DATA FROM FALLING SPHERE EXPERIMENTS INCLUDING COMPARISON TESTS BETWEEN DIFFERENT SYSTEMS*

Lawrence B. Smith

Sandia Laboratories
Albuquerque, New Mexico

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SUMMARY

A discussion is given of the falling sphere program conducted by Sandia Laboratories. The 30 experiments conducted between October 1964 and June 1969 are categorized according to their results. The results from a series of comparison tests made in May 1968 between a variety of systems used to measure density are also discussed with emphasis on possible system errors. It is concluded that more effort needs to be expended to determine the size of errors arising from drag coefficient uncertainties and velocity and acceleration measurements.

INTRODUCTION

The falling sphere program at Sandia started in October 1964 with units provided by the U.S. Navy from a discontinued program at Kwajalein. Since that time we have conducted 30 such experiments mainly launched from Kauai, Hawaii, but also from Johnston Atoll and Tonopah Test Range, Nevada. This system uses the 66-cm diameter passive sphere designed and developed by Peterson, et. al., at the University of Michigan.[1] Although there are 3 spheres per Nike-Cajun payload, it has not been possible to obtain simultaneous data from all three because of a lack of precision radars. Thus at Kauai the NASA FPS-16 man-in-space radar at Kokee has been our primary tracking unit. Contiguous to the Sandia launch site is the Navy Bonham Air Landing Field which has a number of less precise radars and usually one MPS-25. Position data from radars other than the FPS-16 or MPS-25 have not been usable for density calculations, although I do hope to combine their output with the other tracks for study on atmospheric dispersion. In an operation the Kokee unit is requested to track the first sphere, the MPS-25 to follow the second, and an MPS-26 or equivalent to track the third.

From October 1964 through June 1969 we have conducted 30 falling sphere experiments. The results have been:

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21 experiments where density, temperature, and wind data were obtained from at least one sphere

3 experiments where radars did not acquire sphere (all three at Johnston Atoll)

5 experiments with improper sphere inflation

1 experiment with radar computor malfunction

Of the 5 spheres listed as improperly inflated, 2 were ejected at too low an altitude as a result of rocket or payload malfunction, and the other 3 showed slow fall rates indicating underinflation. As with most sphere experimenters we verify the fall rate versus altitude of each sphere with a mean from many observations. Underinflation was also implied by the fact that these spheres were from a new group whose shelf life had not been verified. A check of the remaining units in the group indicated several with less than the original 8 grams of isopentane.

In the 3 experiments where the FPS-16 radars did not acquire any spheres, the problem was believed to be operator and not sensor related. With all 3 the radar operators were inexperienced in sphere operations. A signal-to-noise ratio of greater than 10 db is usually observed. A description of these operations and a compilation and analysis of the data from 15 of these experiments is provided by reference 2.

SYMBOLS

C_D	drag coefficient
λ	mathematical technique for checking sphere inflation
ρ	density
σ_R	root-mean-square range error
σ_ϵ	root-mean-square angle error

COMPARISON TESTS

On May 16, 17, and 23, 1968, a series of 14 individual rocket systems were launched from Kauai on a closely coordinated schedule. The purpose was to measure atmospheric density by several different techniques and compare results. The following schedule was maintained:

	System	Identification	Date	Launch Time (LST)	Altitude (km)
1.	Rocketsonde	Arcasonde	May 16, 1968	2130	20-60
2.	Instrumented Sphere (AFCRL)	154-106	May 16, 1968	2300	72-110
3.	Rocketsonde	Arcasonde	May 17, 1968	0530	20-60
4.	Passive Sphere	154-110	May 17, 1968	0015	30-110
5.	Rocketsonde	Arcasonde	May 17, 1968	1437	20-60
6.	Passive Sphere	154-111	May 17, 1968	1530	30-110
7.	Ionization Gages	152-112	May 17, 1968	1633	125-300
8.	Rocketsonde	Arcasonde	May 23, 1968	1030	20-60
9.	Passive Sphere	154-102	May 23, 1968	1000	30-110
10.	Instrumented Sphere (AFCRL)	154-103	May 23, 1968	1100	72-110
11.	Passive Sphere	154-105	May 23, 1968	1510	----
12.	Ionization Gages	154-113	May 23, 1968	1515	125-300
13.	O_2 Absorption	152-115	May 23, 1968	1745	80-160
14.	Pressure Probe	154-104	May 23, 1968	1200	30-100

In the above, the Arcasonde and the passive and instrumented falling spheres are operational systems. The ionization gage payload on a Nike-Tomahawk contains 3 cold cathode and one hot cathode gage. The O_2 absorption experiment used photometers aboard a Nike-Tomahawk to observe the attenuation in the 1600 Å and 1216 Å lines of the solar spectrum on both ascent and descent. This system included an automatic pointing system (ACS). The O_2 profile with height was converted to mass density by assuming a N_2/O_2 rate of 4 to 1. The ram and static pressure system was the standard instrumented probe on a Nike-Apache. Pressure inside the probe was measured by Metro-Physics thermocouples and related to ambient pressure across the shock wave from wind tunnel tests on this probe geometry.

Figure 1 shows observations of density taken over a 4 hour time interval by the instrumented sphere, the passive sphere, the radiosonde and the Arcasonde. Between 72 and 95 km the sphere data differ by as much as 30 percent. Results on the second day are indicated in Fig. 2 where measurements by the optical and the probe pressure techniques are also included. At these altitudes quoted uncertainties in the optical data are of the order of ± 20 percent and those of the probe data are 10 to 15 percent with the greater uncertainty in these probe results on the positive side. In Fig. 2 data from other systems fall between the density profiles from the instrumented sphere as a lower limit and the passive sphere as the upper limit. Except for the region above 100 km all measurements indicate a notable similarity in their variation with altitude. Above 100 km the sphere data diverge significantly. Between 70 and 100 km comparison with the other measurements is not conclusive because of the large error bars. Below about 60 km, comparison between passive sphere, pressure probe, Arcasonde, and radiosonde shows very good agreement. All differences are less than 10 percent, a result which can easily be attributed to small time and space variations. Such variations have been observed by a variety of other sounding techniques in most of the altitude region between 30 to 110 km.

Passive sphere experiments 154-110 and 154-111 indicated normal flights on the basis of their fall rate versus altitude as shown in Fig. 3 and on the basis of their acceleration and velocity on an expanded altitude scale as shown in Fig. 4. A λ check as suggested by Engler[3] was also made on both flights at the altitude of acceleration maximum. The results of 1.6 and 1.2×10^{-4} m^{-1} were well within the limits proposed by Engler for slightly lower altitudes. It is thus assumed both Sandia spheres were properly inflated. No such checks were made on the AFCRL sensor but the experimenter expressed confidence that the sphere inflated properly.

In an attempt to at least indicate the reason for the observed density differences in the sphere data, comparisons between pertinent parameters from four sphere flights are listed in Table I. The four flights consisted of two instrumented spheres (IS) and two passive spheres (PS). Differences between the two types of systems are given as percent difference in density but as absolute difference (Δ) in other parameters.

TABLE I

Launch 2300 and 0015 LST on 16 and 17 May 1968

Altitude km	Density gm/cm^3 x 10^9			Mach No.			Reynolds No.		
	IS	PS	% Diff	IS	PS	Δ	IS	PS	Δ
99	0.6	0.8	-25	4.9	3.3	1.6	17	35	18
95	1.2	1.0	20	5.2	3.1	2.1	33	46	13
90	2.9	3.9	-24	5.5	3.5	2.0	86	203	117
85	7.2	7.0	3	5.6	2.9	2.7	209	270	61
80	16.6	20.3	-18	5.6	2.6	3.0	578	765	187
75	37.1	47.7	-22	5.4	1.6	3.8	1090	1070	20

	C_D			Drag Accel. m/sec^2			Fall Speed m/sec		
	IS	PS	Δ	IS	PS	Δ	IS	PS	Δ
99	1.6	1.9	0.3	0.2	-4.9	5.1	1417	951	466
95	1.4	1.8	0.4	0.4	0.7	0.3	1443	964	479
90	1.2	1.3	0.1	0.8	10.3	9.5	1472	945	527
85	1.1	1.3	0.2	2.0	19.0	17.0	1499	873	626
80	1.0	1.2	0.2	4.4	32.6	28.2	1519	702	817
75	1.0	1.1	0.1	9.6	17.0	7.4	1525	427	1098

Launch 1000 and 1100 LST on 23 May 1968

Altitude km	Density gm/cm^3 x 10^9			Mach No.			Reynolds No.		
	IS	PS	% Diff	IS	PS	Δ	IS	PS	Δ
100	0.4	0.5	-19	4.9	1.6	3.3	14	12	2
95	1.5	1.3	15	5.2	2.2	3.0	33	65	32
90	2.0	3.4	-41	5.5	2.1	3.4	86	98	12
85	6.6	9.2	-28	5.6	2.2	3.4	209	297	88
80	15.4	18.8	-18	5.7	1.8	3.9	508	465	43
75	34.2	42.3	-19	5.4	1.3	4.1	1092	766	326

	C_D			Drag Accel. m/sec^2			Fall Speed m/sec		
	IS	PS	Δ	IS	PS	Δ	IS	PS	Δ
100	1.6	2.4	0.8	0.2	-8.5	8.7	1411	520	891
95	1.4	1.6	0.2	8.9	-5.9	14.8	1446	568	878
90	1.2	1.5	0.3	4.1	-2.1	6.2	1474	605	869
85	1.1	1.3	0.2	1.8	6.2	4.4	1500	598	902
80	1.0	1.2	0.2	0.8	10.1	9.3	1522	517	1005
75	1.0	1.0	0.0	0.4	10.8	10.4	1529	374	1155

For the altitude region of interest the spheres are in transitional flow between continuum and free molecular flow. The literature shows quite a variance or scatter of the drag coefficient data in this regime and accordingly this parameter is the most readily suspected as the cause of the differences. The Sandia program uses University of Michigan[1] derived drag tables which are based on measurements by Ashkenas[4] and May[5] for the transitional region and on measurements by Goin[6] in the subsonic region. From Mach 2.5 to 4 these coefficients are considered independent of Mach number. The AFCRL coefficients were taken from measurements by Sims[7] and Aroesty.[8] These appear to be quite independent of Mach number although this is not so stated by the authors.

If drag coefficient uncertainties are not the fundamental cause of the differences, the problems must be in the determination of velocity and acceleration since the only other parameters are area and mass and both are carefully measured. The passive sphere depends upon position versus time coordinates provided by the radar to determine velocity and acceleration.

At the time of this writing no empirical data were available on the magnitude of radar tracking errors in the 100 km region. However, if the results quoted by Engler[3] can be extrapolated to the 80- to 100-km layer, the contribution to the density from radar tracking errors is less than 3 percent. This estimate resulted from a comparison of densities calculated from two independent FPS-16 radar tracks of the same balloon. The validity of this extrapolation is enhanced by the fact that Engler's data show the variation increases with decreasing altitude. Thus the maximum difference in densities was found in the 50-60 km layer rather than in the higher 60-70 km layer implying it may be less above 80 km. Also, the difference was nearly independent of the type of smoothing. A similar experiment for altitudes between 80 and 110 km is to be conducted at White Sands this month.

An attempt was made to compute the effect of tracking errors by generating a fictitious set of position data which incorporated random radar errors. The regular computer program then used these fictitious data to compute new accelerations and velocities from which new densities were calculated for comparison with the real time data. Each new coordinate was generated by a Monte Carlo process that algebraically added to the real time range and angle value the product of a random number and an assumed RMS radar error. The random numbers were taken from a normal distribution with zero mean and unit standard deviation.

The above technique was tried with 2 sphere experiments with results as shown in Table II. Although errors frequently quoted for a well maintained FPS-16 are $\sigma_\epsilon = 0.1$ mil in angle and $\sigma_R = 5$ meters in range, the tabulated results are based on more conservative errors as given. Each coordinate was assumed to be independent of the others and no correlation was assumed between the measured parameters or with themselves, i.e., range error was not assumed to depend on distance or angle to target, etc.

Table II shows the percent deviation in density as computed using random number generation of sphere position data relative to densities obtained from original real time data. Radar errors are given as RMS percent for ϵ = angle error in degrees and R = range error in meters. Apogee altitudes for experiments 154-110 and 154-111 were 144 km and 152 km, respectively.

TABLE II

Altitude km	Percent deviation in density			
	Experiment			
	154-110	154-111	154-110	154-111
	$\sigma_\epsilon = 0.001^\circ$ and	$\sigma_R = 10$ m	$\sigma_\epsilon = 0.0005^\circ$ and	$\sigma_R = 10$ m
100		1.9	0.2	-4.7
99	-0.1	4.5	0.4	-2.3
98	3.1	11.0	-0.4	7.6
97	-0.5	3.8	0	-1.5
96	-2.6	3.4	-0.6	0
95	-2.8	3.6	-0.2	0
94	-3.0	2.2	-0.4	0.5
93	-2.2	3.7	0.2	1.2
92	-0.8	2.2	0.2	0.7
91	0.6	1.6	-0.2	0.2
90	0.7	1.2	0	0.3
<90	≤1	<0.6	≤0.2	≤0.4

On the basis of Table II random radar tracking errors are generally less than 3 percent. It is, of course, possible that a fixed bias causing errors may exist. However, in view of the excellent equipment and operating personnel at the NASA Kokee site it appears unlikely that these real time coordinate data were so skewed.

One other possibility exists. The velocity-position data from the instrumented sphere reduction is obtained from integration of the telemetered acceleration measurements. The beginning altitude results from a radar track while each subsequent position and sphere velocity is a sum of previous values. An error in each such determination would be cumulative with an unknown magnitude.

CONCLUSIONS

The comparison tests described in this paper have shown that the falling sphere technique provides atmospheric data in good agreement with other systems from 30 to about 70 km. The technique is also capable of altitudes much above 70 km although these tests indicate the errors in density so derived may be as great as 20 to 30 percent, significantly greater than the usual 5 to 10 percent error quoted. It is not apparent what causes such errors nor is it apparent whether they are unique to one of the two types of spheres described here or if they result from an accumulation of several small errors.

The literature provides a variety of drag coefficient data for the transitional region. One highly desirable product of this conference would be to standardize such data so that sphere experimenters would at least have a common input. The new technique of computing coefficients by a Monte Carlo calculation shows promise and could be used.

Additional studies are needed on the accuracy of radar tracking and the possibility of cumulative errors in the velocity-position data from the instrumented sphere.

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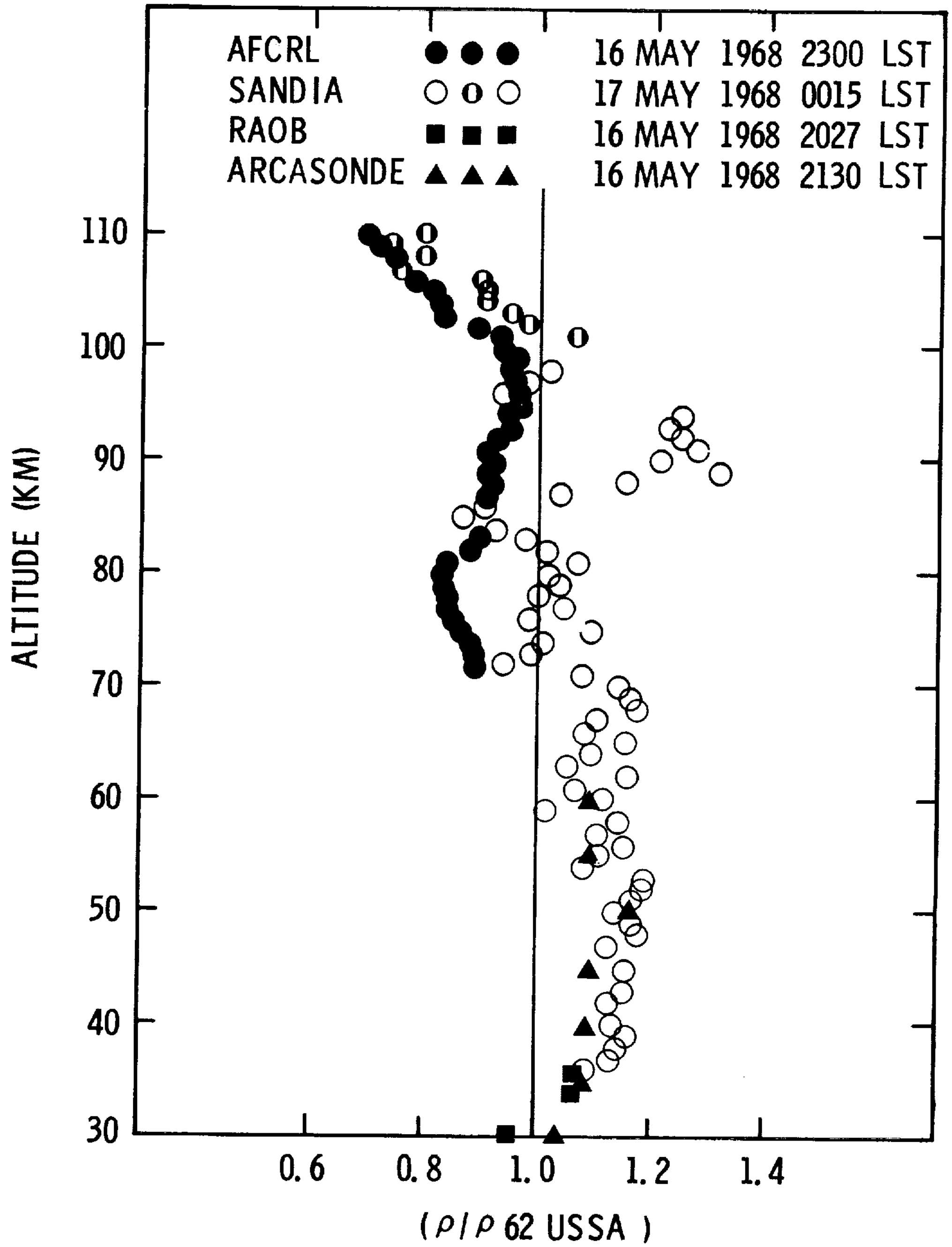

Figure 1.- Atmospheric density measurements on May 16-17, 1968, at Kauai, Hawaii, with the data normalized to the 1962 U.S. Standard Atmosphere (USSA). (Data listed as AFCRL and Sandia pertain to falling spheres of the instrumented and passive type, respectively.)

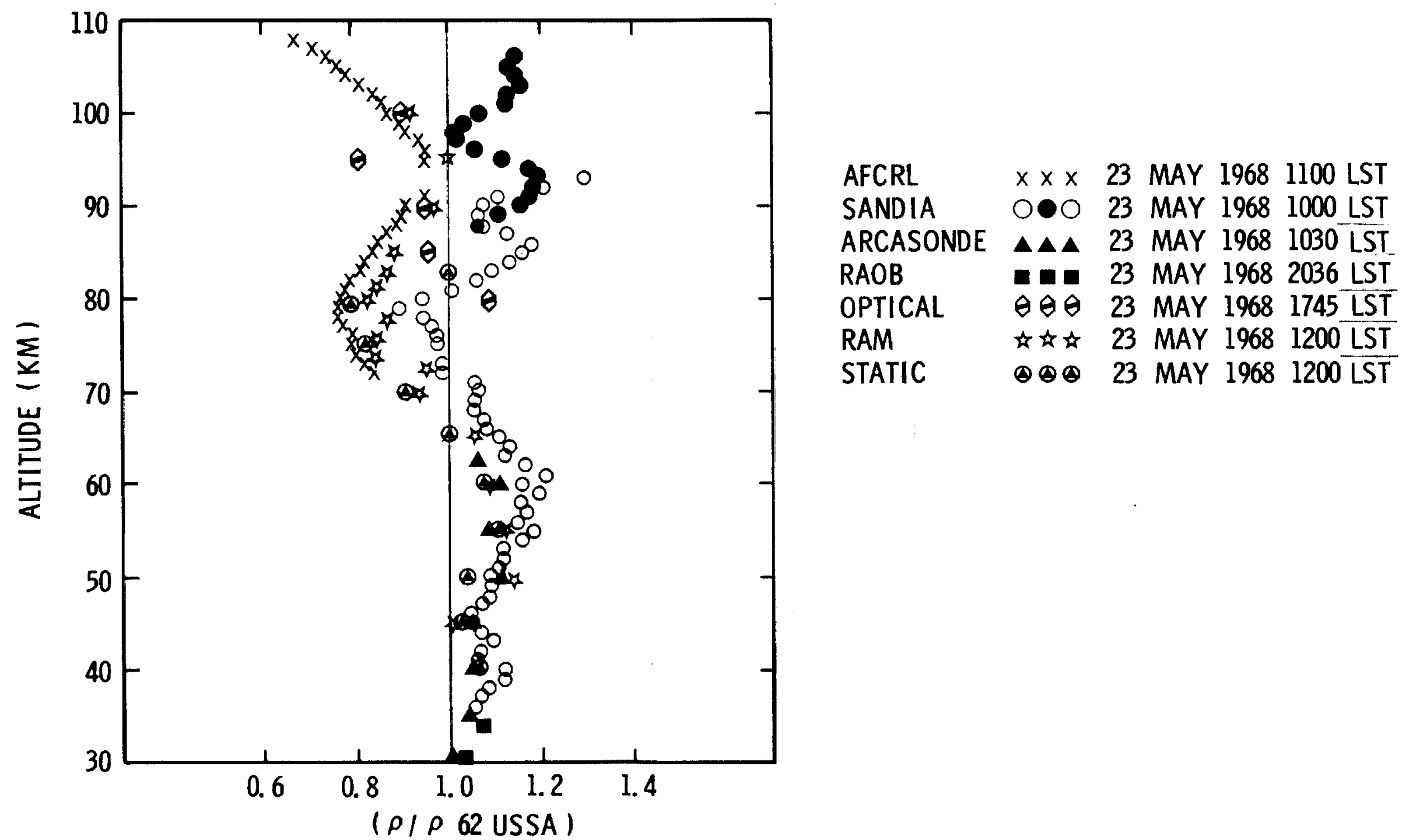

Figure 2.- Atmospheric density measurements on May 23, 1968, at Kauai. (See text for brief description of the measurement techniques listed.)

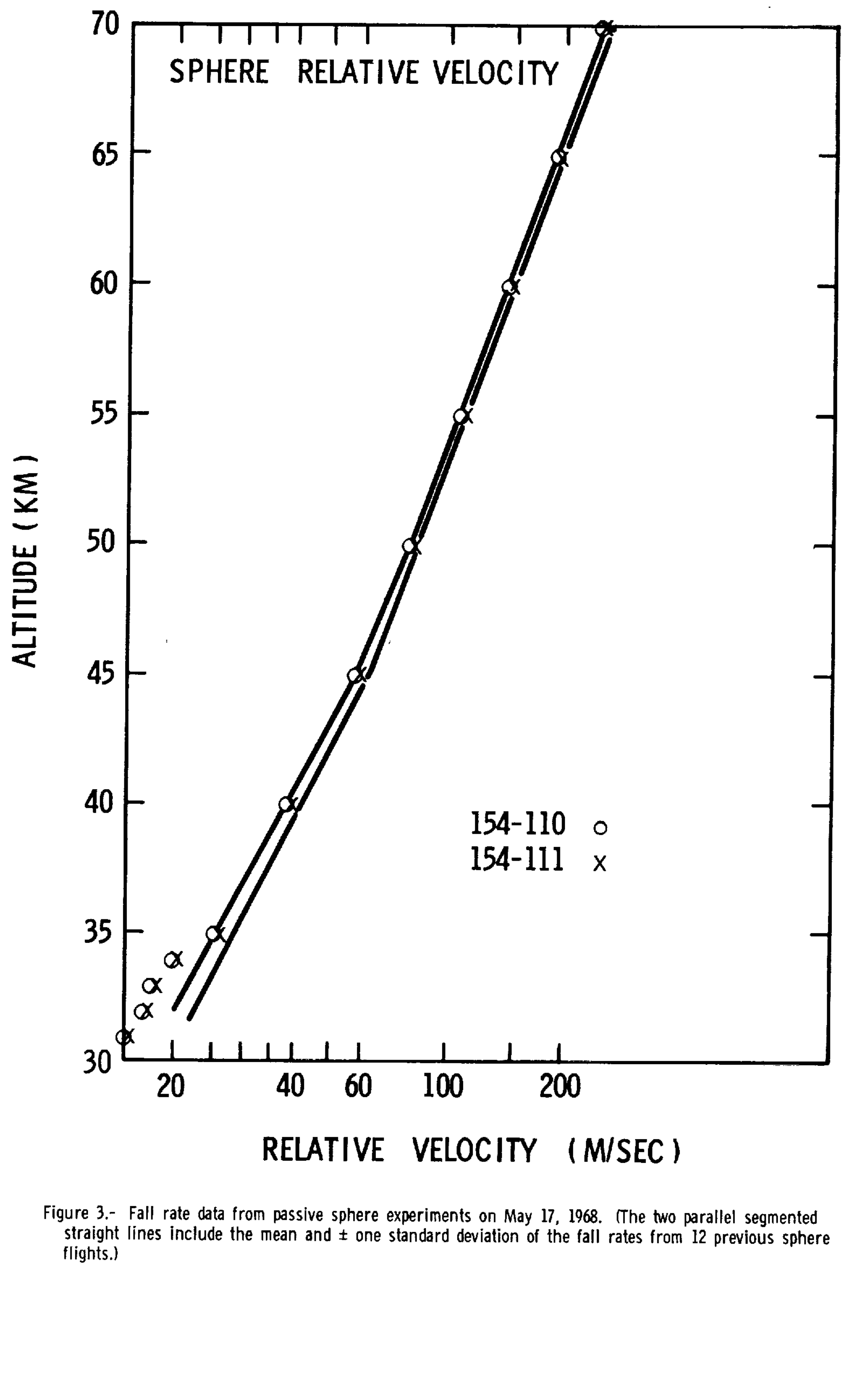

Figure 3.- Fall rate data from passive sphere experiments on May 17, 1968. (The two parallel segmented straight lines include the mean and ± one standard deviation of the fall rates from 12 previous sphere flights.)

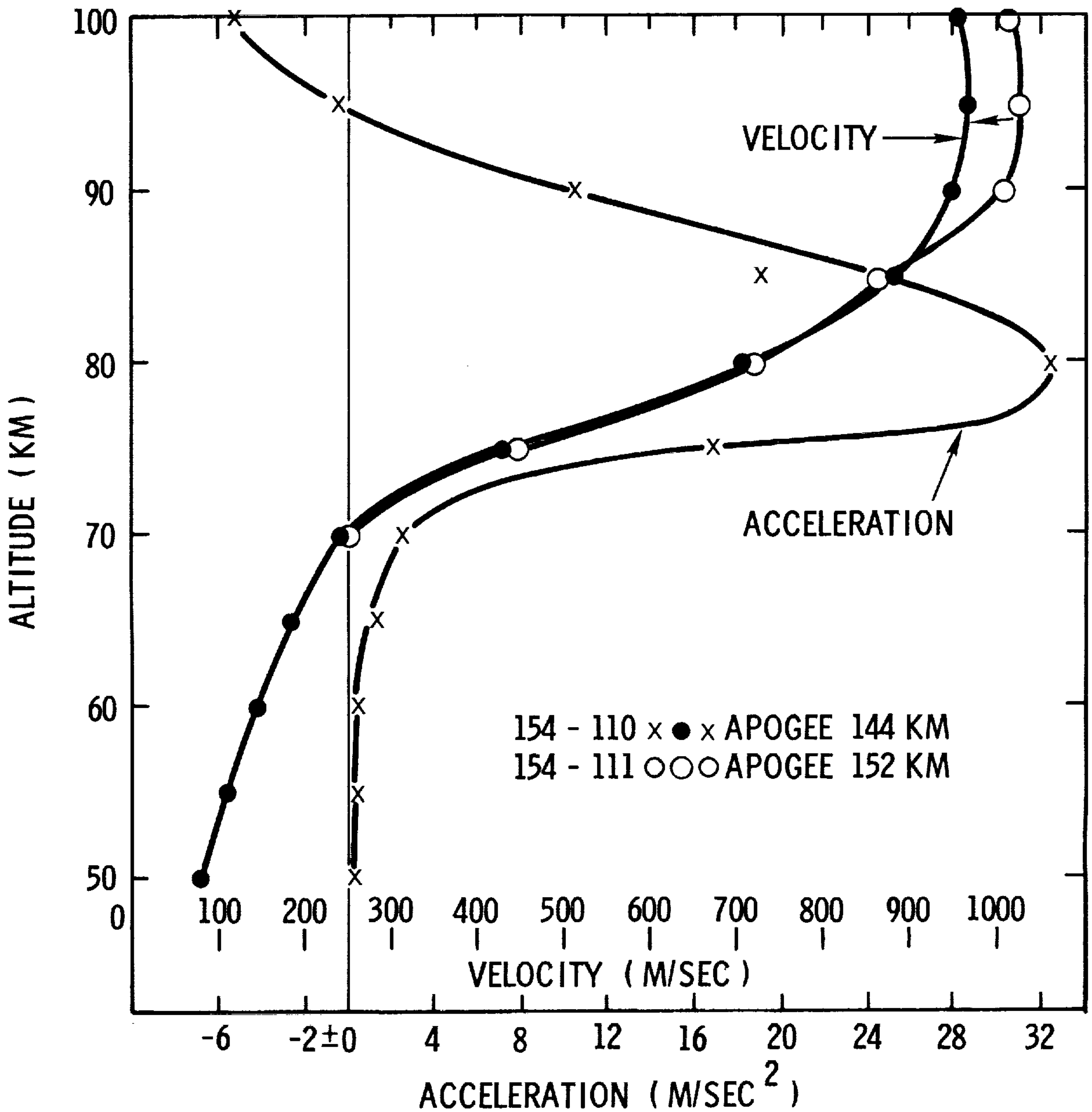

Figure 4.- Acceleration and velocity curves for two spheres released at 144 and 152 km over Kauai in May 1968.