BMFT-FB-W 81-052

Bundesministerium für Forschung und Technologie

Forschungsbericht W 81-052

Luft- und Raumfahrt

– Weltraumforschung/Weltraumtechnologie –

SOUNDING ROCKET PROGRAM AERONOMY PROJECT: ENERGY BUDGET CAMPAIGN 1980 EXPERIMENT SUMMARY

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December 1981

ATMOSPHERIC DENSITY, TEMPERATURE, AND WIND MEASUREMENT TECHNIQUES DURING THE 1980 ENERGY BUDGET CAMPAIGN

by

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1. INTRODUCTION

Rocket systems first used in the mid-1940's for exploration of the upper atmosphere generally were large and complex. Meteorological data were obtained from them as a secondary objective and, for the most part, presented only gross information on atmospheric structure. Nevertheless, this information provided confirmation of an atmospheric structure which, up to the time of these measurements, could only be hypothesized. Although the few sporadic measurements were valuable they were expensive to obtain and still did not satisfy the requirements for a more complete understanding of atmospheric behavior. In the late 1950's and early 1960's requirements were continually expressed by many organizations for more complete and comprehensive knowledge of the structure and behavior of the stratosphere and mesosphere and its relation to the rest of the atmosphere. This region, comprising one percent or less by weight of the total atmosphere was assumed static and uninteresting, but the available data were beginning to show that this might not be true.

The desire to study the characteristics of the stratosphere and mesosphere led to the development in the United States of the small inexpensive meteorological rocket. This small rocketsonde can measure density, temperature and wind data from approximately 20 km to 90 km using a variety of sensors. The techniques and system reliability have improved since first used so that confidence in the systems now allows considerable creditability to be placed on the measurements. Thus, short-term atmospheric variations may be studied. Measurements obtained from these systems during the Energy Budget

Campaign provide a valuable contribution to our knowledge of the background and dynamic atmospheric conditions and to the understanding of measurements of other parameters.

2. INSTRUMENTATION

Two meteorological rocketsonde systems were used at ESRANGE during the Energy Budget Campaign. One of these, the Super Loki Datasonde, telemeters data to a ground station where ambient temperatures are calculated between 20 and 70 km. The other system, the Super Loki Sphere, is a passive system tracked by radar which allows density to be calculated between 30 and 90 km. When flown simultaneously the two systems give redundant data in the altitudes between 30 and 70 km. These redundant data may provide unique information on atmospheric behavior. A description of each system follows.

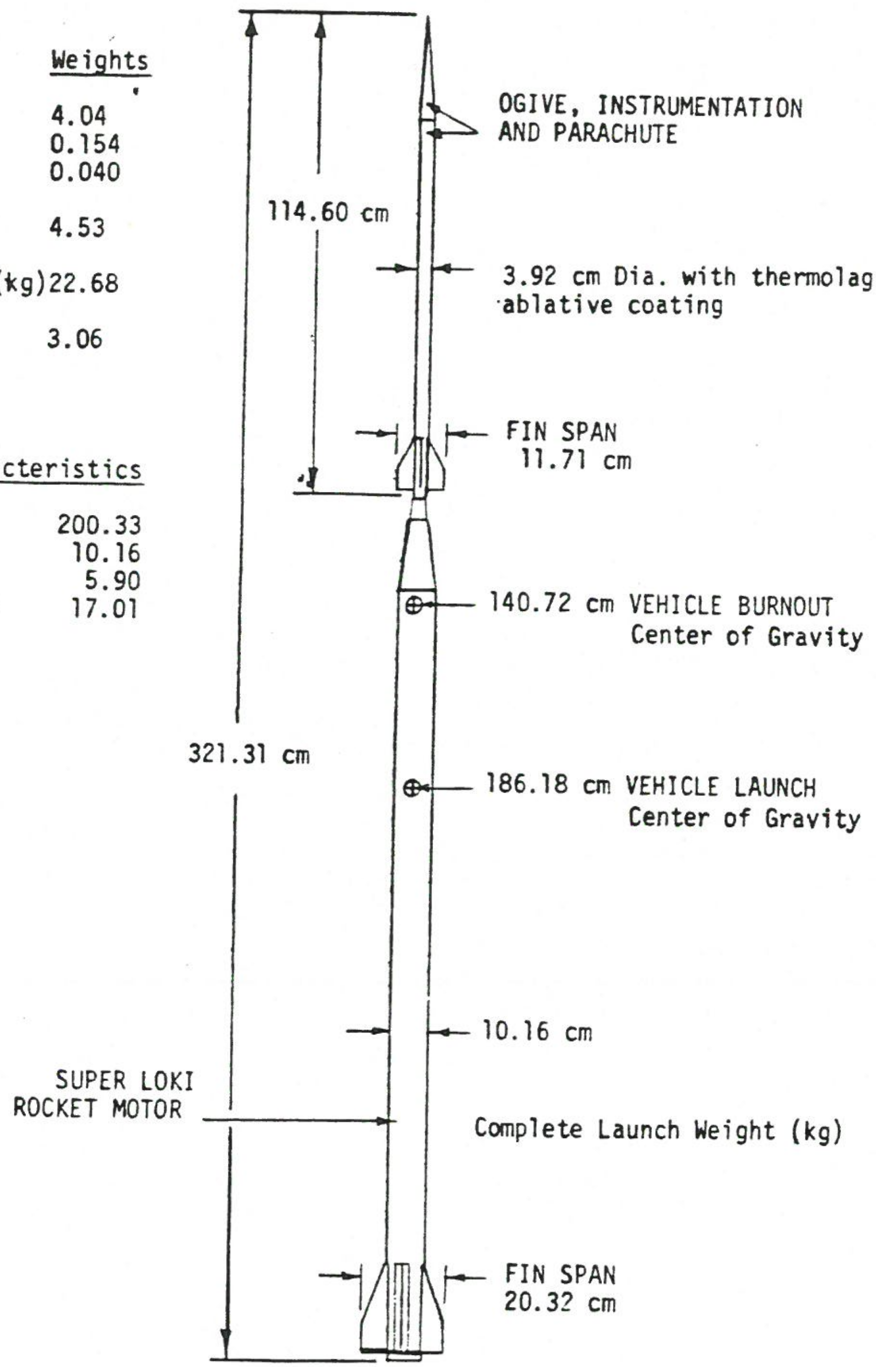
Super-Loki Datasonde - The Super-Loki Datasonde System consists of the spin stabilized Super-Loki rocket motor and the Datasonde payload which is contained in a dart-type vehicle. A 3.66-meter long helical rail launcher provides support and imparts spin to the system during the launch phase. The rocket motor is a high-thrust, solid propellant unit with a burning time of approximately two seconds. At rocket motor burnout, dart separation occurs. The dart consists of an ogive, body assembly (dart body), and tail assembly and is coated with an ablative material to reduce the effect of rather severe aerodynamic heating. The dart body contains the decelerator (parachute) and instrument payload. The dart tail contains the delay and ejection system. After separation from the rocket motor the dart coasts to apogee where payload ejection occurs approximately 120 seconds after liftoff. Following ejection, the Datasonde instrument transmits temperature data over a carrier frequency of 1680 MHz while descending on the decelerator. Figure 1 is a drawing of the Super-Loki Datasonde System.

The Datasonde decelerator called a "Starute" also serves as a wind sensor. Portions of the "Starute," shown in Figure 2, have been metalized to facilitate radar tracking. Atmospheric wind data are obtained from the positional data obtained by the tracking radar.

The temperature sensor is a small, aluminized bead thermistor (about 0.25mm in diameter) whose electrical resistance varies inversely with its temperature. The thermistor, shown in Figure 3, is attached to a mylar loop mount by means of short lead wires. The mylar loop is coated with thin aluminum on the side facing the transmitter and serves to reflect long-wave radiation from the instrument's body. As the temperature varies during the instrument's descent the varying thermistor resistance controls the modulation rate

Datasonde Dart	Weights
Dart Hardware (kg)	4.04
Parachute (kg)	0.154
Instrument (kg)	0.040
Complete Dart (kg)	4.53
Booster Rocket Motor (kg)	22.68
(kg)	
Interstage (kg)	3.06

Rocket Motor Without Interstage Characteristics	
Length (cm)	200.33
Diameter (cm)	10.16
Inert Weight (kg)	5.90
Propellant Weight (kg)	17.01



Complete Launch Weight (kg) 30.27

Figure 1. Schematic of the US Super-Loki Datasonde system showing dimensions and weights of the various components.

Descent System Characteristics

Parachute Type	Ram-air inflated
Canopy Material	1/4 mil mylar
Flying Width (m)	1.3
Flying Area (m^2)	4.55
Parachute Weight (grams)	155
Parachute-Sonde Ballistic Coefficient (kg/m^2)	.146

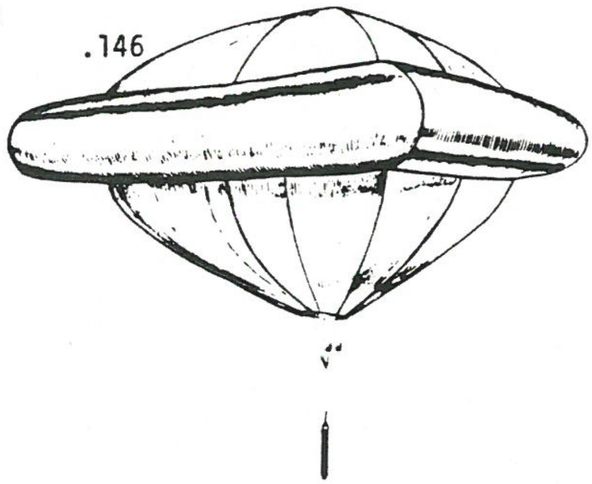


Figure 2. Super-Loki Datasonde Starute. This is a balloon-parachute device that descends slower than a conventional parachute and is considerably more stable. Twenty-two percent of the area is metalized to facilitate radar tracking.

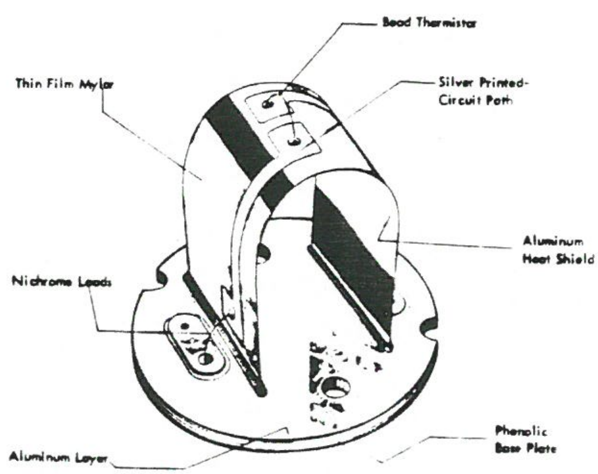


Figure 3. Details of thermistor loop mount.

of the data circuit. The temperature signals are interrupted periodically through electronic switching to permit the transmission of a reference resistance value. This reference frequency is used to monitor changes in the instrument's electronics.

Super-Loki Sphere - The Super-Loki Sphere is almost identical in size to the Super-Loki Datasonde. The same motor type is used with both systems. The sphere is inflated after deployment from the dart body at an altitude of about 115 km.

The passive sphere payload is a one-meter diameter inflatable spherical balloon made from 1/2-mil mylar which is aluminized for radar tracking. A small charge of an inert gas is used to inflate the sphere to a super pressure of about 10-12 mb, or approximately 32 km altitude. Sphere collapse occurs when the ambient pressure exceeds the sphere's internal pressure.

Tracking of the falling sphere by a high-precision radar is an absolute requirement in order to obtain usable atmospheric density and wind data. Temperature data are obtained from the density data through the application of the perfect gas law.

3. MEASUREMENT TECHNIQUE

After the temperatures sensed by the Datasonde thermistor are received at the ground and time-correlated with altitudes obtained from the radar track a series of heat transfer equations is applied which corrects the measured temperature to the ambient temperature. The method of correction developed by Henry (1967) was adapted for use with the Datasonde loop mount by Krumins and Lyons (1972). Although the correction terms are small at low altitudes they increase sharply as 70 km is approached. The corrections consist of those for aerodynamic heating, emissivity, sensor lag, and radiation. The aerodynamic heating term is proportional to the fall velocity squared ($\dot{Z}^2$) and, as will be seen later, at ESRANGE this correction term was larger than normal. The emissivity term is proportional to the fourth power of the thermistor temperature T_t^4, while the lag term is dependent on the atmospheric lapse rate. The radiation correction includes short- and long-wave radiation and is fixed for each altitude. Only long-wave radiation corrections are applied at night.

From the profile of corrected temperatures and a knowledge of the pressure at some initial altitude (usually near 20 km) pressures may be calculated by integration of the equation of state and hydrostatic equation. Thus the hypsometric relation

$$P_1 = P_o \cdot \exp\left[-g\Delta Z/R'\bar{T}\right]$$

may be solved for each increment of altitude. In this equation g is gravity, ΔZ is the altitude increment, R' is the specific gas constant, and $\overline{T}$ is the mean temperature in the interval ΔZ. Density is then determined from the gas law. The initial pressure P_o, is normally obtained from a radiosonde observation close in space and time. The technique requires a 5-6 km overlap of the radiosonde and rocketsonde measurements so that a match of the representative temperature profiles can be obtained at the tie-on level. Thus, any inaccuracies in the data at the tie-on level (i.e., altitude, pressure, or temperature) result in a constant percentage bias in the computed pressures and densities. The inaccuracies may also be due to radiosonde measurement errors and/or space and time differences between the radiosonde and rocketsonde.

Radar tracking of the Starute permits the horizontal winds to be calculated. The wind reduction method is simple in that successive position differences and their corresponding time differences are used to calculate wind direction and speed. Because of the decelerator's rapid descent at the higher altitudes, resulting in slow response to horizontal changes in the wind, it is necessary that corrections be applied to the wind data. The correction equation,

$$W_x = \dot{X} - \frac{(\dot{Z}-W_z)(\ddot{X}+C_x-B_x)-g_x}{\ddot{Z}+C_z-B_z-g_z}$$

is general (the meridional wind W_y uses the same equation) and includes all possible effects regardless of their relative magnitude. However, many of the terms may be ignored since the buoyancy force B is insignificant for the altitudes over which we measure, the coriolis term C has little or no effect below 90 km, and the horizontal component of gravity g_x is about 10 percent the magnitude of the error in g_z so that it too may be ignored. With all these assumptions the corrected wind reduction equation becomes

$$W_x = \dot{X} - \frac{\dot{Z}\ddot{X}}{|\ddot{Z}-g|}$$

where $\dot{X}$ and $\ddot{X}$ are the Starute's horizontal velocity and acceleration, and $\dot{Z}$ and $\ddot{Z}$ represents its vertical velocity and acceleration. The method of wind reduction for the sphere is identical to that for the Starute. Note, though, that the sphere's fall velocity is 2-3 times that of the Starute and as a result the wind velocity profile is considerably smoother, especially above 50 km.

Reduction of the sphere data to obtain density requires a precision radar since the first and second derivatives calculated from the position data must be extremely good. The equation for determining density is

$$\rho = \frac{2m(\ddot{Z}-g_z-C_z)}{C_d A|V|(\dot{Z}-W_z) + V_b g_z} .$$

Since the calculation of density ρ begins near 90 km the effects of the coriolis and buoyancy terms may be ignored. Direct measurements of the vertical wind W_z are not possible and it must be assumed equal to zero. Thus, the equation for density reduces to the simplified form of

$$\rho = \frac{2m(\ddot{Z}-g_z)}{C_d A|V|\dot{Z}} .$$

The terms in this equation are sphere mass m, drag coefficient C_d, sphere cross-sectional area A, and motion of the sphere relative to the air V.

Once the density is obtained pressure and temperature may be determined. Hence,

$$P(Z) = P_o - \int_{Z_1}^{Z_2} \rho g dz$$

and

$$T(Z) = \frac{1}{R'} \cdot \frac{P(Z)}{\rho(Z)} .$$

The initial pressure P_o is dependent on a "guess" temperature obtained from the US Standard Atmosphere (1962). Thus $P_o = R'T_o\rho(Z_o)$. It follows that the accuracy of the subsequent values of the calculated parameters depends on how close the guess temperature is to the actual temperature. Because of this limitation it is assumed that the temperatures calculated within two scale heights (10-12 km) of the first data point are not representative of the actual atmosphere.

4. SUMMARY OF ENERGY BUDGET CAMPAIGN MEASUREMENTS

The goal of the temperature and wind measurements was to provide highly reliable information on the temperature and wind structure between 30 and 85 km. A number of radiosondes released from three stations in Scandinavia provided information on the structure from the surface to near 30 km. Radiosondes also were launched from ESRANGE during each salvo, but these reached only 15-20 km. Nevertheless, the combination of radiosonde and rocketsonde measurements will provide complete temperature and wind profiles from the surface to 85 km. Satellite remote sounder measurements from NOAA-6 and TIROS N also provide information on the mesoscale gradients of temperature and geopotential and will permit ready examination of the measurement deviations from the mean

TABLE 1. SUMMARY OF LAUNCHINGS FOR ENERGY BUDGET CAMPAIGN

Launch Date 1980	Launch Time GMT	Payload Type*	Data Available km	Comments
Nov.				
7	2200	D	20-70	
7	2250	S	60-85	
10	0010	D	20-70	
10	0100	S	No	
10	0218	S	60-85	
10	2200	D	20-70	
10	2346	S	60-85	
11	0101+30	S	No	Salvo C
11	0155+30	S	60-85	
11	0226+30	D	20-70	
12	0220+30	D	20-70	
12	0107	S	60-85	
15	2235+30	D	No	
15	2330+30	D	No	
16	0512+30	S	60-85	
16	0633	D	20-70	
16	0722	S	60-85	Salvo B
16	0751+30	S	60-85	
16	0823	D	20-70	
27	2245+30	D	20-70	
28	0047	S	60-85	
28	0329	S	60-85	Salvo A_1
28	0419+10	D	20-60**	
Dec.				
1	0024	S	60-85	
1	0139	S	60-85	
1	0233+30	D	20-70	Salvo A_2
1	0324	D	20-70***	

* D = Datasonde
S = Sphere
** Low Apogee
*** Wind Data Only

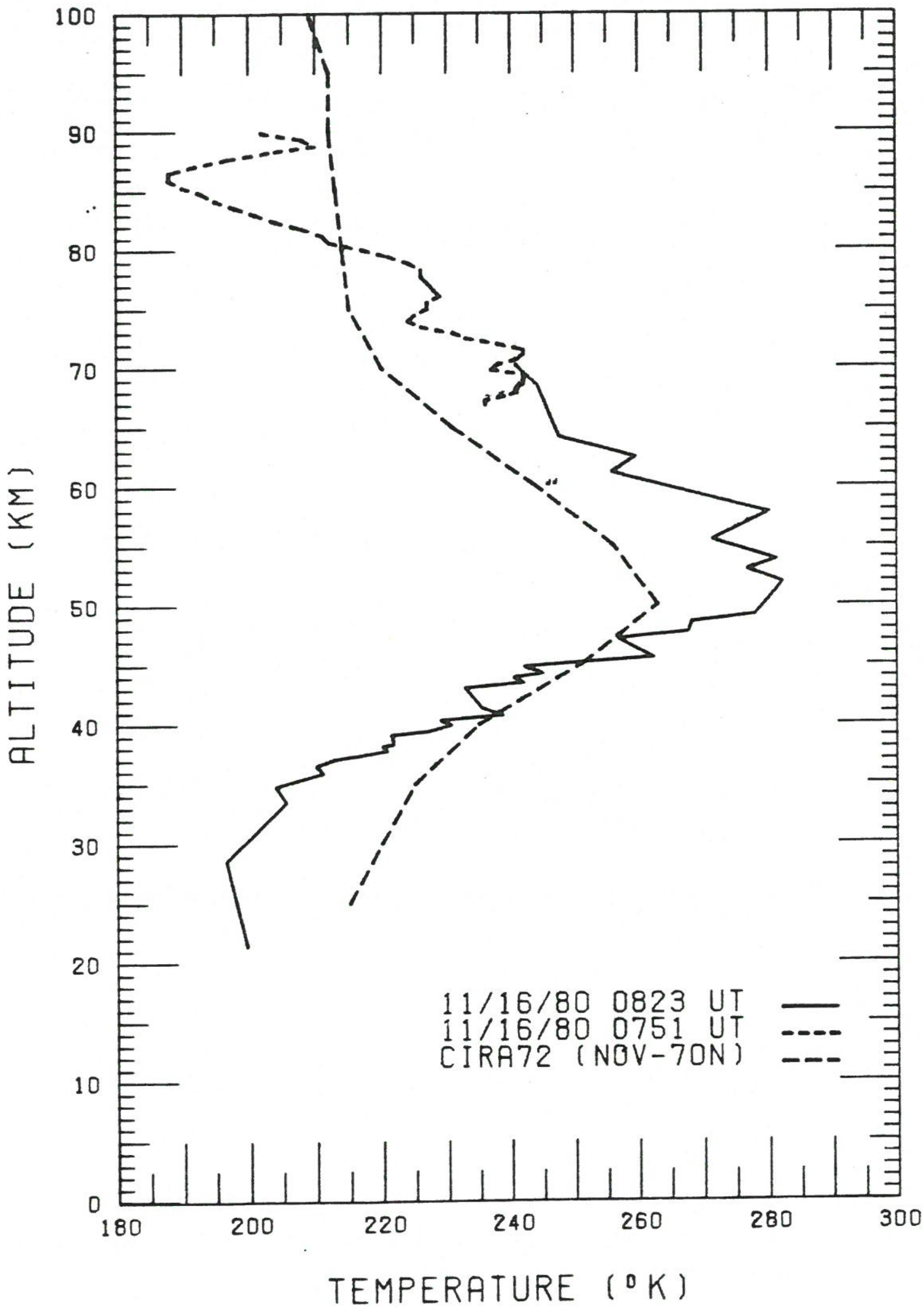


Figure 4. Temperature measurements obtained from the Datasonde (solid line) and Inflatable Sphere (dashed line) instruments during the Salvo B condition existing at ESRANGE during the morning of November 16, 1980.

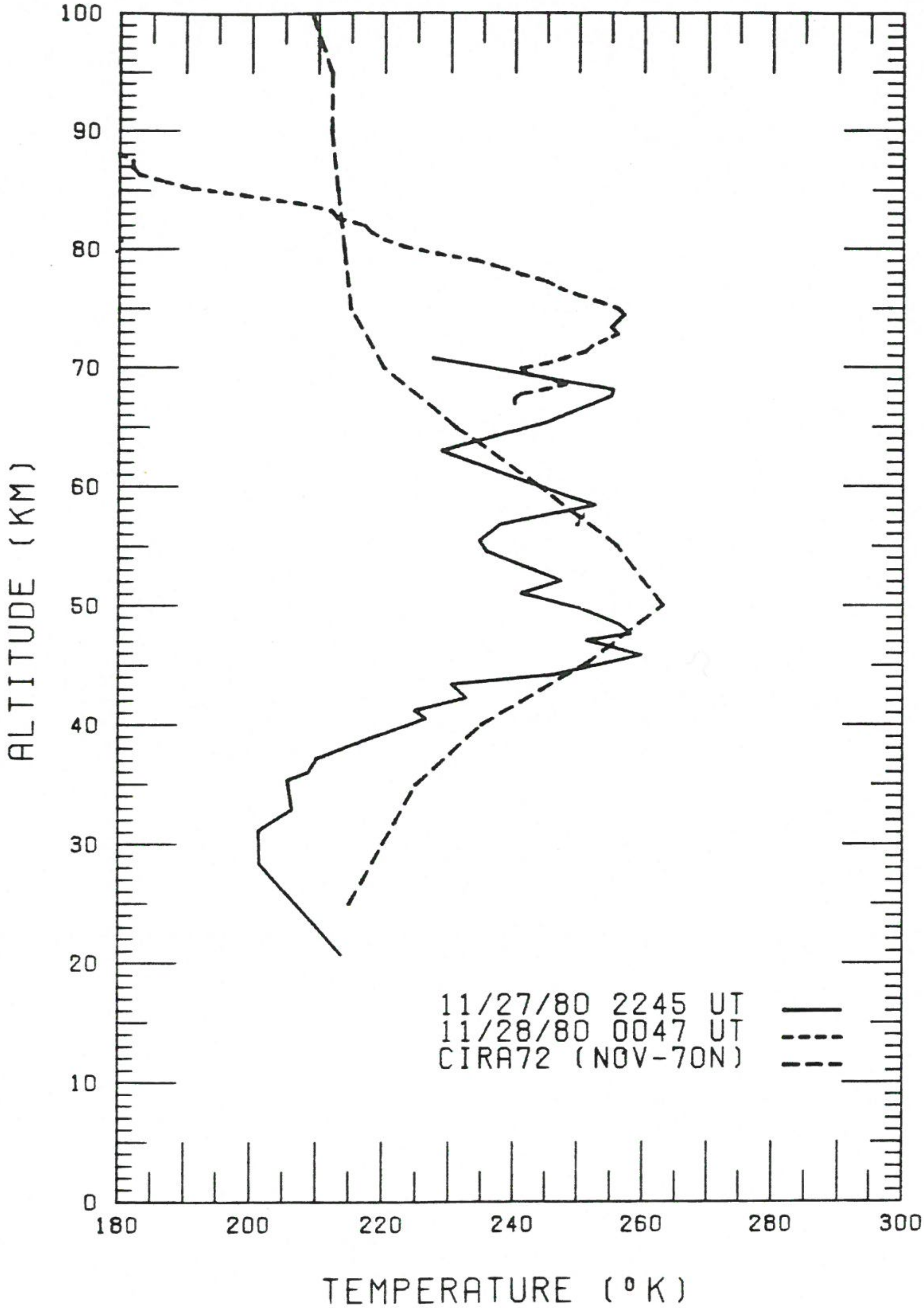


Figure 5. Datasonde (solid line) and Inflatable Sphere (dashed line) temperature profiles at ESRANGE during Salvo A_1 on the night of November 27-28, 1980.

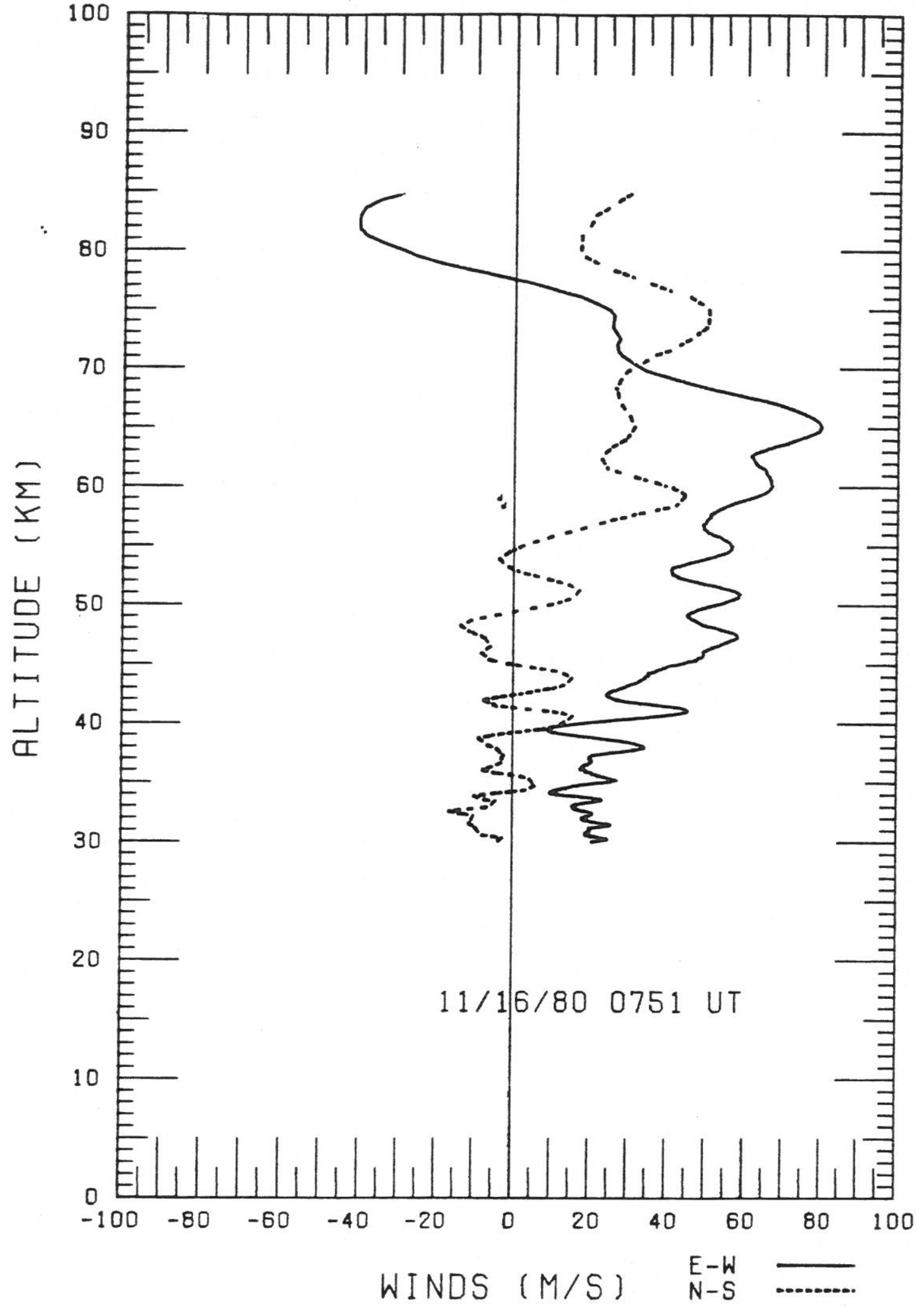


Figure 6. Meridional- and zonal-component winds obtained from the Inflatable Sphere during Salvo B.

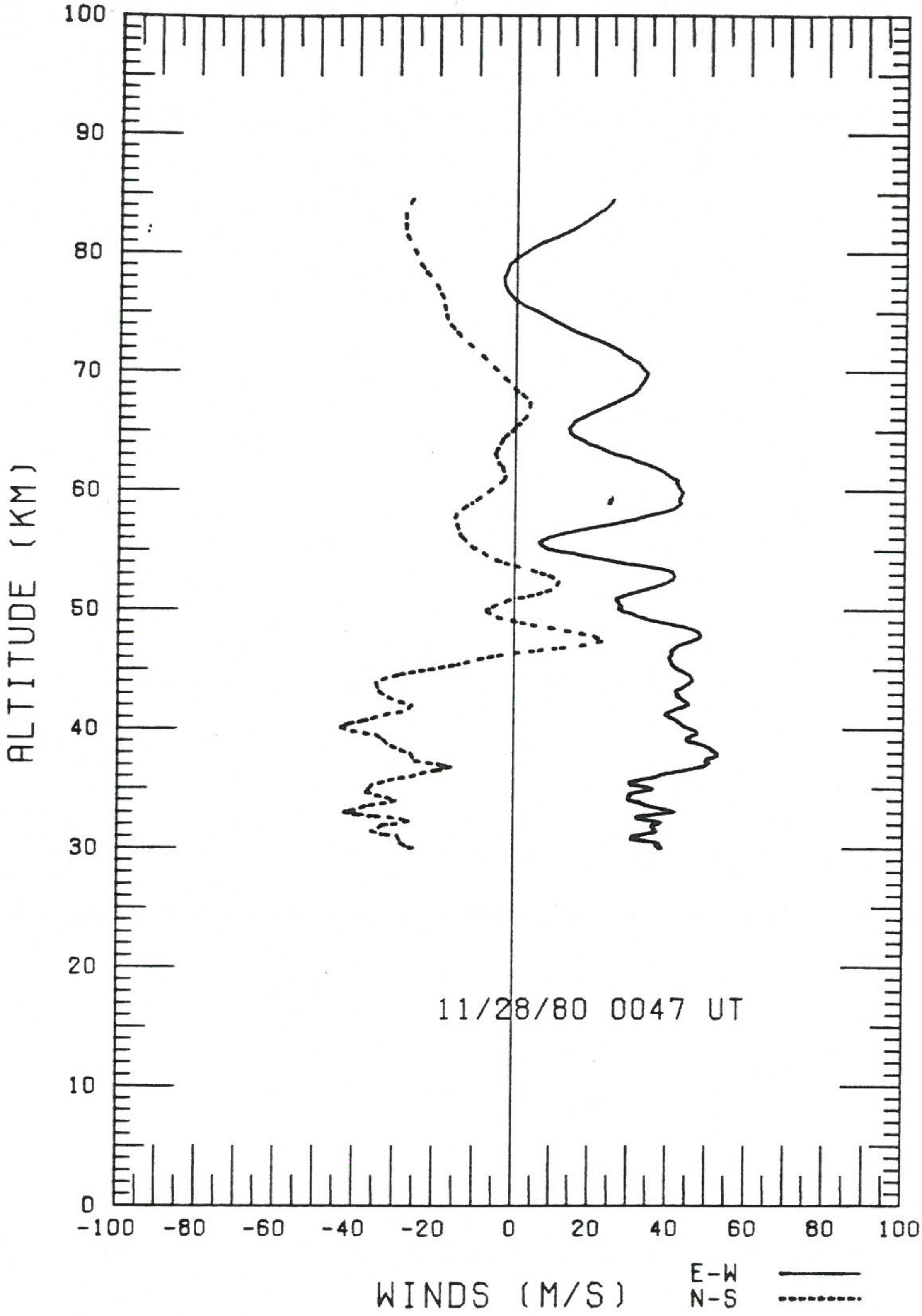


Figure 7. Meridional- and zonal-component winds obtained from the Inflatable Sphere during Salvo A_1.

profiles. Comparison of these data with model profiles [CIRA 72(70°N-NOV)] provides another aspect of Energy Budget Data in relation to an undisturbed atmosphere.

Because of the launch site altitude and other launch constraints the Datasondes reached excessively high apogees. These high apogees resulted in a very fast fall velocity of the instrument and produced anomalous Starute behavior until a more dense atmosphere was reached. This high fall velocity, besides affecting the wind sensing capability, also caused much larger aerodynamic heating of the payload thermistor. This in turn led to larger emissivity corrections of the sensor since emissivity is proportional to T_t^4. Finally, because of the deeper heat absorption resulting from the higher aerodynamic heating the capability of the sensing element becomes somewhat inhibited from responding to changes in the ambient environment. In spite of this abnormal fall velocity very little physical damage to the payloads was detected.

The inflatable passive sphere performance was somewhat disappointing since a majority of the reductions indicated sphere collapse at altitudes above 60 km and, thus, limited the altitude range of the measured densities. The lower limit of the densities is near the upper limit of the Datasonde temperature measurements and enables temperature/density profiles to be determined. Wind data are available from about 30 km to 85 km. The reason for the large number of collapsed spheres has not been determined.

Table 1 provides a summary of the meteorological rocketsonde launchings. As can be seen, twenty-seven Super Loki systems (13 Datasonde; 14 Sphere) were expended during the Energy Budget Campaign. These flights provided 21 successful observations of temperature, density, and wind and a few observations of wind data only. Examples of some of the temperature and wind measurement data are given in Figures 4-7. The vertical profiles are for the Datasondes and Spheres launched on November 16 and 28, 1981.

It can be noted from Figure 4 that on November 16, 1980 the stratospheric temperatures below 40 km were much colder than the model atmosphere predicted by the CIRA72, while the temperature is much warmer than the reference atmosphere above 45 km. Although temperatures measured by the Datasonde and Sphere between 60 and 70 km differ slightly, it clearly is obvious that the mesosphere is warmer than CIRA72 up to 80 km. During the morning of November 16 a Salvo B condition with moderately active aurora and geomagnetic activity was occurring. On the other hand, Figure 5, representative of conditions during the morning of November 28 during a Salvo A condition, indicates that the stratosphere and lower mesosphere between 45 and 60 km had cooled considerably since November 16. In fact this region of the atmosphere is colder than that given by the CIRA72. However, the sphere indicates that the temperatures in the mesosphere above 65 km are much warmer than CIRA72.

The wind profiles for the same observation times indicate that on November 16, 1980, Figure 6, the meridional component was generally from the south with occasional northerly components, and the zonal wind was from the west except in the vicinity of the mesopause. On November 28, an entirely different wind situation can be observed. Figure 7 shows that the meridional component was predominantly northerly while the zonal component is from the west but with a reduced magnitude below 70 kilometers.

Before conclusions can be made about the cause of the observed temperature changes, results from: the mass spectrometer measurements of Krankowsky and Lammerzahl, and of Smith and Kopp, the hot-wire sensor of Williams, and the falling sphere experiment of Philbrick should be examined. Likewise the balloon-borne temperature measurements of Friedrich launched from Stamsund and ground-based measurements such as from the infrared photometer/spectrometer of Baker and Lange, must also be compared. The additional meteorological rocket measurement from South Uist, UK provided by Carruthers and from Heiss Island, USSR provided by Danilov should also provide enlightening information. Examination of the sphere and Datasonde temperature and wind profiles suggests that considerable structural changes are occurring quite rapidly in the vertical. Whether this is the result of gravity waves propagating upward or occurs from some other source, e.g., thermal heating resulting from the geomagnetic activity and auroral activity, has not been determined. What is obvious is that more measurements are needed. The measurement program should include daily launchings, occasional launchings of 3-5 rocketsondes per day and even a few mini-series of measurements which will provide sufficient data to look at atmospheric scales of motion from minutes to hours. The local warmings apparent in this Energy Budget data cannot be traced in time very well, therefore attempts at future measurements might be supplemented with continuous ground based techniques which can provide information on the temporal behavior of the temperature.

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