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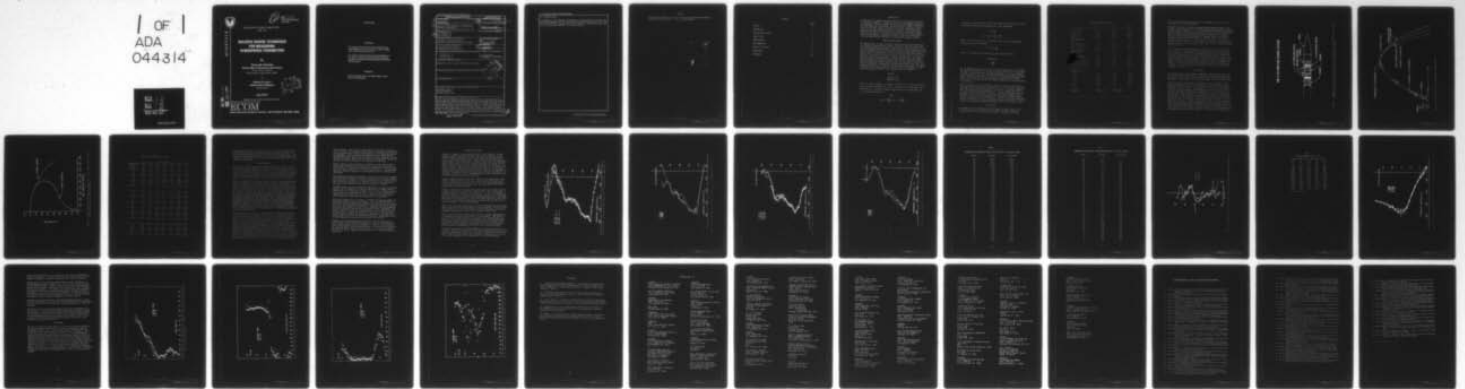
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# BALLISTIC SPHERE TECHNIQUES FOR MEASURING ATMOSPHERIC PARAMETERS

By

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**July 1977**

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) A near real-time method for measuring atmospheric winds, temperature, density, and pressure was initiated and tested by the US Army Atmospheric Sciences Laboratory at White Sands Missile Range (WSMR), New Mexico. The technique used a 0.1-m sphere deployed from a small meteorological rocket and tracked by a high precision radar to acquire data from position measurements. Total elapsed time from launch to sphere impact was 11 to 13 minutes. Spheres were tracked by several radars, and comparable temperatures were attained between spheres. Comparisons			

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20. ABSTRACT (cont)

of temperature with independent radiosondes and rocketsondes were also made and showed good agreement with two identifiable bias areas at 25 km and 35 km. Wind data showed excellent comparability with differences in direction occurring primarily in light wind conditions of less than 10 m/s.

PREFACE

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## INTRODUCTION

In response to a request from Ballistic Missile Defense Advanced Technology Center (BMDATC), a program to measure the atmospheric parameters of temperature and wind in real time was initiated at WSMR, New Mexico. The requirement was to determine the feasibility of making the measurements in near real time by using ballistic sphere techniques. Near real time for this purpose is defined as collecting the required data between 5 and 50 km altitude within 15 minutes of an initial command. The ballistic sphere is a passive device deployed from a meteorological rocket and tracked by a ground-based radar. Data are derived solely from the radar position information recorded during sphere descent.

## THE BALLISTIC SPHERE

For approximately 15 years inflatable spheres deployed from meteorological rockets have been used to measure atmospheric winds and temperature and to derive density and pressure between 30 and 90 km altitude. In 1972 the Meteorological Rocket Network [1,2] started a routine sounding program at five locations using a 1-m inflatable sphere deployed from a Super Loki rocket system. Data accuracies vary from 2 percent rms between 30 and 80 km to 10 percent rms at 90 km altitude. Uncertainties are caused primarily by radar noise and computer program filtering bias. The computer program devised by the University of Dayton Research Institute (UDRI) under contract to Air Force Geophysics Laboratories (AFGL) [3] (formerly Air Force Cambridge Research Laboratories) uses equations of motion, an initial assumption of temperature, measured drag values, radar data, and hydrostatic equations to calculate the atmospheric parameters. The theory and discussions of accuracies are covered in the cited reference. The simplified equations used in the computations are as follows:

Density

$$\rho = \frac{2m (g_z - \ddot{z})}{C_d A V (\dot{z} - w_z)}$$

where  $m$  = mass of sphere,  $g_z$  = gravity (vertical)  $\dot{z}$ ,  $\ddot{z}$  = vertical velocity and acceleration of sphere,  $C_d$  = drag coefficient,  $A$  = sphere cross sectional area,  $V$  - velocity of sphere with respect to the atmosphere, and  $w_z$  - vertical wind velocity.

Wind

$$W_x = \dot{x} - \frac{\ddot{xz}}{z - g_z}, \quad W_y = \dot{y} - \frac{\ddot{yz}}{z - g_z}$$

$W_x$  and  $W_y$  are wind velocity in the X and Y directions and  $\dot{x}$ ,  $\ddot{x}$ ,  $\dot{y}$ , and  $\ddot{y}$  are sphere velocity and acceleration in X and Y directions.

#### Pressure

$$P_i = P_{i-1} + \int_{z_{i-1}}^{z_i} \rho g dz$$

NOTE: An initial pressure  $P_o$  is computed from an initial temperature estimate by using the equation

$$P_o = T_o \rho_o \frac{R}{M_a}$$

where R is universal gas constant;  $M_a$  is molecular wt of air.

#### Temperature

$$T = \frac{PMa}{R\rho}$$

For the BMDATC requirement a new set of sphere criteria had to be devised. The sphere size had to be on the order of 0.1-m diameter so that it would fit into an existing rocket. The mass and diameter had to be calculated for proper rate of fall. The relationship between Mach number, Reynolds number, and drag coefficient had to fit the altitude region between 5 and 50 km. To achieve these goals, theoretical trajectories for several spheres were computed, and a 0.1-m, 0.100 kg candidate was selected (Table 1) as optimum.

Table 1 is broken into five sections. Section 1 lists the altitudes at which the sphere has vertical accelerations of  $-7$  and  $-3 \text{ msec}^{-2}$ , the altitude band of vertical velocities greater than Mach 1, and the altitude at which the Reynolds number exceeds  $2 \times 10^5$ . It is at this point that air flow around the sphere becomes turbulent. Derived thermodynamic data is degraded. Section 2 tabulates time of fall in various regions of the trajectory. Section 3 is a computation of temperature errors caused by assumed vertical motion of the atmosphere. Section 4 describes one-sigma errors of temperature at various altitudes caused by radar noise. Section 5 lists the theoretical temperature biases errors at 55, 50, and 45 km.

#### FLIGHT TESTS

Two sphere sizes were used during this program: a 0.12 m and a 0.1 m. The former was utilized because it was readily available, while the smaller sphere had to be fabricated to order. Fortunately, a larger

TABLE 1  
 COMPUTED TRAJECTORY CHARACTERISTICS  
 OF 0.1-m SPHERE DEPLOYED AT 80 km ALTITUDE

	100 gram	150 gram	200 gram
1. Alt for $\ddot{z} = -7 \text{ m/s}^2$	63.73 km	61.38 km	59.93 km
Alt for $\ddot{z} = -3 \text{ m/s}^2$	56.94 km	54.75 km	53.23 km
Alt band for Mach No. >1	36.89 km 78.62 km	34.15 km 78.62 km	32.16 km 78.62 km
Alt for turbulent flow Re No. > $2 \times 10^5$	<100 m	2.43 km	4.1 km
2. Time of fall 50 to 20 km	2 min 23 s	1 min 58 s	1 min 43 s
Time of fall 50 to 10 km	5 min 38 s	4 min 41 s	4 min 8 s
Time of fall apogee to 4 km	10 min 0 s	8 min 33 s	7 min 44 s
Time of fall 50 km to Re No. > $2 \times 10^5$	9 min 33 s	7 min 57 s	6 min 21 s
3. Temp error at 50 km for vertical wind of 2 m/s	1.851°K	1.710°K	1.644°K
$\Delta T$ from $\Delta W_z = 1 \text{ m/s}$ at 40 km	1.268°K	1.013°K	0.915°K
$\Delta T$ from $\Delta W_z = .5 \text{ m/s}$ at 30 km	1.189°K	0.971°K	0.877°K
$\Delta T$ from $\Delta W_z = .1 \text{ m/s}$ at 20 km	0.555°K	0.459°K	0.396°K
$\Delta T$ from $\Delta W_z = .1 \text{ m/s}$ at 10 km	1.186°K	1.003°K	0.701°K
4. Estimated temp error due to radar noise			
$\sigma_T$ 55 km	1.4478°K	1.937°K	2.307°K
$\sigma_T$ 50 km	0.9917°K	1.180°K	1.267°K
$\sigma_T$ 40 km	0.8611°K	0.715°K	0.676°K
$\sigma_T$ 30 km	1.4375°K	1.247°K	1.129°K
$\sigma_T$ 20 km	2.9672°K	2.490°K	2.185°K
$\sigma_T$ 10 km	6.0480°K	5.146°K	4.644°K
5. Temperature bias error estimation	7.96°K at 55 km 5.41°K at 50 km 2.64°K at 45 km	9.29°K at 55 km 6.75°K at 50 km 2.07°K at 40 km	

rocket, the XM75 [4], was available at the beginning of the tests, and no program delays were encountered.

The sphere was made of two-piece thin-wall spun aluminum, welded at the equator. It was mounted on a lathe and turned in two directions to give a final diameter tolerance of  $\pm 0.13$  mm and a medium polished surface smoothness. Two molded plastic pieces were placed fore and aft of the sphere, and the assembly with appropriate spacers was loaded into the rocket (Fig. 1). The rocket was launched at a quadrant elevation of  $80^\circ$  and reached altitudes of 60-70 km (Fig. 2). At that point a 110-second pyrotechnic delay detonated a small explosive charge and the sphere was ejected into the atmosphere. Radars acquired the sphere and tracked its descent to impact 11 to 13 minutes later. Rate of fall reached 500 m/sec at 55 km (Fig. 3).

Severe radar acquisition problems were encountered on almost every mission. The number of pieces ejected at expulsion varied from three to four depending on the assembly configuration, and proper identification of the sphere was difficult. The FPS-16 and MPS-36 radars at WSMR did not have discrimination capability, and operation judgment was the only source of target selection available. Many variations of assembly techniques, multiple radar assignments, and multiple target assignments were tried, but acquisition of the sphere remained a problem throughout the program. A number of spheres were flown where little or no data were recorded. This problem should be virtually eliminated when discrimination radars are used.

#### RADAR ERRORS

On 8 December 1975, three ballistic spheres of approximately 135 g mass and 0.12 m diameter were launched. The three launches were tracked by four radars: three FPS-16 and one MPS-36 radar. The FPS-16 radars are designated by the numbers, R112, R113, and R114; and the MPS-36 is R354.

Radar tracking accuracies were calculated from the 8 December flights where four radars were used to simultaneously track each sphere. The standard deviation of the error in range was estimated by differencing the ranges from two radars. Assuming that the radar errors are independent and of equal variance, the standard deviation of the difference between range values divided by the square root of 2 is an estimate of the one-sigma slant range error for each radar. Table 2 shows the one-sigma error in range, azimuth, and elevation using various combinations of the radars. From this table, the following conclusions can be made. The FPS-16 radars performed as expected with regard to slant range tracking errors of 3 to 6 m. However, the azimuth and elevation errors are three to four times as large as observed in tracks of larger 1-m spheres [3]. The MPS-36 radar exhibits somewhat larger tracking errors than the FPS-16 radar. Nevertheless as will be seen later, the MPS-36 radar is of sufficient quality to provide reasonable accuracy in temperature and wind measurements from the ballistic sphere. The significantly higher errors

## XM-75 CALIBRATION SPHERE SYSTEM

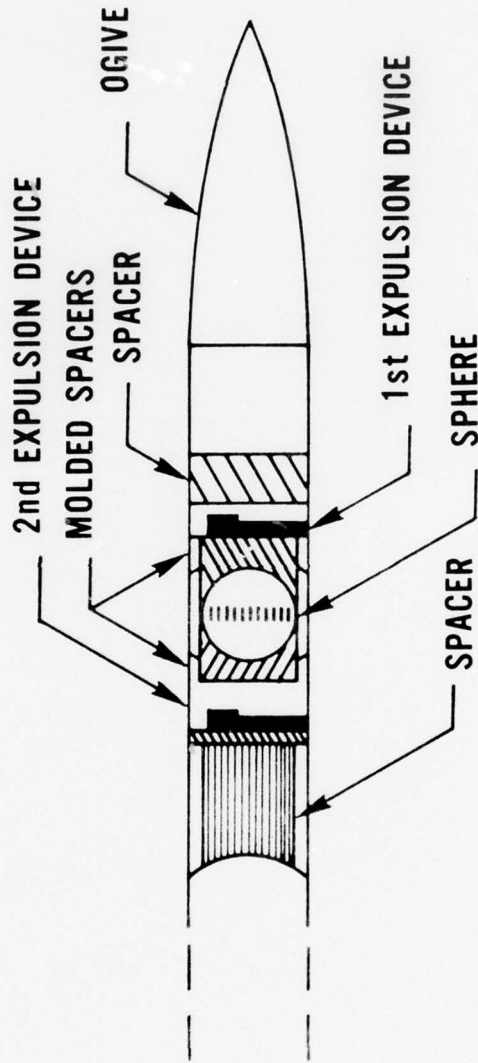


Figure • Assembly cross section of the sphere in the XM-75 rocket. Plastic spacers are molded around the sphere to prevent damage during the expulsion process.

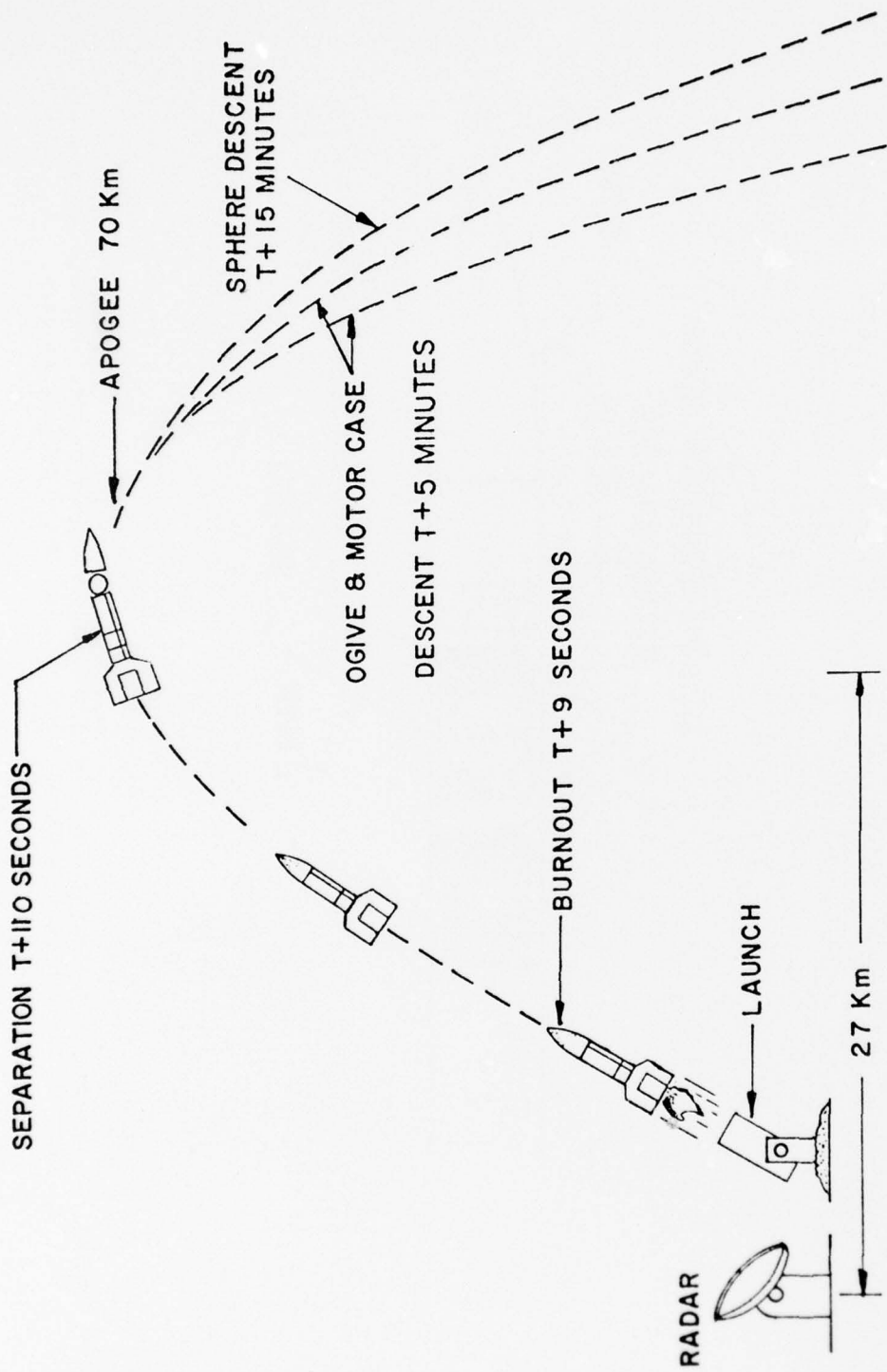


Figure 2. Typical sequence of events during a sphere flight.

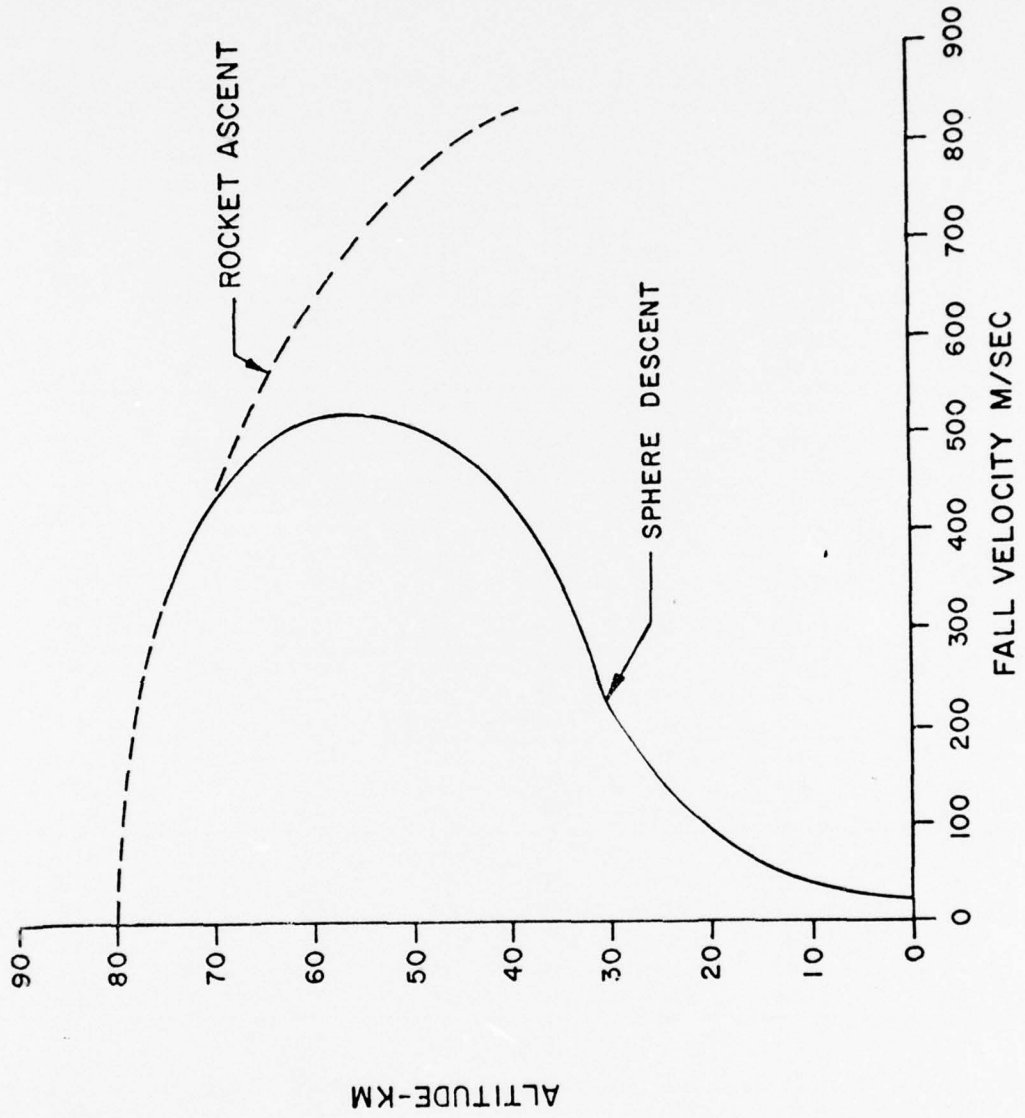


Figure 3. Fall velocity as a function of altitude for a rigid sphere deployed from a meteorological rocket at 70 km altitude.

TABLE 2  
 NOISE LISTED IN ORDER OF:  $\sigma_R$  (m),  $\sigma_E$  (mils),  $\sigma_A$  (mils)

Flight and Radars	Starting Altitudes						
	60 km	50 km	40 km	30 km	20 km	15 km	10 km
Flight Q22 $\sigma_R$	76.10	4.69	3.59	4.08	3.01	2.46	2.17
Radars { R112 $\sigma_E$	4.682	.442	.388	.334	.344	.276	.301
R354 $\sigma_A$	1.462	.525	.323	.458	.343	.279	.299
Q22	11.22	4.68	4.71	4.50	3.44	3.76	3.54
R113	1.188	.364	.359	.312	.265	.236	.256
R114	.550	.369	.495	.375	.361	.273	.286
Q22	11.81	4.78	4.35	4.86	3.45	3.35	3.17
R112	1.596	.433	.375	.351	.331	.312	.223
R114	.628	.451	.423	.548	.380	.388	.363
Q22	75.31	3.92	3.47	4.23	3.69	3.19	3.03
R114	5.212	.407	.472	.327	.349	.392	.310
R354	1.492	.347	.333	.380	.321	.272	.321
Q23	6.45	6.16	4.10	3.57	3.54	3.70	3.53
R112	.441	.464	.327	.367	.287	.295	.235
R113	.654	.777	.489	.318	.338	.384	.319
Q23	4.84	7.47	4.25	4.24	3.49	3.71	3.84
R113	.308	.465	.378	.343	.278	.307	.222
R114	.510	1.151	.475	.331	.264	.298	.333
Q23	4.90	4.61	3.64	4.52	3.44	3.44	3.49
R354	.502	.296	.597	.392	.324	.323	.280
R114	.547	.553	.287	.377	.329	.325	.298
Q23	6.26	6.29	4.36	4.29	3.99	3.97	4.10
R112	.475	.433	.408	.408	.378	.340	.258
R114	.849	1.192	.441	.439	.416	.402	.397
Q23	5.74	8.43	3.51	3.99	3.38	3.02	2.87
R112	.467	.445	.480	.387	.269	.201	.266
R354	.766	1.148	.393	.440	.367	.320	.293
Q24	22.90	5.16	4.64	4.37	3.63	3.80	3.12
R113	.487	.425	.403	.366	.305	.324	.298
R114	.969	.482	.501	.386	.414	.335	.192
Q24	25.50	5.51	5.17	4.67	4.04	3.75	3.46
R112	.582	.355	.374	.381	.378	.291	.198
R113	.897	.556	.470	.340	.330	.323	.218

in azimuth and elevation found in the FPS-16 tracks of the smaller ballistic spheres required a considerably larger smoothing interval to be used in the data processing than for reduction of 1-m sphere data. Thus the computer program previously used for the 1-m inflatable sphere was completely revised, and a new concept of data treatment was devised which reduced program biases.

#### DATA REDUCTION

The Ballistic Sphere Data Reduction Program (BSDRP) uses radar input of slant range, azimuth, and elevation angles at time increments of 1/10 of a second to produce atmospheric measurements of winds, temperature, density, and pressure for that region of the atmosphere between approximately 2 and 50 km. It was designed to be used either on a real-time computer system or with batch processing. When used on a real-time computational system, output should lag radar computer input by less than 1 minute.

Some of the features of the program are as follows: The program employs quadratic smoothing to obtain the velocities and accelerations needed to solve the equations of motion and obtain atmospheric measurements. The number of data points used in the quadratic smoothing is an input parameter of the program and can be varied at the discretion of the user, depending on size and mass of the sphere. For applications of the 0.12-m, 135-g ballistic spheres with tracking by an FPS-16 radar, 63 data points were used in the data processing. The BSDRP also provides the option to effectively increase the smoothing interval at two specified altitudes by successively doubling the time interval. This is achieved by averaging consecutive data points. Thus, the number of data points used in the smoothing remains the same throughout the flight, but the time spacing between data points increases by a factor of 2 each time the smoothing interval is doubled. In the case of the 0.12-m ballistic sphere with FPS-16 radar tracking, the smoothing interval was expanded at 25 km and 10 km to maintain a noise error in temperature of less than 2 degrees over the entire altitude range.

Another feature of the ballistic sphere program is the removal of bias errors resulting from smoothing. This removal was achieved as follows. The initial position and velocity of the ballistic sphere was calculated from the radar data shortly after apogee. From these initial conditions a theoretical sphere trajectory was generated by assuming the sphere fell in the 1962 Standard Atmosphere with no winds present. This theoretical profile was then treated as if it represented radar coordinates. The N-point quadratic smoothing was used to generate atmospheric parameters of winds, temperature, density and pressure. Any differences between the computed parameters and the 1962 Standard Atmosphere values represented bias in the measurements due to smoothing. These differences in density, temperature, and winds were stored in a bias correction array. Bias errors in pressure were not stored since using the ideal gas law, pressure can be determined directly from temperature and density measurements. After generation of the bias correction table, processing of the radar

data continued. Radar data were processed by the ballistic sphere program to provide calculations of winds, density, temperature, and pressure at time increments of 1 second (two seconds after the smoothing interval was expanded). Corrections were then applied to this biased data by determining from the bias correction table the proper correction for the specified altitude. Subtraction of this bias from the BSDRP calculation provided an unbiased estimate of the atmospheric parameters.

Another feature of this program is its ability to remove the often observed unreal temperature perturbation when a sphere penetrates Mach 1. This fictitious oscillation results from an inability to accurately calculate the drag coefficient as it passes through Mach 1. The bias error correction technique employed in this program effectively removes this oscillation.

The program also provides an estimate of the noise errors in the computed values of winds, temperature, density, and pressure by assuming independent radar errors in range of 5 m and in azimuth and elevation of 0.4 mil. These radar error estimates were obtained by differencing coordinates from dual FPS-16 radar tracks of the 0.12 m ballistic spheres.

The BSDRP ballistic sphere program was designed for use with the CDC 6600 computer but was adapted to the Univac 1108 computer at WSMR. During flight tests, radar data were transmitted to a central recording facility and recorded on a packed magnetic tape. Tapes were then used with the computer program to produce a data list. Delayed time processing of 15-20 minutes from launch time was successfully accomplished.

With each firing, or set of firings, a conjunctive radiosonde (RAOB) and rocketsonde (ROCOB) observation was made. The radiosonde ascended on a balloon and measured temperature, pressure, and winds between the surface and 30 km. The rocketsonde descended on a parachute and measured temperature and winds between 65 km and 25 km. Comparisons were then made between data collected from the ballistic sphere and the independent techniques. Comparisons were also made between the various radars tracking the same sphere. Because of operational constraints a time and space variation existed between the conjunctive measurements and spheres which could account for part of the observed differences. Rocketsonde and radiosonde temperature accuracies are typically  $\pm 2^{\circ}\text{C}$  rms [2].

Generally, the temperature data from ballistic spheres appeared to be valid between 5 km and about 42 km altitude. Above 42 km, the data deviates significantly from the rocketsonde observation. This deviation may have been caused by excessive radar noise or magnus forces induced by the spinning sphere. Below 5 km, the sphere entered drag crisis where the drag coefficient changed rapidly with very little change in Reynolds number [5].

## ANALYSIS OF FLIGHTS

Figure 4 is typical of data collected from a 0.120 m sphere. On this mission, launched on 8 December 1975, four radars tracked the sphere simultaneously. Differences in data, therefore, are directly attributable to individual radar errors. There is generally excellent agreement between 4 and 20 km altitude. Between 20 and 35 km, the temperature values differ by up to 7°K with the greatest difference coming from the MPS-36. Above 35 km, there is a gradual divergence up to about 10°K at 50 km. Radars 112 and 114 show excellent agreement over the entire range from 4 to 42 km. Above 50 km, the data is not usable. The difference between temperatures derived from the various radars may, in addition to inherent radar capability, be largely influenced by the servobandwidth of the radar. Tracking at a low servobandwidth can produce the type of oscillation observed in radars R113 and R354.

Figure 5 compares radar 114 with data collected from conjunctive rocket-sonde and radiosonde on the same day. Two distinct biases appear, one at 24 km (10°K) and the other at 35 km (5°K). The data diverge significantly above 42 km and probably reflect the upper limit of this ballistic sphere measurement system.

Figure 6 compares the temperature data derived from five radars tracking a single 0.1-m sphere launched on 7 October 1976. There is excellent agreement between 4 and 25 km, then differences of up to 10°K between 30 and 35 km, and up to 7°K between 35 and 42 km. Figure 7 is a temperature comparison between the sphere and the ROCOB/RAOB measurements. One radar was selected as representative. Again, the biases appear at 25 and 35 km. At 25 km the sphere-derived temperature is warmer than the RAOB, and at 35 km the sphere is colder than the ROCOB.

Table 3 lists the observed differences between ROCOB/RAOB and the averaged temperature data from 10 radar tracks of 0.120-m spheres. The biases are quite apparent at 25 and 35 km, with an observed divergence above 42 km. Otherwise, temperature differences are generally within  $\pm 2^\circ\text{K}$ .

Table 4 lists the observed temperature difference between ROCOB/RAOB and the averaged data from 10 radar tracks of 0.1-m spheres. The biases at 25 and 35 km are still evident in approximately the same magnitude and direction. The biases may result from inaccuracies in drag coefficient data, magnus effects induced by the spinning sphere, or possibly other factors. Figure 8 graphically illustrates the statistical differences between spheres and ROCOB/RAOB for both the 0.1- and 0.12-m spheres.

As previously stated, the ROCOB and RAOB data differences are given as  $\pm 2^\circ\text{K}$  rms. Table 5 lists and Fig. 9 illustrates temperature data collected from four radiosondes flown on 7 October 1976. Release times varied from 0705 to 1030 Mountain Standard Time. Maximum differences occur at 15 to 17 km, with a magnitude of 6°C between the 0730 and 1030 releases.

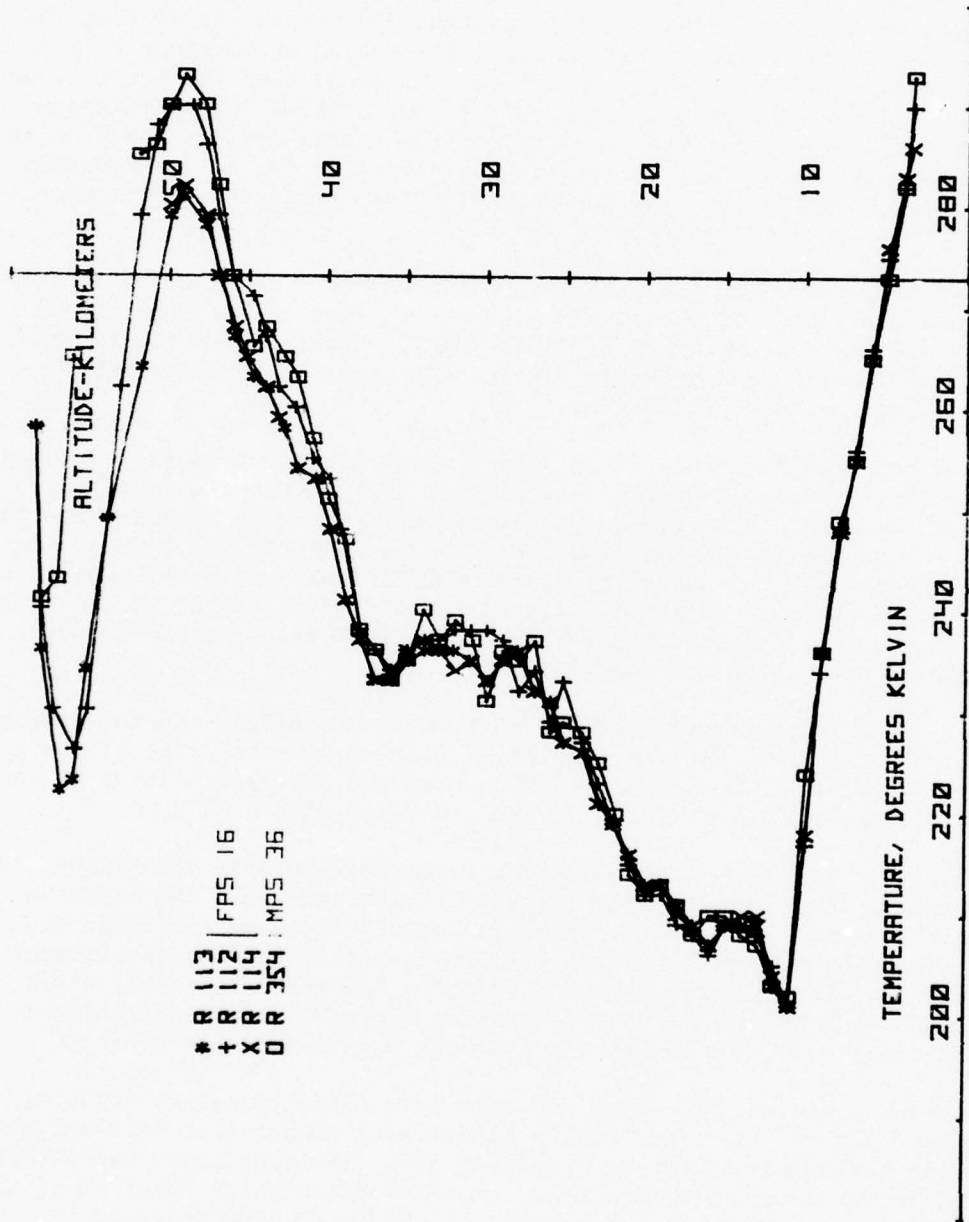


Figure 4. Temperatures derived from four radars tracking a 0.12-m single sphere launched at WSMR on 8 Dec 75.

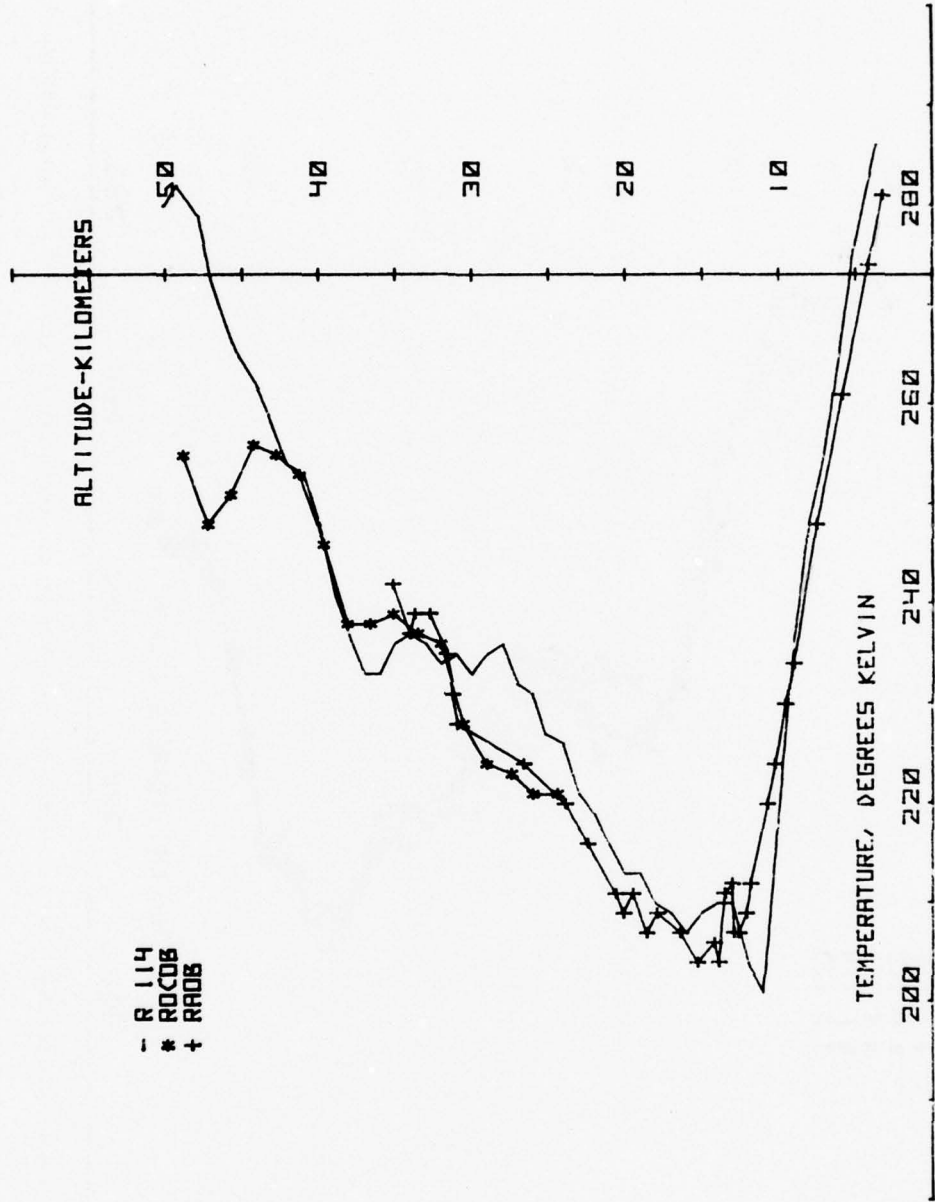


Figure 5. Temperature comparison between 0.12-m sphere tracked by R114 and the RDCOB/RAOB measurements, 8 Dec 75.

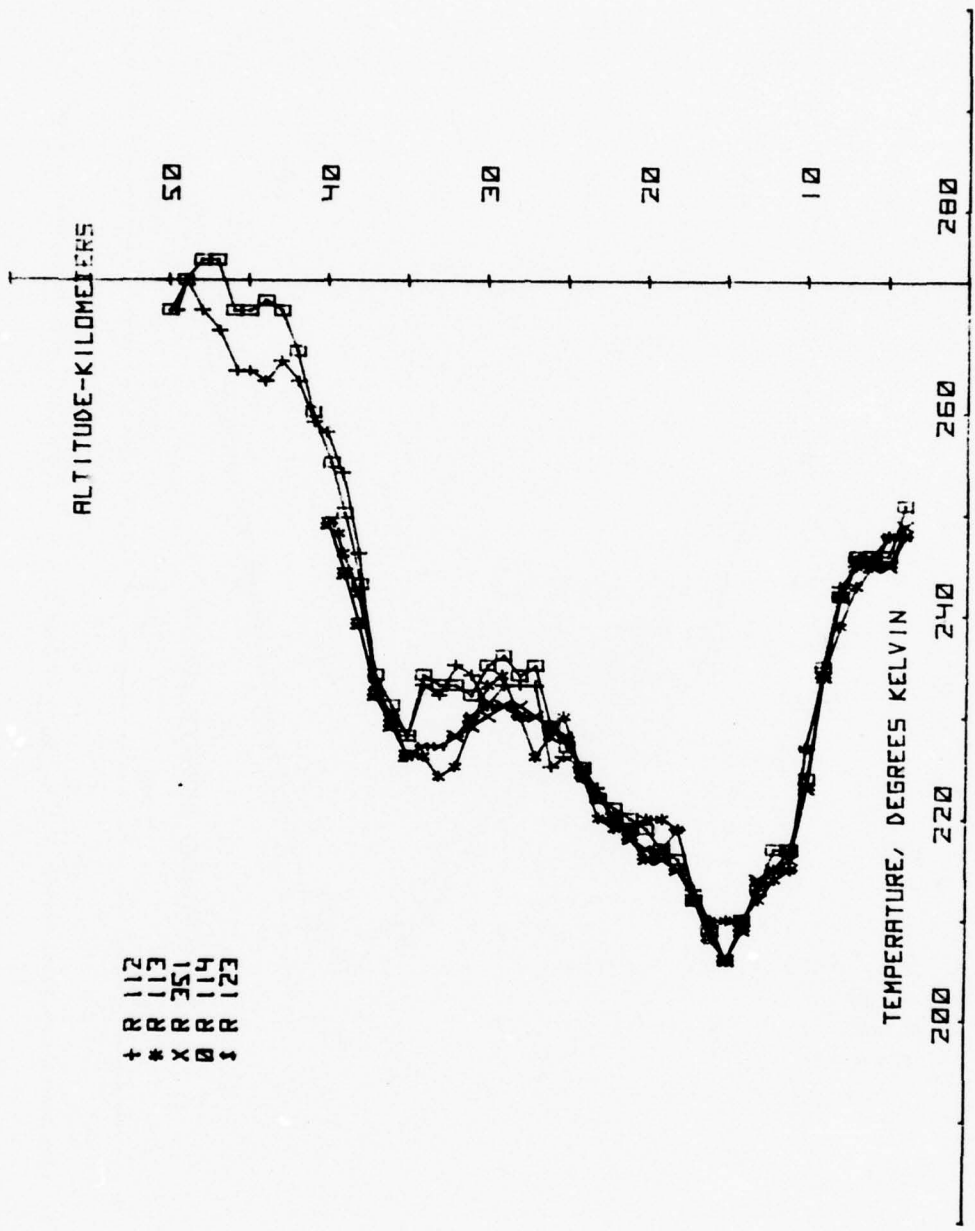


Figure 6. Temperatures computed from radar tracks of a 0.1-m sphere launched 7 Oct 76. Five radars tracked this mission.

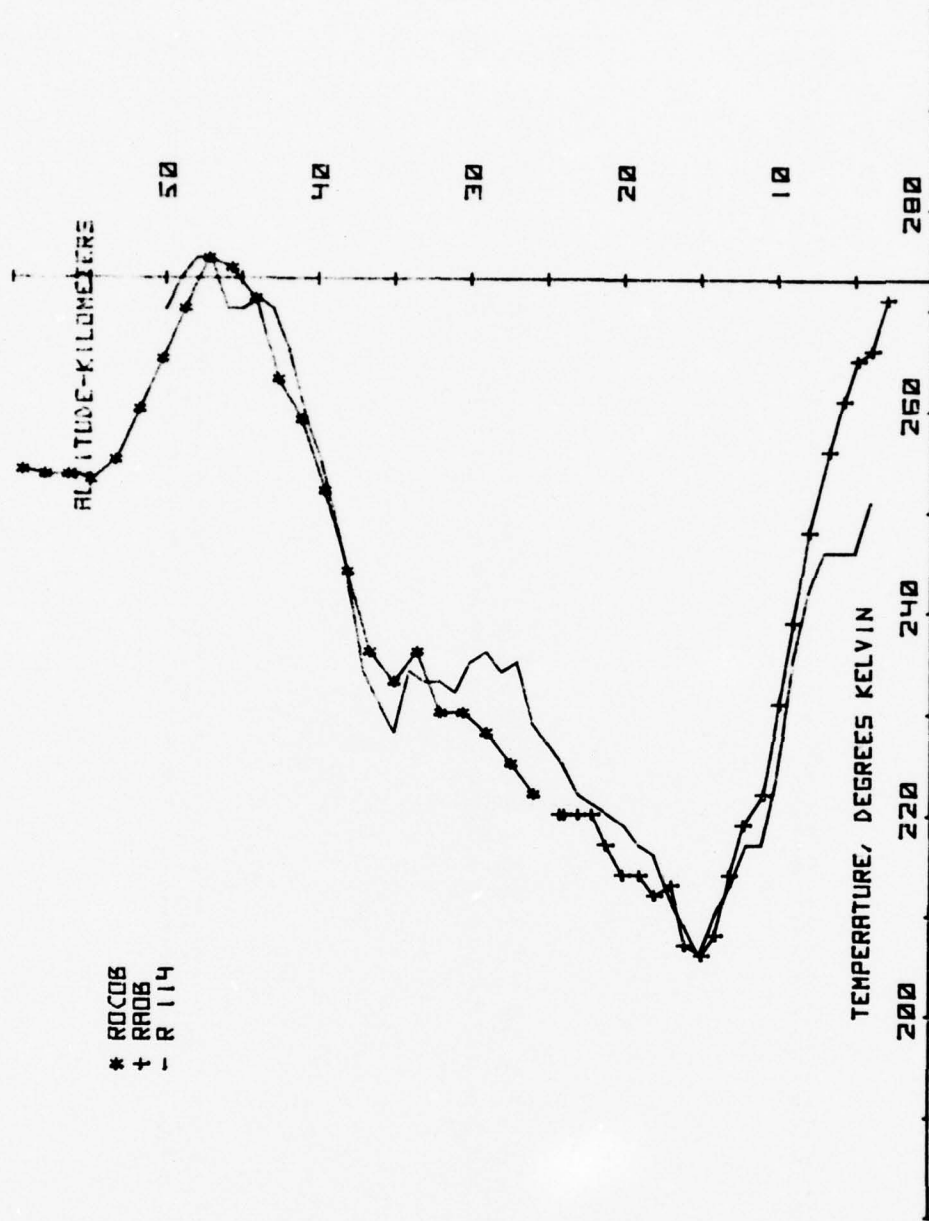


Figure 7. Comparison of temperature data from R114 tracking the 0.1-m sphere and ROCOB/RAOB launched on 7 Oct 76.

TABLE 3

TEMPERATURE DIFFERENCE, ROBOB AND RAOB MINUS 0.12-METER SPHERE

Alt-km	Diff(°K)	Std Dev(°K)
50	-17.4	11.3
49	-18.3	14.8
48	-22.7	14.4
47	-19.4	11.4
46	-12.1	9.3
45	-5.6	9.5
44	-4.1	8.7
43	-3.0	7.4
42	-2.9	7.1
41	2.0	5.3
40	-1.1	4.8
39	-1.4	4.9
38	1.4	3.6
37	4.4	3.8
36	5.6	1.3
35	5.4	2.6
34	6.9	3.3
33	1.4	1.3
32	0.6	2.6
31	-3.1	4.1
30	-5.3	3.3
29	-6.5	4.2
28	-7.0	3.6
27	-7.3	3.6
26	-6.8	1.4
25	-6.3	3.3
24	-5.3	2.2
23	-3.9	2.2
22	-3.6	2.3
21	-3.3	1.5
20	-3.1	1.0
19	-2.6	1.9
18	-1.1	0.8
17	-0.5	0.9
16	-1.5	1.8
15	-2.8	2.3
14	-0.6	2.1
13	2.6	1.5
12	2.6	5.2
11	10.6	10.0
10	2.3	6.9
9	-1.6	2.5
8	-3.8	2.2
7	-1.7	3.1
6	-0.9	6.6
5	-0.9	10.0
4	1.3	12.0

TABLE 4

## TEMPERATURE DIFFERENCE, ROBOB AND RAOB MINUS 0.1-METER SPHERE

Alt-km	Diff( $^{\circ}$ K)	Std Dev( $^{\circ}$ K)
50	-4.0	
49	-4.0	
48	-0.5	3.5
47	4.5	5.0
46	7.0	4.2
45	5.0	4.2
44	4.0	5.7
43	-2.5	3.5
42	-5.5	2.1
41	-0.5	0.7
40	1.5	4.8
39	0.5	4.4
38	1.5	2.9
37	6.3	1.0
36	4.0	0.8
35	6.0	1.2
34	5.0	4.1
33	6.0	4.2
32	0.2	4.1
31	-0.8	2.2
30	-2.0	2.0
29	-5.0	2.1
28	-4.6	3.8
27	-3.9	4.8
26	-4.4	2.7
25	-5.3	2.6
24	-3.0	2.3
23	0.2	3.5
22	1.7	2.4
21	-1.5	1.6
20	-2.4	2.5
19	-1.9	3.8
18	-0.9	5.0
17	0.9	1.5
16	-1.7	1.2
15	-0.2	1.9
14	-1.6	1.0
13	0.8	2.8
12	-0.6	2.4
11	3.0	4.1
10	0.6	4.6
9	1.2	4.1
8	1.8	4.6
7	4.7	5.8
6	8.9	8.8
5	13.4	7.3
4	-5.0	1.4

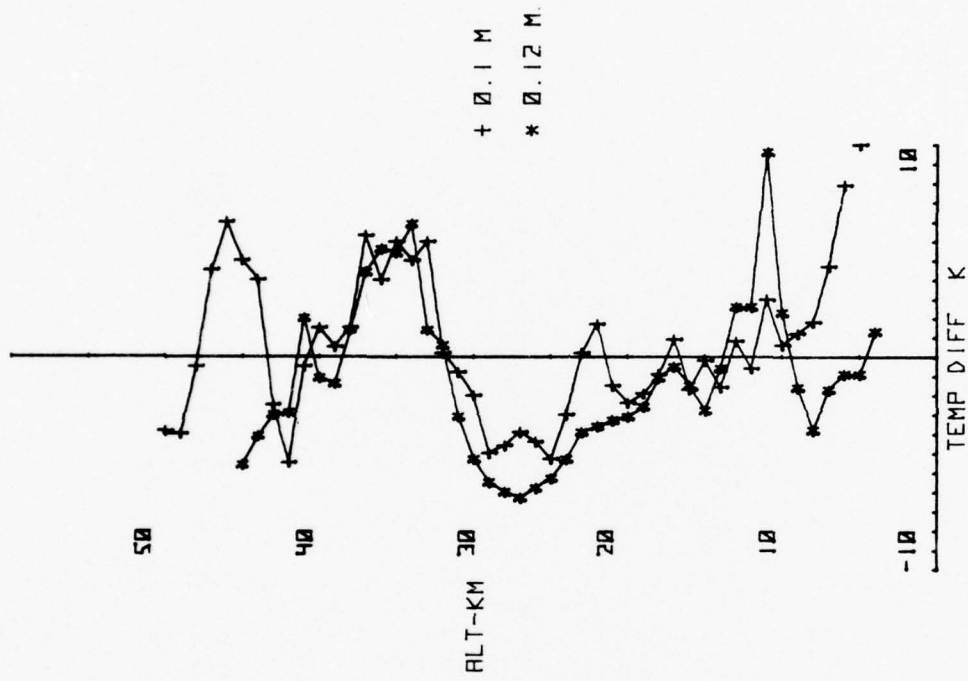


Figure 8. Temperature differences between 0.1-m and 0.12-m spheres and ROCOB/RAOB soundings from 10 radar tracks.

TABLE 5

## RADIOSONDE TEMPERATURE TEST, 7 Oct 76

WS-0100; WS-0705; HOL-0715; JAL-0740; JAL-1030 MST

Alt-km	WS (°K)	HOL (°K)	JAL (°K)	JAL (°K)
1.524	281.2	281.0	279.9	281.8
3.048	272.0	271.2	270.6	270.0
4.572	268.8	265.7	264.5	264.3
6.096	258.5	257.8	259.3	259.1
7.620	250.4	248.1	249.3	249.3
9.144	239.1	237.2	238.1	239.3
10.668	225.2	225.1	225.5	227.1
12.192	214.4	214.3	213.8	215.1
13.716	209.9	209.3	209.8	211.5
15.240	205.6	205.4	209.8	211.9
16.764	212.5	212.2	206.3	206.9
18.288	212.1	212.3	210.4	212.4
19.812	216.2	216.1	217.4	214.7
21.336	217.4	214.3	215.6	217.9
22.860	999.0*	220.2	220.8	219.2
24.384	999.0	222.0	222.5	999.0
25.908	999.0	223.6	223.4	999.0
27.432	999.0	224.8	224.1	999.0
28.956	999.0	225.6	226.3	999.0

\*999 denotes missing data

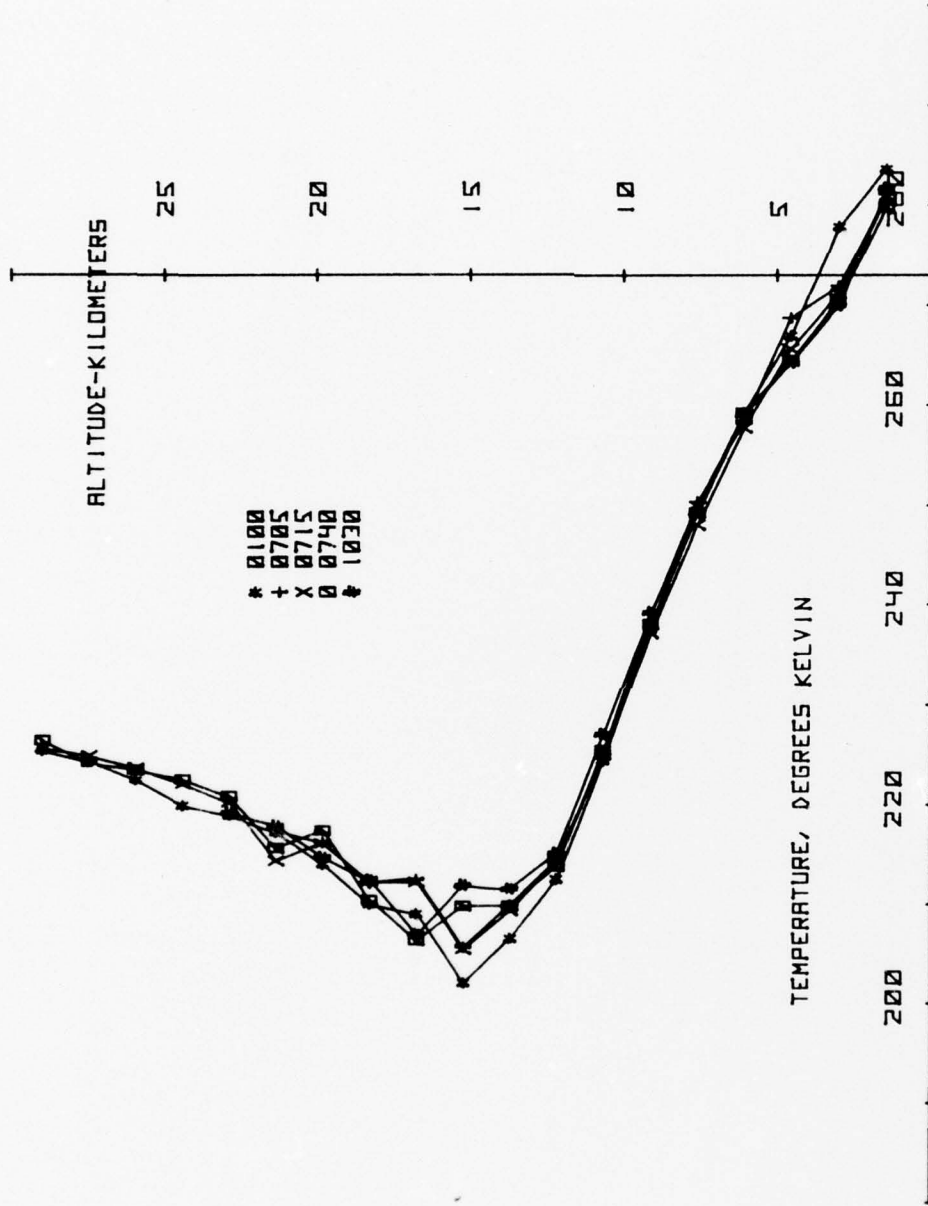


Figure 9. Temperature profiles measured by five RA0BS on 7 Oct 76. Releases were made between 0705 and 1030 MST.

These data are presented only to illustrate a pitfall in comparing two sets of measurements. The natural time and space variability of the atmosphere in addition to nominal system accuracies must be considered.

Figures 10 and 11 show wind speed and direction versus altitude for a 0.12-m sphere flown on 8 December 1975. Data are from two FPS-16 radars and from ROCOB and RAOB. Between 4 and 27 km, the wind speed agreement between the two systems is excellent with differences of only a few meters per second in evidence. Light winds, less than 10 m/sec, were observed only between 17 and 28 km. Between 28 and 40 km, the sphere indicated winds from 5 to 10 m/sec greater than ROCOB/RAOB. The profiles converge at about 40 km and are in good agreement up to 46 km. The data from the two radars is almost identical throughout the entire profile.

Wind direction compares favorably between ROCOB/RAOB and sphere. Points of large variability appear only under light wind conditions. Differences of up to 60° appear at 28 km where the corresponding winds are less than 10 m/sec.

Figures 12 and 13 illustrate wind speed and direction comparisons for a 0.1-m sphere. As in the previous wind profiles, data are taken from two radar tracks of a single sphere and from the conjunctive ROCOB and RAOB. In this case the wind speed is less than 10 m/sec between 18 and 40 km. The corresponding direction graph shows a wide scatter of data. Below 18 and above 40 km, where wind speeds are greater than 10 m/sec, the agreement is generally within 10°.

#### CONCLUSIONS

The 0.1- or 0.120-m ballistic sphere is a relatively accurate method for the purpose needed of deriving the atmospheric parameters of wind and temperature between 4 and 42 km altitude. Below 4 km, turbulent flow conditions for the sphere prevent the measurement of temperature. Above 42 km, inaccurate radar tracking or tracking at a low servobandwidth prevents accurate temperature and wind measurement. Between 4 and 42 km, temperatures compare favorably with conjunctive radiosondes and rocketsondes with apparent biases occurring at 25 and 35 km. Winds are comparable at all altitudes in both speed and direction except under light wind conditions when wind direction is inaccurate. The technique should be applicable to users requiring fast, real-time measurement of the atmosphere. The bias may result from inaccuracies in drag coefficient data, magnus force effects on the spinning sphere, or other factors. Additional studies will be required to determine if the biases can be successfully removed.

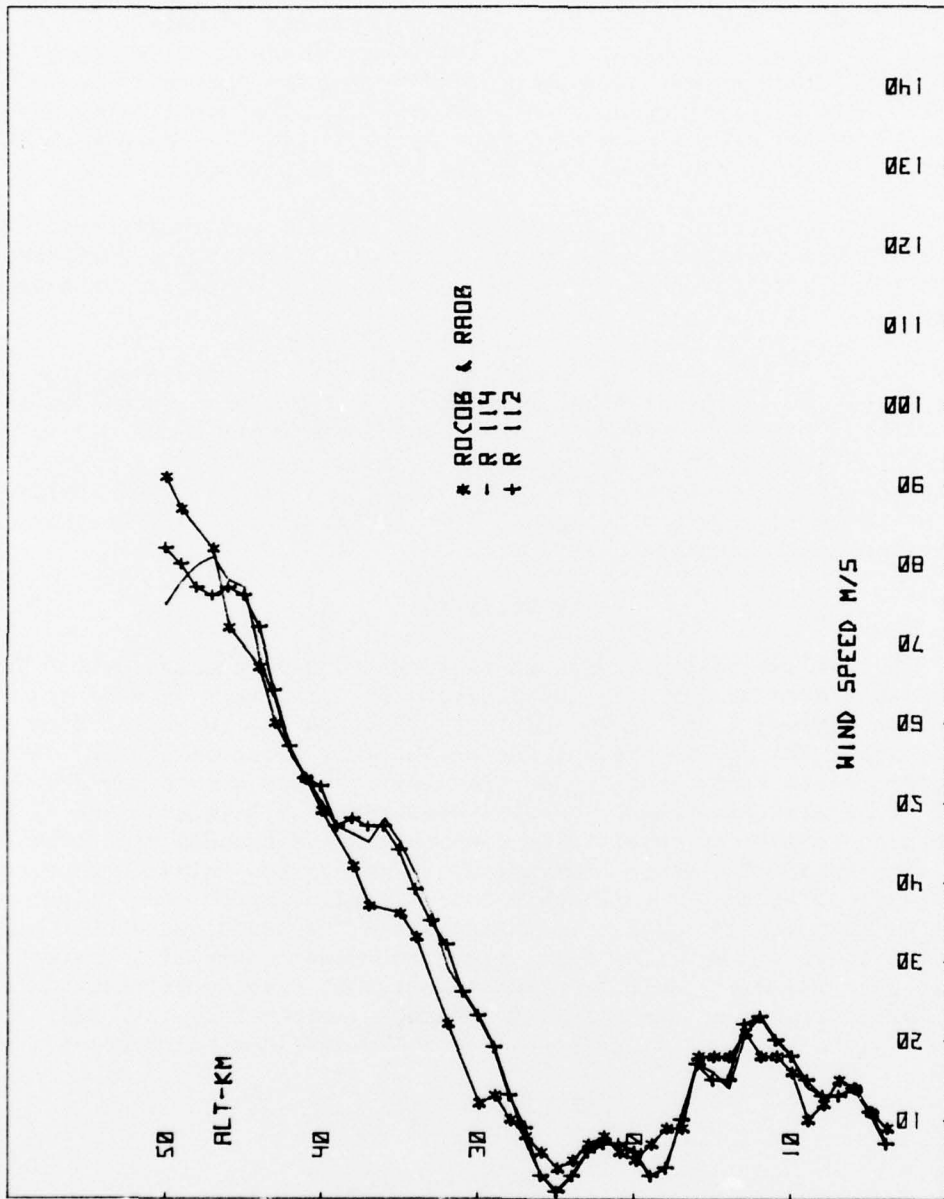


Figure 10. Comparison of wind speed between sphere and RAOB/RAOB on 8 Dec 75. Sphere is 0.12 m in diameter. Data from R112 and R114 are plotted.

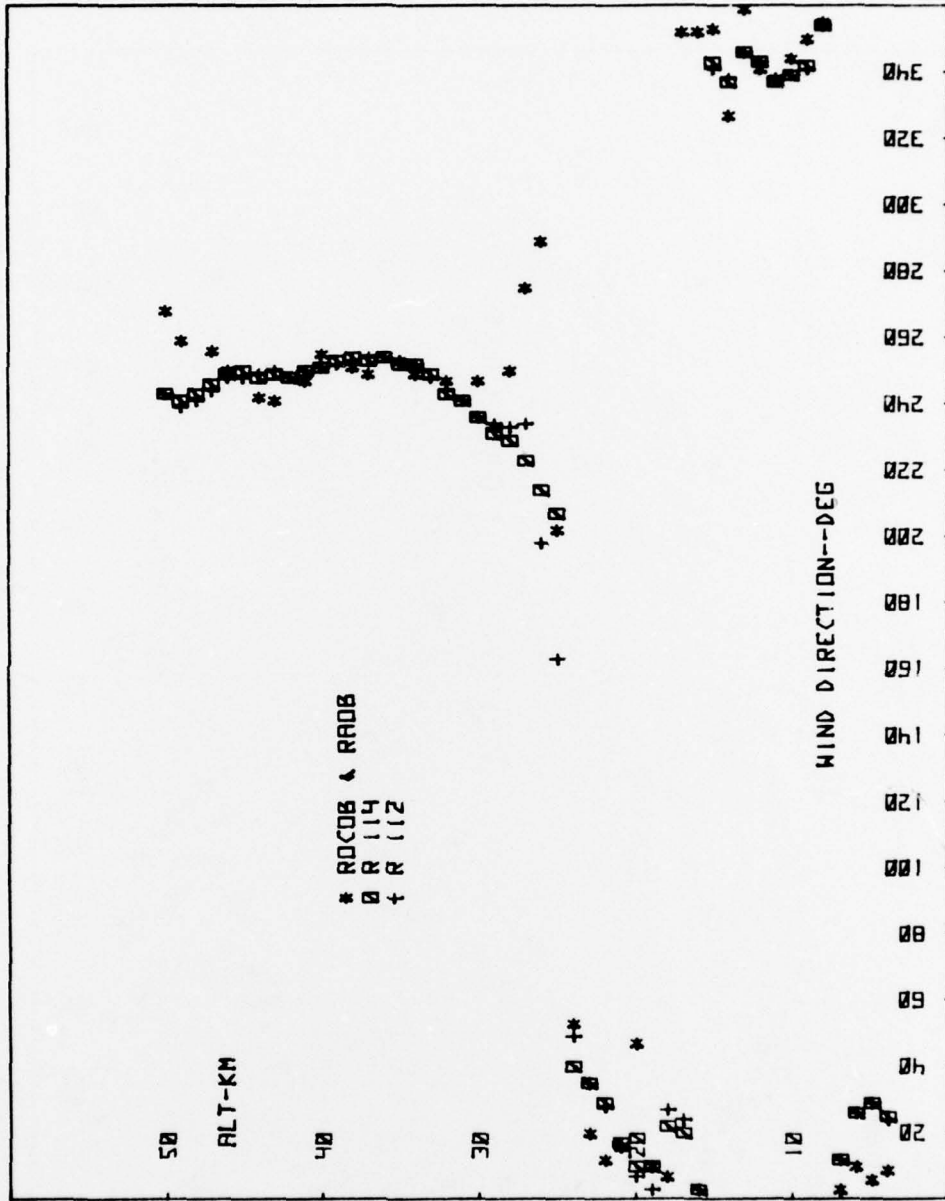


Figure 11. Comparison of wind direction between sphere and ROCOB/RA0B on 8 Dec 73. Two radars are represented.

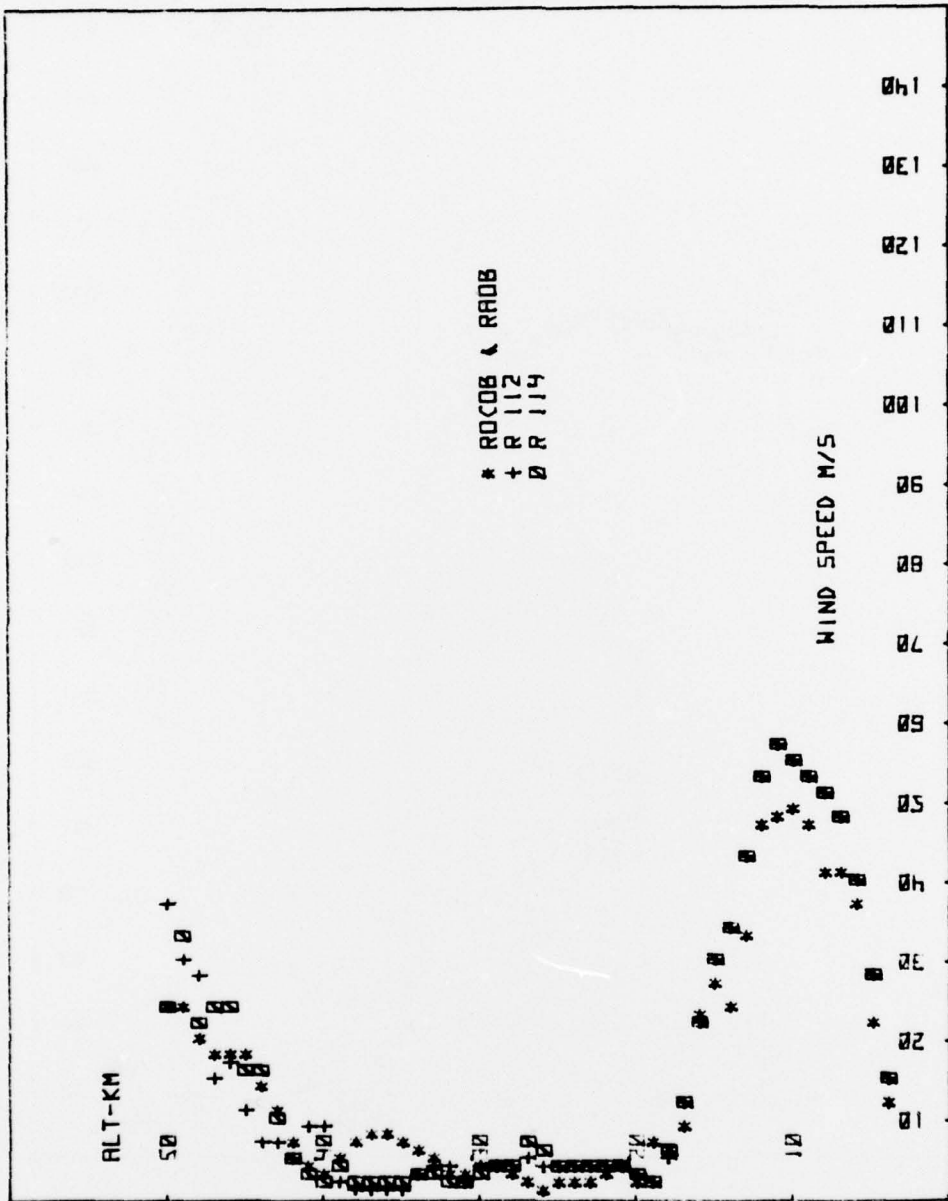


Figure 12. Wind speed comparison between 0.1-m sphere and ROCOB/RAOB on 7 Oct 76. Data from two radars are plotted.

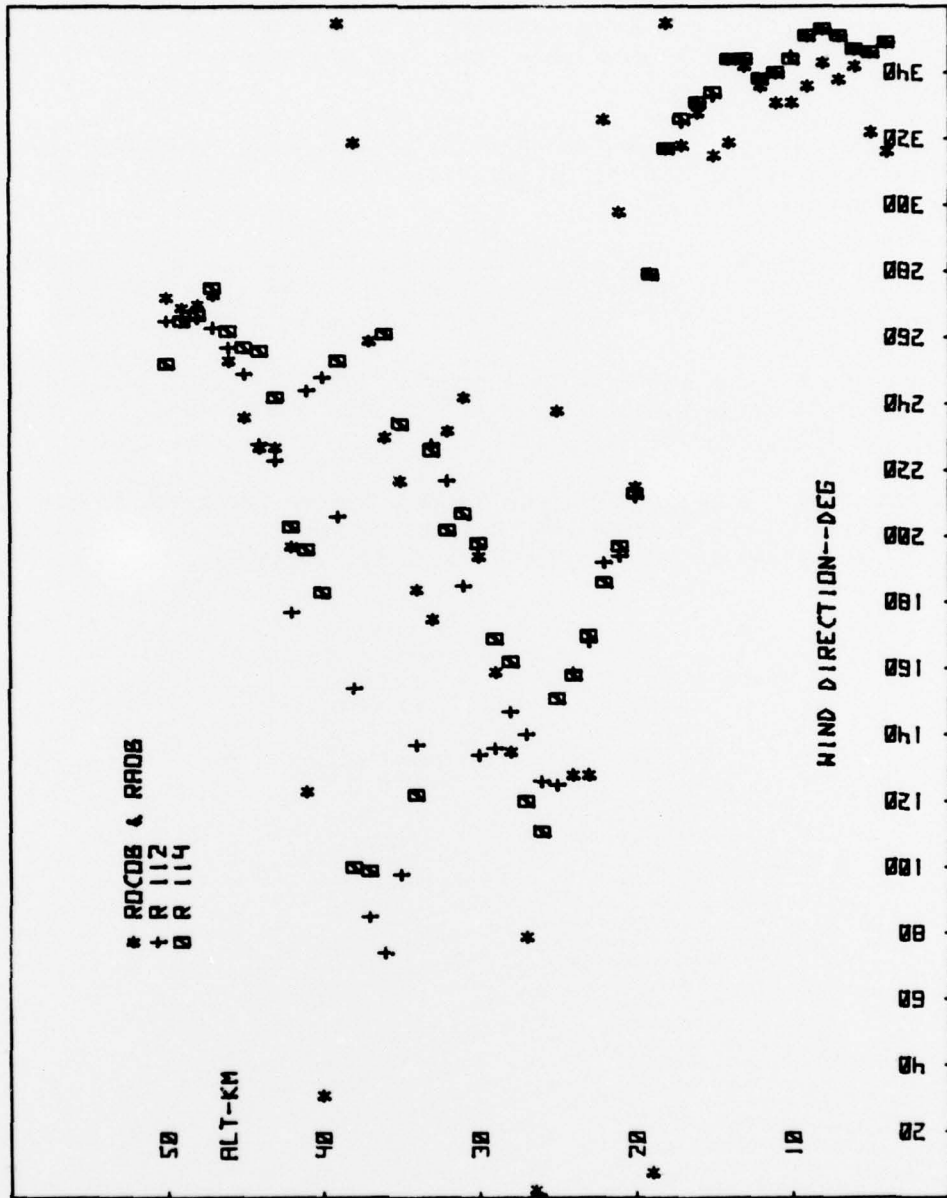


Figure 13. Comparison of wind direction between sphere data and R0C0B/R0A0B. Data from R112 and R114 are plotted.

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