0.5 to 3% depending on the error in the temperature guess at the starting altitude. The temperature error itself

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[a] Based on Table I (ref. 1).

[b] See discussion of temperature error in following section.

TABLE II

Error in temperature $T(z)$ due to error in initial temperature T_o at starting altitude z_o

Δz	$\rho_o/\rho = e^{-\Delta z/H}$	ΔT (°C)[a] $\pm 10°$	$\pm 20°$	$\pm 40°$	$\pm 60°$
H/2(4 ≅ km)	0.606	6.1°(2.5%)[b]	12.1°(4.8%)	24.2°(9.5%)	36.4°(14.5%)
H(8 ≅ km)	0.368	3.7°(1.5%)	7.4°(3.0%)	14.7°(6.0%)	22.1°(9.0%)
3H/2(12 ≅ km)	0.223	2.2°(1.0%)	4.5°(2.0%)	8.9°(3.5%)	13.4°(5.5%)
2H(16 ≅ km)	0.135	1.4°(0.5%)	2.7°(1.0%)	5.4°(2.0%)	8.1°(3.0%)

[a] ΔT is potential error in T_o in a given climatic regime.

[b] Percentages computed from a base temperature of 250°K.

was obtained by evaluating the term, $\left(\frac{\rho_o}{\rho}\right)\Delta T$, where ΔT is identified with the potential error in T_o (eq. 3) for a given climatological regime.

If a certain level of temperature accuracy is desired, say 2.5%, it is thus not generally possible to estimate the first altitude of "good" data without some preconceived idea of the temperature variability at the station of interest. In low latitudes, we know from rocket grenade observations, for example, that if the temperature in the U.S. Standard Atmosphere Supplements, 1966 (ref. 12), is used for T_o, the true temperature will not likely differ by more than 20°. Thus, from Table III it can be seen that nearly ambient temperature would be achieved at a height separation of about 10 km. In high latitudes in winter, however, the temperature variability is typically much greater, and it is doubtful that ambient temperatures will be sensed at separations less than 2 scale heights. The summer mesopause is known to have very cold temperatures associated with it, with the scale height possibly as low as 4-5 km, so that near 80 km real temperatures might be sensed in relatively short order.

The other error source for temperature is error in the densities themselves and it should be noted that it is the error over the layer of integration that matters, not just the error at altitude (eq. 3, Appendix). According to Engler (ref. 1) various density error profiles are possible. However, it may not always be possible to describe the height configuration of the density error in individual profiles, so that in some cases the total error in temperature may not be ascertainable. At the very least, Table III clearly illustrates that the temperatures provided in the first few kilometers below the first level of density data should not be construed as real temperatures. At times the reported temperatures may fortuitously come close to the real values, but we know of no way to readily distinguish these cases. The practice of publishing complete temperature profiles in the data books of the Meteorological Rocket Network thus seems questionable, at least without some qualification as to the validity of the data at the topmost levels. Jones and Peterson (ref. 3), however, consider publication justifiable on the grounds that although the absolute values of the temperature may be in error, "valid trends can often be seen."

For the height range in which reasonably accurate temperatures may be expected, comparison with data obtained by other techniques is desirable. Since this topic was to be considered in depth by other speakers, only a few remarks will be made here.

Jones and Peterson (ref. 3) have discussed the extent of agreement of data obtained with the aid of the University of Michigan 66-cm sphere, with grenade (layer-average) temperatures and with HASP rocketsonde data in August 1965, at Wallops Island. Initially, the sphere and grenade measurements differed appreciably, the sphere temperatures being warmer. Improvements in the microphone array for the grenade measurements and in the sphere drag coefficients resulted in better agreement. In a combined sounding in which grenade and sphere measurements were separated at most by 10 minutes, the temperatures were found to agree generally within a few degrees. Oscillations in the sphere temperature curve were not present in either the grenade data nor in the HASP rocketsonde data at lower altitudes. Certain oscillations should, of course, not be expected in the grenade temperatures, in view of the layer-averaging; their absence in the HASP data, however, suggests that the oscillatory part of the sphere data may be erroneous. Jones and Peterson gave several possible explanations, namely, a poor radar track, a deflated sphere, peculiar aerodynamics of the sphere, or the effect of large vertical motions in the atmosphere. The first two were not judged to be the cause in this case; there were arguments against aerodynamic behavior as a cause; and the vertical motion effect could not be evaluated owing to a lack of suitable information.[2]

In the case of temperatures from ROBIN soundings, S. Teweles (private communication to N. Engler, Jan. 7, 1964) pointed to an apparent discrepancy between ROBIN and grenade temperatures but subsequently Engler determined that the ROBIN data used for comparison did not meet the criteria for acceptability (balloon collapse above 50 km). Indeed, even now, there is no extensive set of ROBIN and grenade data available, to our knowledge, obtained under similar observing conditions, which would permit definitive comparison. The situation with respect to rocketsonde thermistor data does not seem much better, since in the altitude region where ROBIN temperatures should be most reliable, about 45-60 km (assuming the thermodynamic data commence at ∿70 km), the thermistor temperatures are subject to increasing error with height. The results of comparisons of ROBIN and Arcasonde temperatures at altitudes near 50 km will be presented in the next section.

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[2] The subject of vertical motions was to be considered by another speaker; it is generally agreed that vertical motions are important only if they are of the order of m sec^{-1}. Although perhaps rare, motions of this magnitude may be possible, above 30 km. In the stratosphere vertical motions of cm or mm sec^{-1} have been generally found (Miller, ref. 13), but during a stratospheric warming in 1966, upward motions as high as one-half meter sec^{-1} were estimated (Quiroz, ref. 14). Above the mesopause motions near 10 m sec^{-1} have been reported. Thus the effect of vertical motions may be a difficult problem to evaluate until better statistical knowledge of the motions is obtained.

ILLUSTRATIVE DATA

Cape Kennedy, Dec. 7, 1964

A ROBIN sounding for Dec. 7, 1964 has been selected to illustrate the broad agreement of the ROBIN data with atmospheric measurements by other methods (Fig. 5). On this date the zonal wind indicated by the sphere increases at an extraordinary rate between 30 and 55 km; the local vertical shear near an altitude of 33 km is about 20 m sec^{-1} km^{-1}, a value which may be considered statistically rare. At 55 km the westerly wind component exceeds 100 m sec^{-1} and is three times as great as the tropospheric wind maximum at the same station. So unusual a sounding might be questioned, especially in view of the westerly firing angle (to the east) at Cape Kennedy.

Later the same day, however, a wind profile based on the tracking of a parachute indicated close agreement with the ROBIN profile (the observed differences are probably due to real atmospheric variation). Figure 6 shows the synoptic situation on Dec. 9 (maps were not analyzed for Dec. 7); a very strong jet is found at the 0.4 mb level (about 55 km over Florida), with strong winds observed as far west as Hawaii. At the 5-mb level (about 35 km), the winds are light over Florida and to the south, in agreement with the data for Dec. 7.

The temperature and density profiles for this date are also of some interest. In view of our earlier discussion, realistic sphere temperatures would be expected at Kennedy some 10 km below the starting altitude and indeed, good agreement with rocketsonde thermistor temperatures can be seen just above 50 km. Near 55 km, comparison is precluded by the likelihood of increasing error with height in the thermistor measurements (Quiroz, ref. 15). The reality of the temperature difference at 42-44 km would be difficult to ascertain. It seems reasonable to conclude that reliable temperatures are indicated by both methods of observation at least in the height range 44 to 52 km. A statistical comparison of sphere and thermistor temperatures will be described below.

The ROBIN densities are 7-10% lower than the Arcasonde densities, for which the observation time is in mid day. Part of this difference may be due to diurnal variability. The possibility of a systematic bias will be explored below.

Ascension Island Temperature Comparison, March-June 1964-65

The period March-June 1964-65 was chosen for the comparison of temperatures from Arcasonde thermistors (1965) and from ROBIN sphere soundings (mainly 1964). The comparison was limited to three altitudes, 46, 50, and 54 km, where data from both sources should be considered reasonably reliable. The thermistor data have not been corrected for possible aerodynamic, radiational, and conduction heating errors, which have been estimated at about 2 degrees (total) at 46 km, increasing to about 5 degrees at 54 km (Drews, ref. 16). The number of ROBIN soundings (18) is small, but nevertheless represents one of the densest clusters of such soundings available, save for the experimental series at Eglin AFB in 1960-62.

The observed temperatures are plotted in Figure 7 and relevant statistics are given in Table III. Inspection of this table shows that:

(1) Average temperatures from the two sources agree within about three degrees if the thermistor data are uncorrected.

(2) Sphere temperatures are warmer by a few degrees if compared with corrected thermistor data.

(3) The dispersion of the sphere temperatures, as given by the values of standard deviation, is greater than for the thermistor temperatures. (No attempt was made to smooth the oscillations present in the sphere data; smoothing would have brought the standard deviations into closer agreement.)

While the sample is probably too small to give stable statistics, these data indicate that over a definable height range the sphere average temperatures are at least realistic. Further comparison in a regime of greater variability (middle or high latitudes in winter) is desirable. Moreover, the influence of oscillations of large amplitude needs to be examined further.

An interesting feature in Figure 7 is the indication of a diurnal temperature increase from 04-05 GMT to 16-18 GMT in three pairs of observations. At 46 km, the two thermistor pairs on May 23 and 26 indicate a diurnal range of about 10°C; this range is also indicated by the pair of sphere observations on April 8, which are not subject to any direct radiational error. At 50 km a similar behavior is observed; part of the large temperature increase in the sphere pair, however, may be due to non-diurnal effects

Enigma in Ascension Island Density, August 1964.

Figure 8 depicts the observed densities at Ascension Island in 1964 at two altitudes, 46 and 60 km, based on ROBIN sphere soundings, together with comparative data obtained by other methods. The lower altitude was chosen because at this height the sample of thermodynamic data from descending spheres was still appreciable and would permit comparison with values derived from thermistor measurements; as previously indicated, the error in the latter has been considered small in the upper stratosphere.

TABLE III

Comparison of temperatures from sphere and thermistor soundings, Ascension I., March-June 1964-65

Altitude (km)		SPHERE	THERM.	THERM. IF CORRECTED	SPHERE MINUS CORR. THERM.
54	$\bar{T}$	1.0°C	2.5°C	-2.9°C	+3.9°
	S_T	6.3	4.6		
	N	17	30		
50	$\bar{T}$	6.1	3.5	0.0	+6.1
	S_T	7.6	4.0		
	N	18	31		
46	$\bar{T}$	1.6	1.6	-0.7	+2.3
	S_T	5.1	3.6		
	N	16	31		

Figure 8 shows a number of interesting features, of which the most striking is the unusual and highly improbable behavior in mid-August. A density increase by 35% at 46 km and by 43% at 60 km is indicated by the sphere data in a period of 31 hours. These values greatly exceed the maximum density change in 24 or 48 hours previously indicated from rocketsonde data, namely a change of 19% occurring at a high-latitude station (Quiroz, Lambert, and Dutton, ref. 17). Yet by the criteria for acceptability stated earlier, the soundings in August must be considered reliable soundings. It is noteworthy that the extraordinarily high density on August 17 was again observed two days later, and the low value of August 16 was similar to the value observed earlier on August 12. Correspondence with the Air Force office responsible for the observational program at Ascension Island did not reveal any irregularity in data reduction. Subsequently, Engler (ref. 1) applied his time-of-fall test for suspect balloons and judged the soundings to be valid. Thus, while the values observed on August 17 and 19 were too extreme to inspire credibility, there seemed to be no way of showing that the data were incorrect. In preparing this review, it occurred to us to examine, insofar as possible, the internal consistency of the thermodynamic data with the observed winds. The temperature change from August 16 to 17 amounted to only a few degrees at 46 km. Thus a large pressure increase was associated with the increase in density. Fortunately, pressure data were also available for another rocket station, Antigua (17°N), on August 17. A geostrophic computation, assuming a linear pressure change between the two stations[3], indicates that if the pressures and densities at Ascension are valid, the zonal wind at Ascension should exceed 400 m sec^{-1}. The wind obtained from radar tracking of the ROBIN sphere was at most 25 m sec^{-1} in the vicinity of 46 km. We therefore conclude, on the basis of purely physical reasoning, that the soundings of August 17 and 19 are invalid. Rocket grenade observations were also taken on August 16 and 17, though the results were not available until much later (Smith et al., ref.18). These data, entered on Figure 8, are completely at variance with the sphere results.

This case is but one, although possibly the most dramatic, of several extraordinary sphere soundings encountered by the author, and it emphasizes the need for careful scrutiny of all data by the user. Indeed, all rocket soundings by whatever method require careful review, since the many aspects of data reduction and transcription may increase the possibility for error.

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[3] A non-linear pressure distribution would require an even greater wind than that computed, at some point between the two stations.

Densities from Sphere Soundings Compared with Other Measurements

Another feature of interest in Figure 8 is an apparent discrepancy in densities based on sphere soundings and on thermistor measurements. Ascension Island offers a useful opportunity for comparison because at the end of September 1964 the observational program reverted from an exclusively sphere schedule to a predominantly Arcasonde schedule. Also available for comparison in 1964 are a few grenade and Pitot-static tube measurements at Ascension and several University of Michigan sphere soundings at Kwajalein (9°N, 168°W). From other years, tropical grenade soundings at Natal, Brazil (6°S, 35°W) (1966-67) and Guam (14°N, 145°E) (November 1958) are also entered.

Two points are readily apparent:

(1) The sphere densities are, with rare exceptions, lower than the mean based on thermistor densities; e.g. in September-December, 1964, the mean sphere density is nearly 10% less than the mean based on thermistor measurements.

(2) A greater dispersion is indicated by the sphere measurements.

At the upper altitude, the difference between sphere and thermistor measurements is partly due to the error in the latter, which increases strongly above 55 km, and no attempt has been made to enter individual thermistor values for 60 km.

It is therefore meaningful to concentrate on the data for 46 km, where the error in either set of data should be minimal. Various possible explanations of the observed difference merit considerations, such as unsuspected temperature error in the rocketsonde measurements, error in the drag coefficient used for the sphere reduction, etc.

The effect of a thermistor temperature error may be evaluated with the aid of the integrated hydrostatic equation in the form[4]

$$\rho = \rho_o \left(\frac{T}{T_o}\right)^{-\left(\frac{g}{R\gamma}+1\right)} \qquad (1)$$

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[4] In practice, pressures and densities based on rocketsonde temperature are obtained through use of the approximation $p = p_o \exp(-g\Delta z/R\,\overline{T})$, but as has been shown by Ballard (ref. 19), the departures from results based on the more exact Eq. (1) are negligibly small.

Introducing an error, ΔT, in temperature, held constant over the layer of integration, the density at the upper altitude becomes

$$\rho + \Delta\rho = \rho_o\left(\frac{T + \Delta T}{T_o + \Delta T}\right)^{-\left(\frac{g}{R\gamma} + 1\right)} \tag{2}$$

and the ratio of (2) to (1) is

$$R = \frac{\rho + \Delta\rho}{\rho}\left[\left(\frac{T}{T_o}\right)\left(\frac{T_o + \Delta T}{T + \Delta T}\right)\right]^{+\left(\frac{g}{R\gamma} + 1\right)} \tag{3}$$

For a temperature structure approximating the conditions at Ascension Island[5] and for a hypothetical temperature bias, ΔT, in the thermistor soundings, sustained over the 20-km layer from 26 to 46 km, the solution of Equation (3) yields a density error of approximately +3% if $\Delta T = +3°$, increasing to +8% if $\Delta T = +8°C$. (Over a 10-km layer from 36 to 46 km, a temperature error of 16° would be required to explain a discrepancy of 8% in the density at 46 km.) The rocketsonde temperatures are generally believed to be quite accurate below about 50 km, although some disagreement with radiosonde temperatures near 30 km has yet to be explained (Quiroz, 1969). Since an unreasonably large temperature error is required to explain the density difference in Figure 8, it appears that we must look to some other error source, or more likely, a combination of sources.

According to Engler (ref. 1) uncertainty in the drag coefficient for ROBIN spheres is less than about 2% below 50 km, but improved knowledge of this factor is needed. Luers (ref. 2) and Peterson (ref. 6) have pointed to inconsistencies in the available drag tables and have re-emphasized the need for improved data. An interesting series of measurements with hypersonic rigid spheres (Kwajalein, 1965-1968) has been obtained under conditions for which a high degree of confidence can be placed in the drag data used, according to Salah (ref. 4, 21). Comparative ROBIN and hypersonic sphere measurements, if feasible, might shed light on the drag data used for the inflatable, subsonic spheres.

It is interesting to note in Figure 8 that measurements by the grenade method tend to lie between the sphere and thermistor values. Almost without exception, the grenade densities are lower than the thermistor values. It is therefore our belief that the discrepancy between the sphere and Arcasonde data must be due to error in both methods of measurement.

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[5]Supplemental Atmosphere data for 15°N were used.

Diurnal series, Eglin AFB, May 9-10, 1961

Another example of unusual sphere data is found in the diurnal series for May 9-10, 1961 (Figure 9). The 2000 GMT observation indicates a density increase of nearly 30% from 1600 GMT. This sounding and two soundings at 1015 and 1115 were not used by Cole and Kantor (ref. 20) in their harmonic analysis for data at 60 km. Summing the first two harmonics, Cole deduced a daily range of 12% in the density. The inclusion of the three unused soundings, in particular the data for 2000 GMT, would probably have had a strong influence on the results. To the author's knowledge, these data have not yet been shown to be invalid. Lenhard's (ref. 22) analysis of the wind data for this observational series indicated a weakening of the easterly flow in parallel with the afternoon rise in density, suggesting a diurnal advective effect, but careful study would be required to show a relationship.

USES OF SPHERE DATA AND FINAL REMARKS

Data from falling spheres have already proved useful in a variety of ways, but their full potential has not been exploited. They have already been used in:

(1) the construction of high-level synoptic maps.

(2) preliminary determinations of diurnal variability of density and wind: in the lower mesosphere from ROBIN data, in the stratosphere and mesosphere from Australian spheres (Rofe et al. ref. 23), and in the quasi-isopycnic layer at about 90 km from Michigan spheres (Jones and Peterson, ref. 3).

(3) exploratory studies of small-scale variability (Newell, Mahoney, and Lenhard, ref. 24, Lettau, ref. 11; Mahoney and Boer, ref. 25; Cole and Kantor ref. 26 and others).

(4) models of the density structure in the important region 90-120 km (U.S. Standard Atmosphere Supplements, 1966, ref. 12).

(5) climatological data processing (e.g., Brockman, ref. 27, Salmela and Sissenwine, ref. 28).

With regard to (1), the synoptic analysis program of the Upper Air Branch, National Meteorological Center, has resulted in a continuing series of weekly constant-pressure charts at levels centered at about 36, 42, and 55 km (5, 2, and 0.4 mb), beginning in 1964. (Constant-level density charts have also been produced though less frequently.) Because of the preponderance of rocketsonde data (Quiroz, ref. 15), the utilization ratio of sphere data is small. The analysis technique requires wind and temperature for input, and not surprisingly the temperatures from ROBIN spheres could be used only infrequently. This was due to (1) the typically small height range of valid temperatures and (2) untenable departures from the otherwise smooth temperature fields depicted in the analyses. These departures were at times associated with oscillatory features in the sphere profiles and would have been minimized if smooth profiles had been used. Nevertheless, the sphere data have at times provided missing links in a rocket network of sparse coverage, and they have a strong potential utility in future work, particularly if the height range of valid data is extended.

One of the most promising uses of the data is for better defining the complex density structure from 90 to 120 km. Only a handful of soundings have been used as a basis for deriving structural models of the thermosphere, yet as Figure 1 shows there has been a large increase in the number of soundings obtained in recent years. In addition to providing a better grasp of boundary conditions for thermospheric models (Thomas, ref. 29), improved knowledge will permit more definitive investigation of the influence of variable solar activity at these altitudes (Lindblad, ref. 30; Ellyett, ref. 31).

We have sought to indicate, through a few examples, that the sphere density and wind data are, with rare exceptions, reliable over definable ranges of altitude. Temperatures should be reliable at two scale heights below the first altitude of density data, but the oscillations in temperature, which either are of greater amplitude than those encountered in rocketsonde profiles or are sometimes not present in the latter, need further study. It is recommended that this problem be given special attention, since the full utility of the temperature data cannot be achieved until the reality of the oscillations is ascertained. Other problems for investigation are the apparent systematic difference in densities based on sphere versus thermistor soundings, the accuracy of the available drag data, and the possibility of large vertical motions which might at times affect the sphere results. With regard to high-altitude data from spheres with fast descent rates, consideration should be given to determining an optimum smoothing interval which at the same time suppresses radar error and preserves small-scale atmospheric structure. Finally, it is recommended that comparative experiments in the future be conducted preferably in winter in high latitudes, under conditions which favor the unambiguous separation of observational error from true variability.

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A P P E N D I X

PHYSICAL EQUATIONS FOR REDUCTION OF SPHERE DATA

Atmospheric Variable	Complete Equation	Simplified Equation
WIND	$u = \dot{x} - \dfrac{(\dot{z} - w)\left(\ddot{x} + C_x - B_x\right)}{\ddot{z} + C_z - B_z}$ (1a)	$u \cong \dot{x} - \dfrac{\dot{z}\,\ddot{x}}{\ddot{z} - g}$ (1b)

u, horizontal west-east component
w, vertical motion (atmospheric)
g, acceleration of gravity
C,B Coriolis, buoyancy forces

Equation for v, the horizontal south-north component, is similar. The total wind, $V = (u^2 + v^2)^{1/2}$. For generality, the Coriolis and buoyancy forces in (1a) are retained in the ROBIN program. C is judged significant above 90 km (ref. 1). The buoyancy force $B = (v)_B \rho g$, may be large below about 30 km. In the simplified equation (1b), vertical motion and horizontal Coriolis and buoyancy forces are neglected. This eq. is used after collapse of ROBIN balloon.

Under certain conditions, the acceleration or "response" term, $\dot{z}\,\ddot{x}/(\ddot{z} - g)$, might be neglected if $u \cong \dot{x}$, but Engler shows that error due to neglect of this term may be very large at high altitudes and does not recommend the use of the approximation.

DENSITY In general, $F_D = 1/2\rho V_B^2 C_D A = m a_D$

i.e., $$\rho = \frac{2 m a_D}{V_B^2 C_D A}$$

For ROBIN $$\rho = \frac{2m\left(g_z - \ddot{z} - C_z\right)}{C_D A V(\dot{z} - w) + (v)_B g_z} \qquad (2a)$$

$$\rho \cong \frac{-2m(\ddot{z} - g)}{C_D A V \dot{z}} \qquad (2b)$$

In (2b), Coriolis and buoyancy forces and vertical motion are neglected. This is form of eq. commonly used.

TEMPERATURE In general, $\partial p/\partial z = -\rho g$; $p = \rho RT$.

Integrated hydrostatic equation,

$$T = \frac{1}{\rho R}\int_{z}^{z_o} \rho g\, dz + \frac{\rho_o}{\rho} T_o \qquad (3a)$$

$$T \cong \frac{1}{\rho R}\sum \bar{\rho} g\, \Delta z + \frac{\rho_o}{\rho} T_o \qquad (3b)$$

z_o is starting altitude. Eq. (3b) is used.

Mathematical symbols not defined above:

$\dot{x}$, $\ddot{x}$	dx/dt, d^2x/dt^2, etc.
A	sphere cross-sectional area
a_D	drag acceleration
C_D	drag coefficient
γ	temperature lapse rate, dT/dz
H	pressure scale height ($H = RT/g$)
m	sphere mass
p	pressure
R	gas constant for dry air
ρ	air density
S_T	standard deviation of temperature
$T, \bar{T}$	temperature, mean temperature
V_B	sphere velocity
$(v)_B$	sphere volume

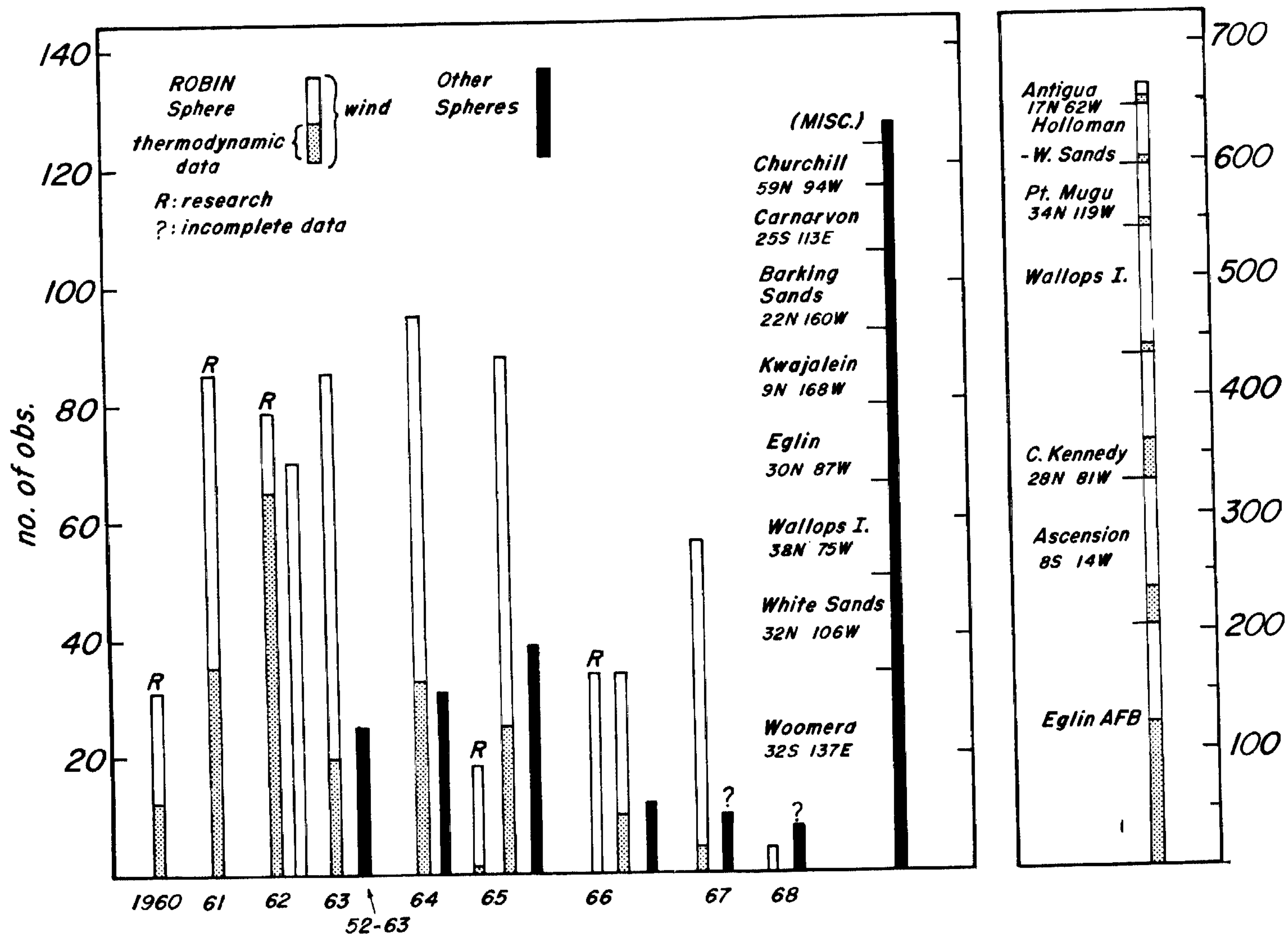

Figure 1.-Number of atmospheric soundings obtained with ROBIN spheres (passive) and with other spheres, both passive and instrumented. Statistics are based on published reports and may be incomplete in the last 2-3 years shown.

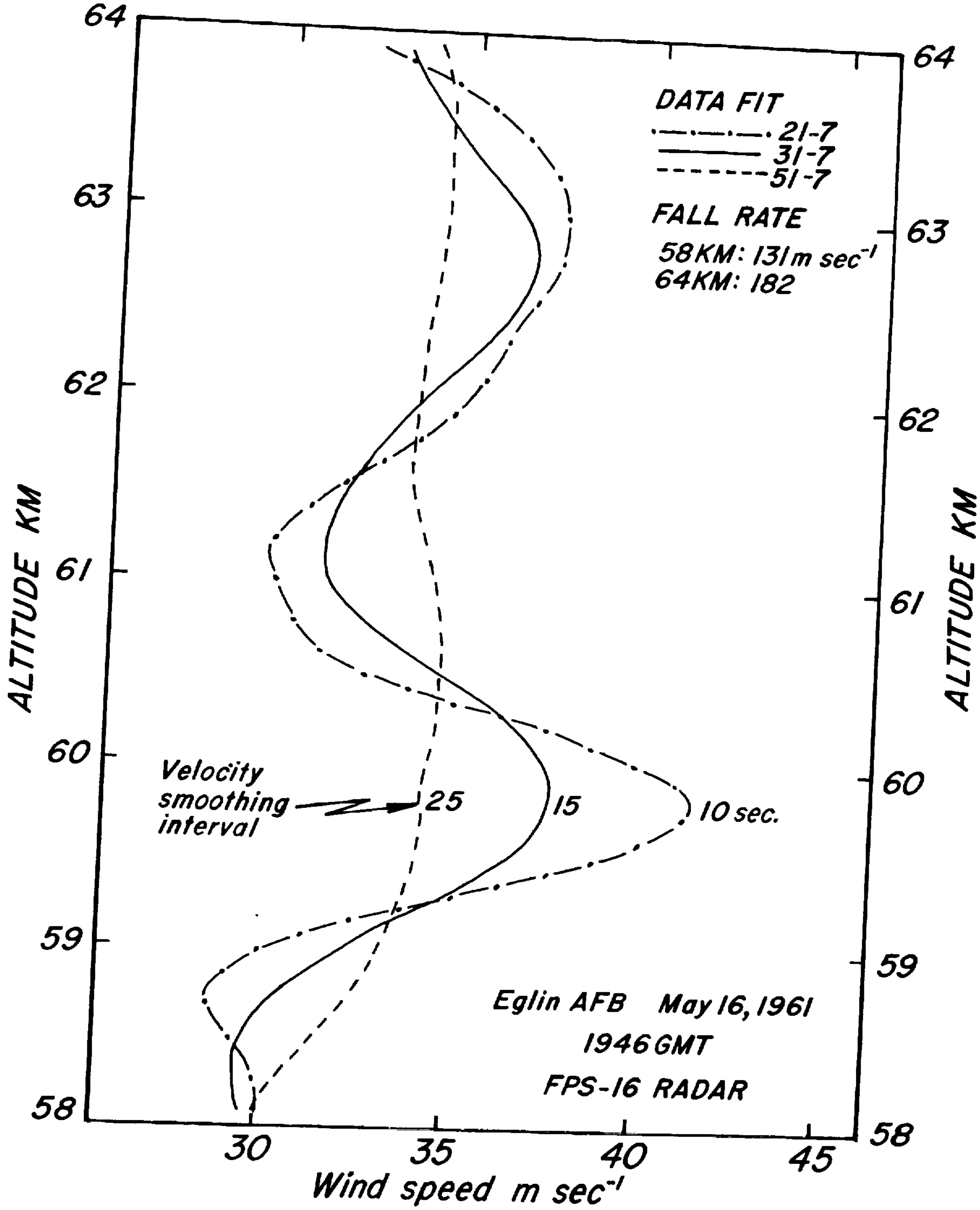

Figure 2.-Variation in amplitude of indicated wind oscillations due to choice of data fit. (Adapted from Figure 9, Engler, ref. 1, which shows additional curves for other fits.)

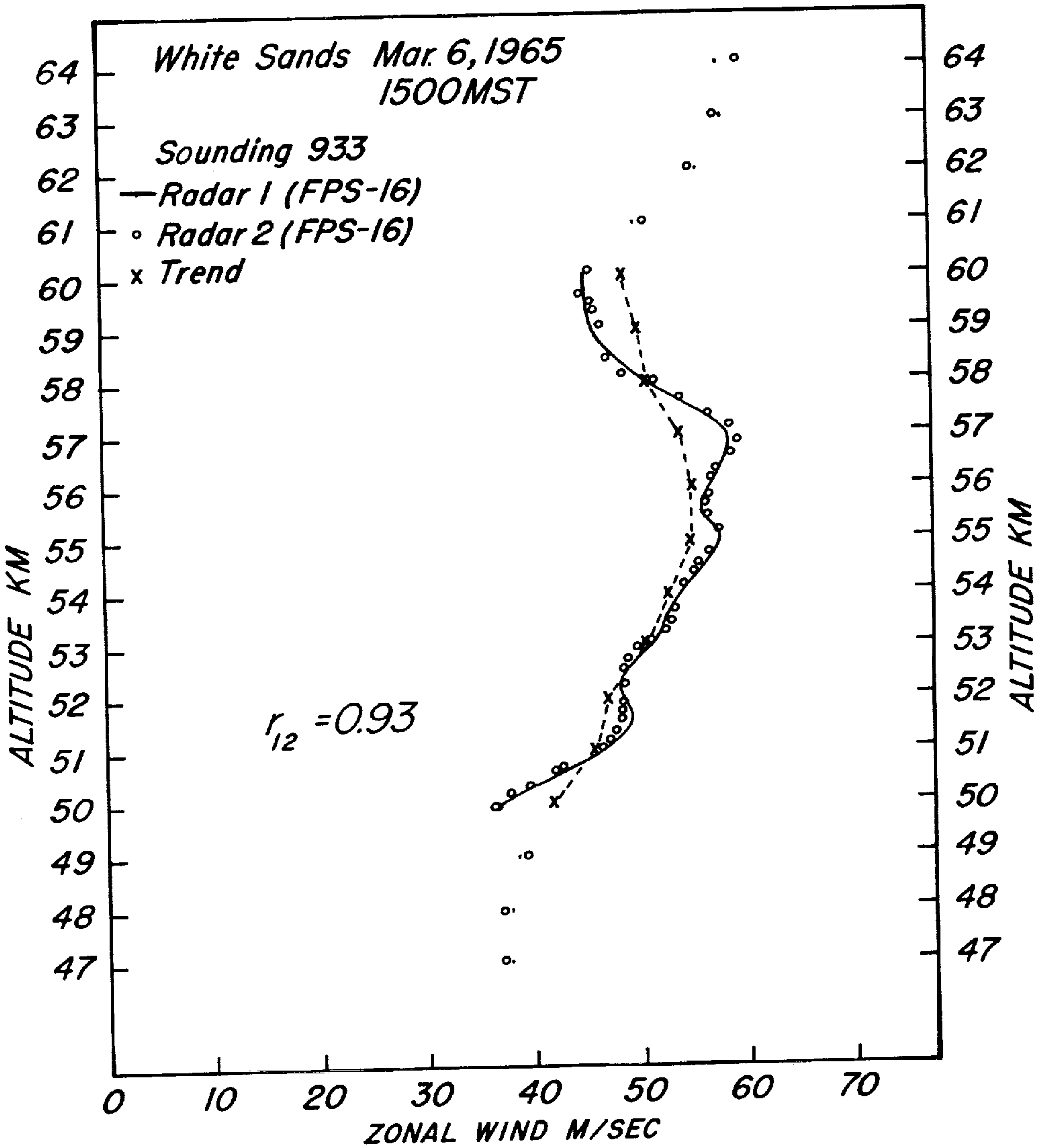

Figure 3.-Plot of wind profiles determined from data of two radars tracking same sphere, indicating high correlation for Engler smoothing interval.

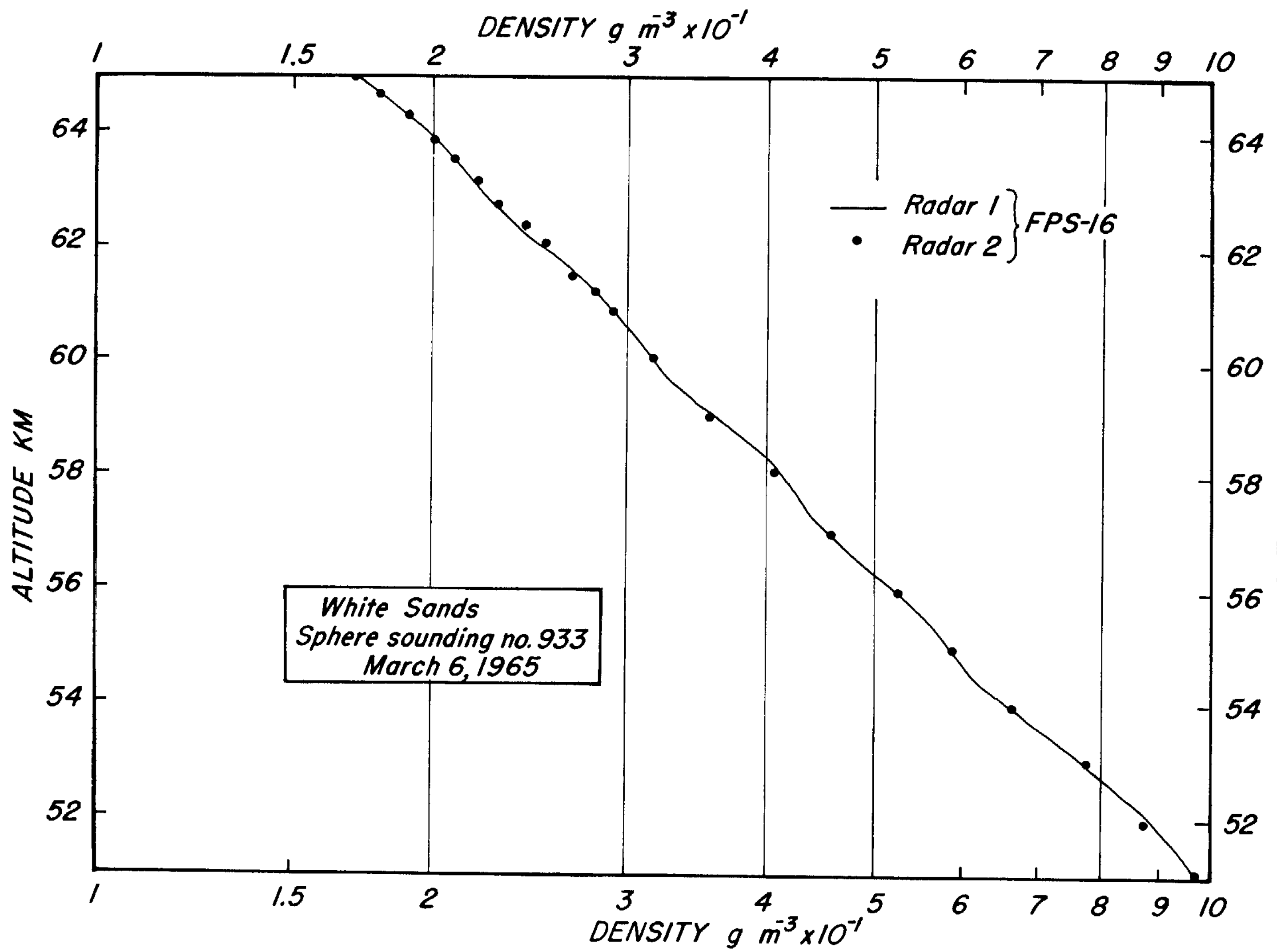

Figure 4.-Density data for same sounding as in fig. 3, showing excellent agreement in values based on data from two radars.

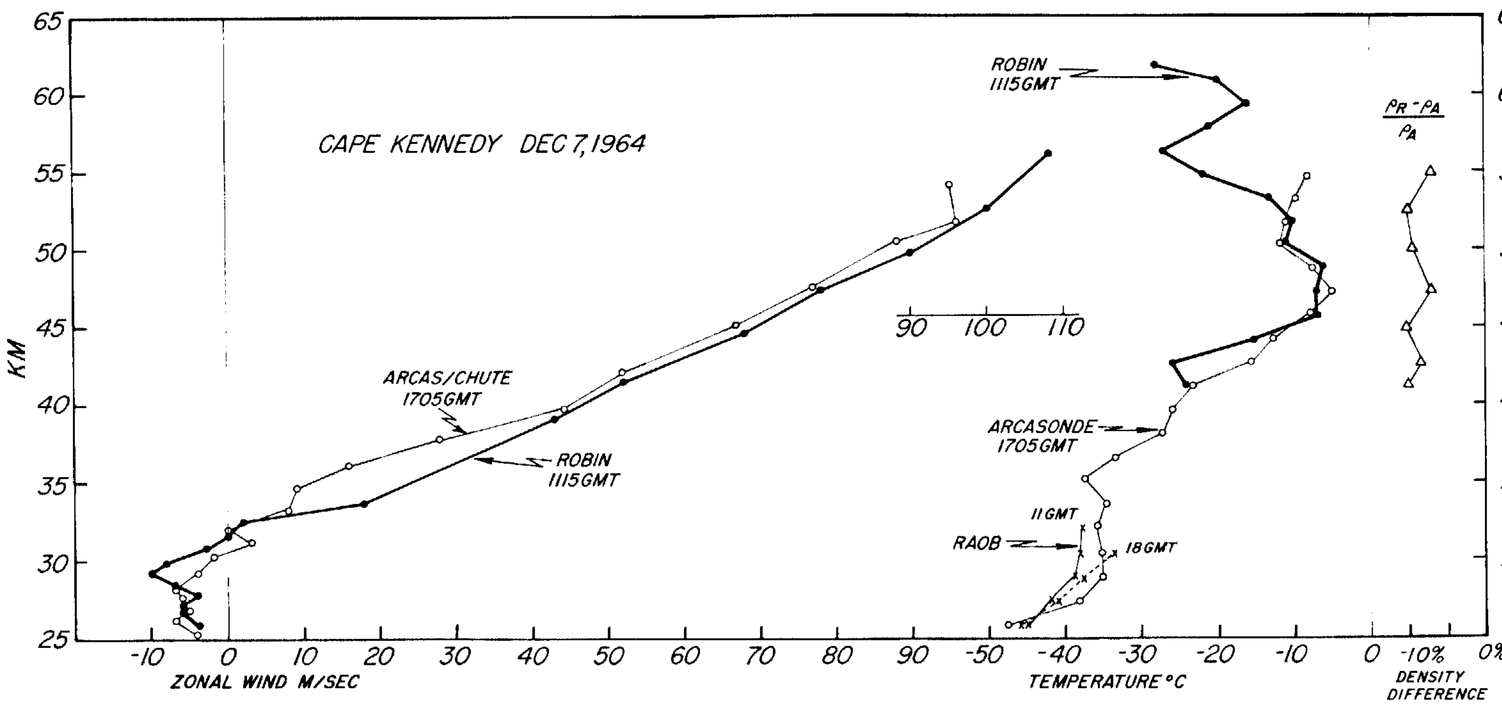

Figure 5.-Wind, temperature and density profiles from sphere sounding at C. Kennedy, Dec. 7, 1964, compared with data from Arcasonde launching 6 hours later.

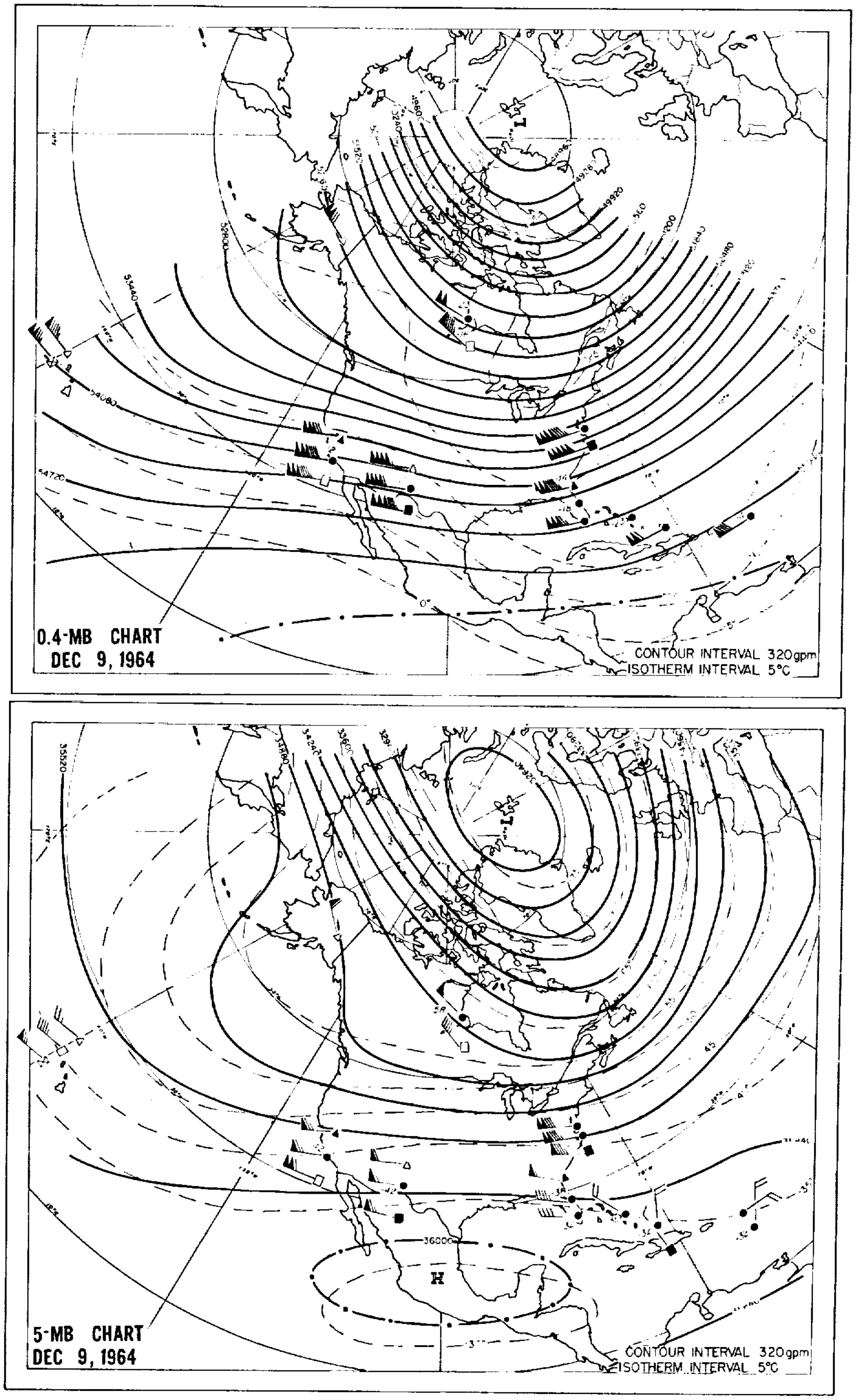

Figure 6.-Constant-pressure maps for the 0.4- and 5-mb levels, Dec. 9, 1964 (Staff, Upper Air Branch, NMC, ref. 32).

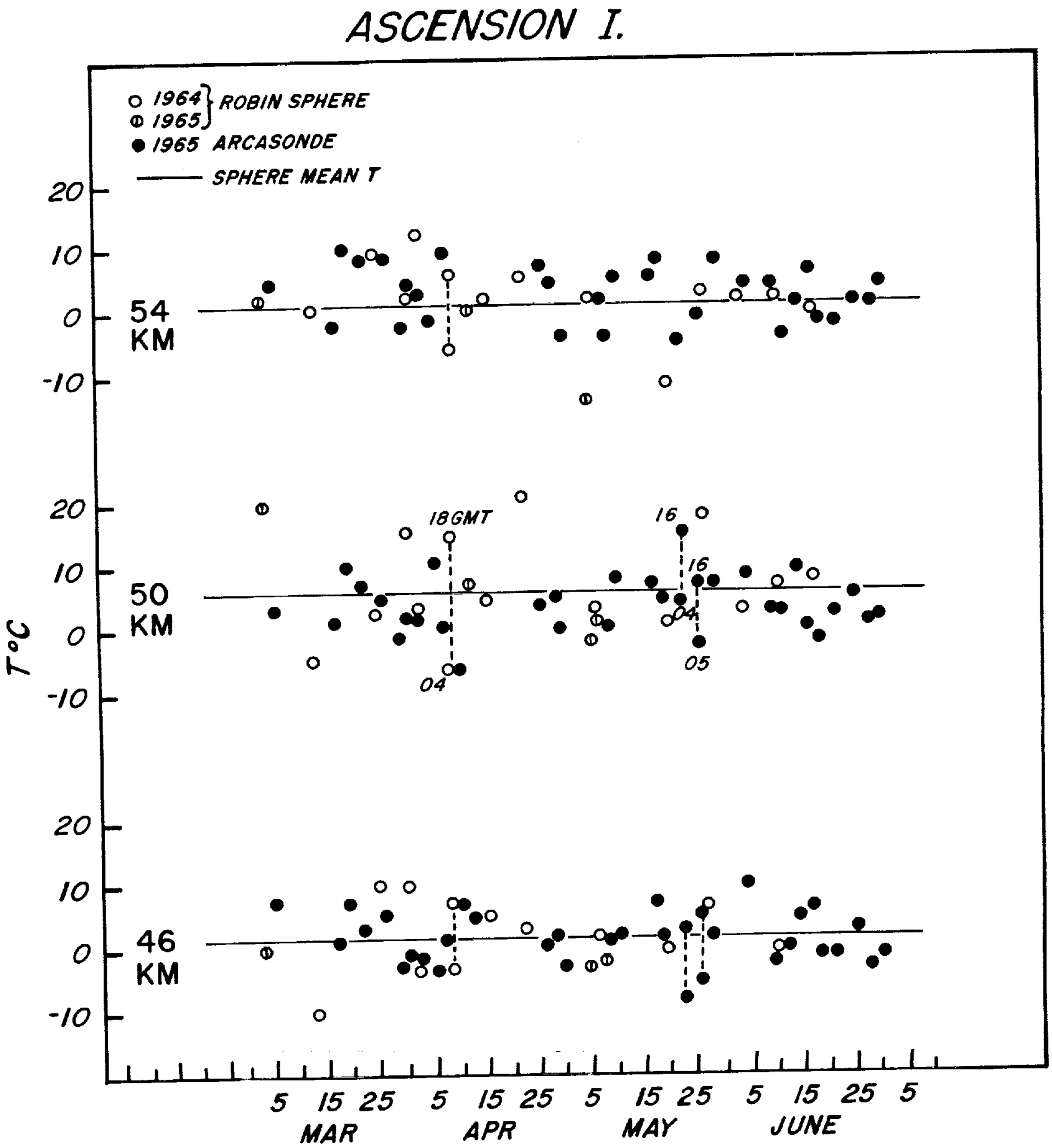

Figure 7.-Comparison of temperatures from sphere soundings, 1964-65, and thermistor soundings, 1965, at Ascension Island. See statistics in table III.

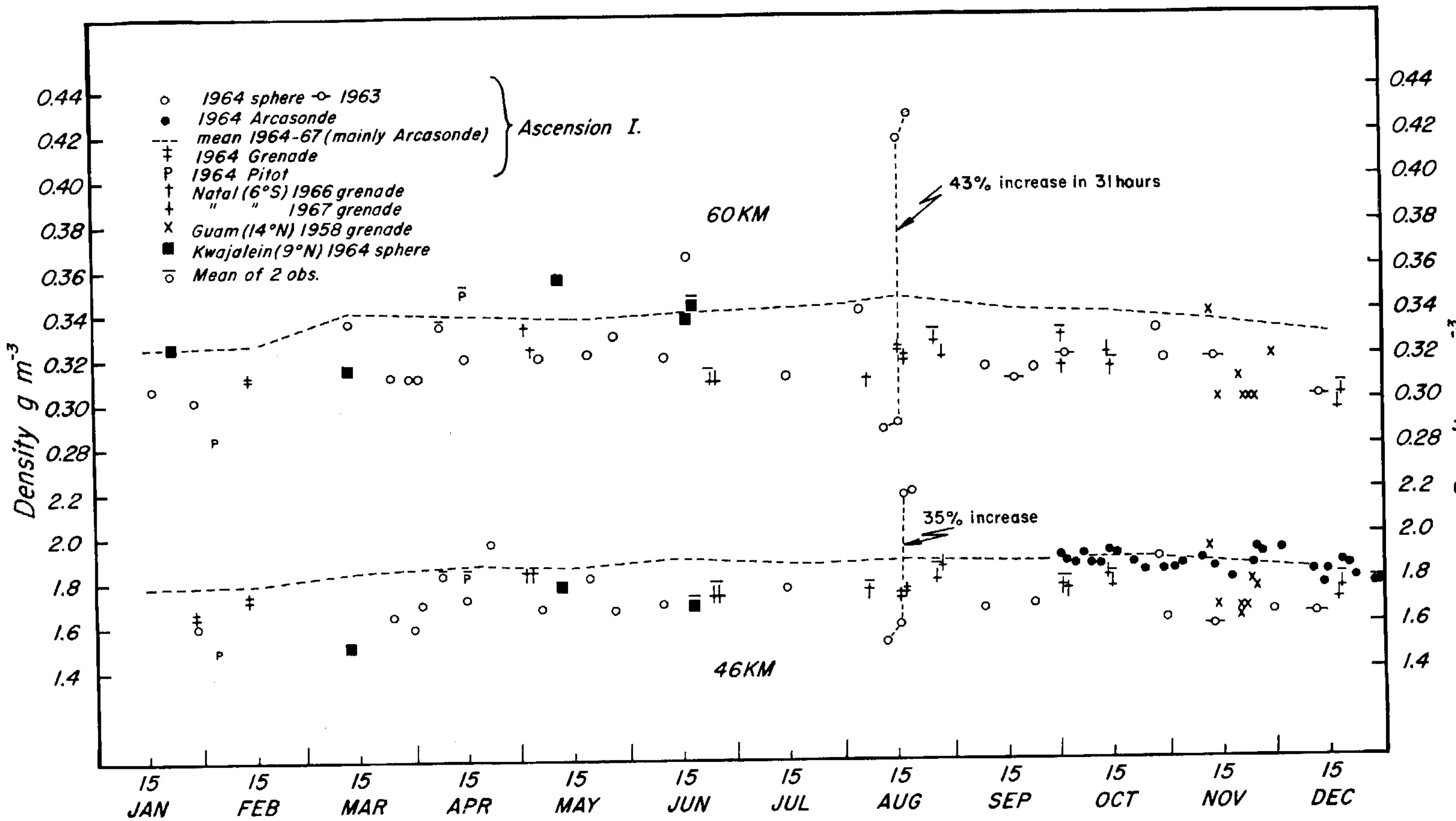

Figure 8.-Densities at 46 and 60 km, Ascension Island, based on sphere soundings (open circles), as compared with values based on thermistor, grenade, and Pitot soundings. Comparative data for other tropical locations are also entered, including University of Michigan spheres for Kwajalein. Spurious density change from Aug. 16 to 17 is discussed in text.

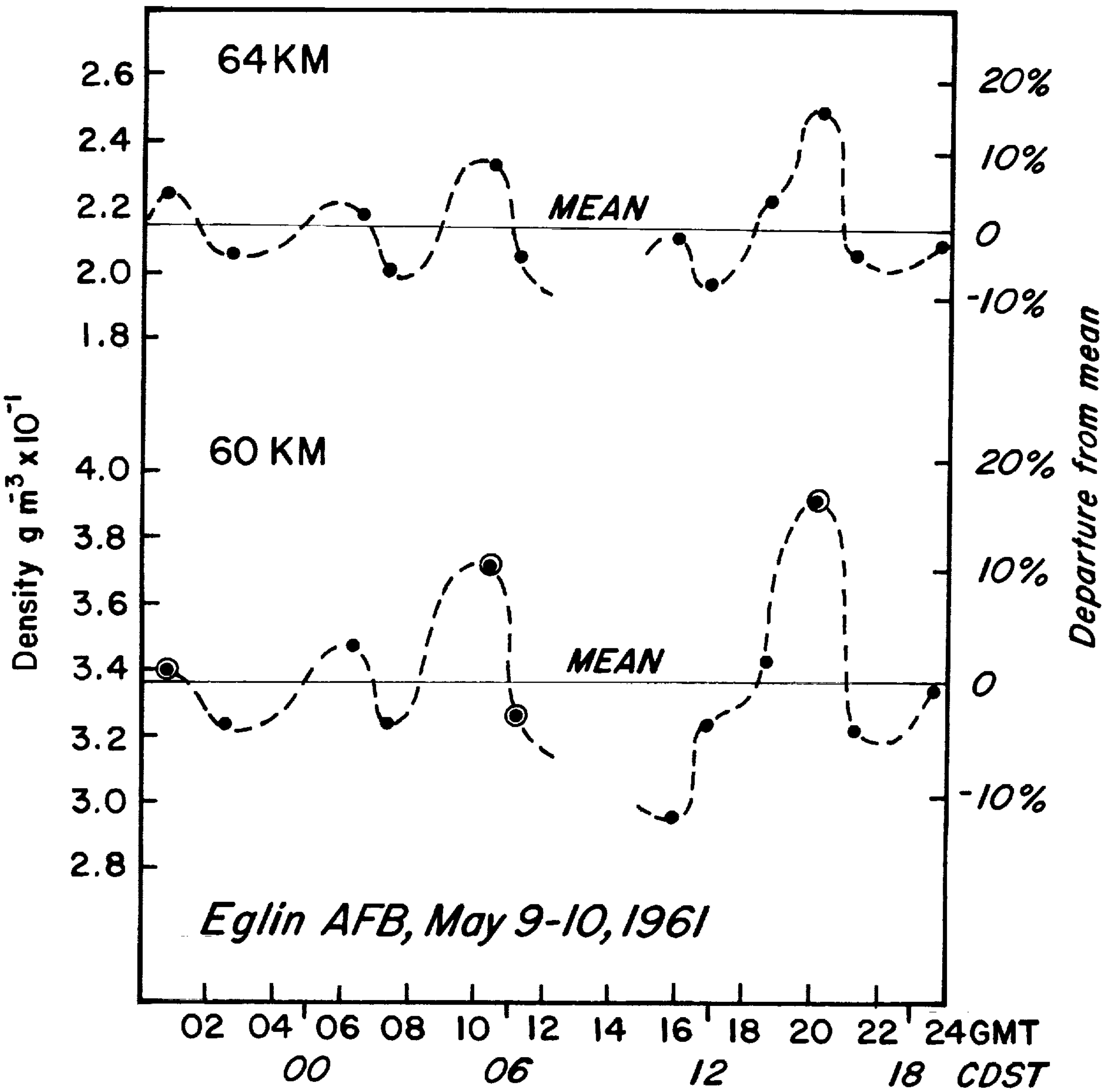

Figure 9.-Densities indicated in May 1961 diurnal series of sphere soundings. Circled values were apparently not used in harmonic analysis of 60 km data by Cole and Kantor (ref. 20).