Soft Landing of Venera 7 on the Venus Surface and Preliminary Results of Investigations of the Venus Atmosphere

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ABSTRACT

A soft landing on the planet Venus was successfully accomplished by the automatic interplanetary station Venera 7. The temperature of the Venus atmosphere was measured during the descent and at the surface after landing. The variation of temperature and pressure with altitude on Venus was determined down to the surface by combining the temperature measurements with descent velocity derived from the Doppler shift data during the descent, and by considering the data collected previously during the flights of Veneras 4, 5 and 6.

On 15 December 1970 the automatic interplanetary station Venera 7 reached the planet Venus. At 08:37:32 Moscow time[1] after a 35-min descent, the apparatus landed on the planet's surface, on the night side, ~2000 km from the sunrise terminator.

The first radio signals transmitted by the descending apparatus were received at 08:02:50. Telemetry information was acquired throughout the entire period of descent through the atmosphere, from 08:02:50 to 08:37:32 and after landing on the surface. The apparatus continued to operate at the surface for ~23 min until 09:00:30.

The design and general structure of Venera 7 are essentially the same as the earlier stations, Veneras 4, 5 and 6, with, however, some important modifications (Pravda, 1971). Since the principal aim of Venera 7 was to land and operate on the Venus surface, the descending apparatus was designed as a landing vehicle. While the total weight of Venera 7 was unchanged (1180 kg), the descending apparatus was about 100 kg heavier than those of Veneras 5 and 6. Taking into account the results obtained in the previous Venera flights and the subsequently developed model of the Venus atmosphere (Avduevsky *et al.*, 1970; Marov, 1971), the Venera 7 descent apparatus was designed to withstand a maximum external temperature of 800K and a maximum pressure of 180 atm.

In addition, since ordinary thermal insulating materials lose their protective properties at such high pressure, new thermal insulation was developed which possessed the necessary qualities. This insulation also served as a damping device to decrease the shock and facilitate landing on the surface.

The descent apparatus of Venera 7 is oblong in shape. Inside of the outer aerodynamic body is a hermetically sealed, spherical container holding the radio-telemetry and measuring devices, the automatic control and thermal control systems, and the power supplies. The capsule is protected by both thermal insulation and by heat protection systems. The heat protection acts as a shield, protecting the apparatus from the high temperatures produced by the aerodynamic drag of the atmosphere. The thermal insulation maintains a favorable heat balance inside the apparatus during its operation in the hot atmosphere and on the planetary surface.

In the upper portion of the descent apparatus a parachute container is housed. For the Venera 7 station a single-cascade parachute system with an extraction parachute was used. The parachute was made of a thermostable material able to withstand temperatures of up to 800 K. To better withstand the heat inflow of the ambient atmosphere near the surface, the capsule was cooled near the end of the interplanetary phase of the mission so that at the moment of departing from the orbital module, the temperature inside the descent apparatus was between −6 and −8C.

The descent apparatus was equipped with instruments to measure the temperature and pressure of the Venus atmosphere. Resistance thermometers and aneroid manometers, with a range of 25 to 540 C and 0.5 to 150 atm, respectively, were installed to measure these parameters.

The carrier frequency of the radio transmitters were stabilized by a thermostatted crystal oscillator. This assured the accuracy of the Doppler frequency shift determination and allowed the measurement of components of the velocity of the apparatus in the Venus-Earth direction. This direction corresponded to an angle equal to 10°20′ with the local vertical on Venus

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[1] The time at which the radio signals were received on earth. The actual landing time was 3 min, 22 sec earlier, with the time delay due to the transit of the signal from Venus over a distance close to 60.6 million kilometers.

in the region of descent. Apparatus velocity measurements as a function of time provided the information necessary to determine height increments during the entire descent phase. This procedure is more accurate than the procedure used earlier to estimate wind velocities in the Venus atmosphere (Kerzhanovich *et al.*, 1970).

2. Measurements

Analysis of the telemetry data has shown that the onboard telemetry commutator, which was to scan the outputs of the measurement devices during the descent and after landing, remained in a fixed position. For this reason only the data on ambient temperature were transmitted. The rms error of temperature measurements, allowing for discrete telemetry readings, was ±20K for the whole range.

The results of the temperature-time measurements with an indication of the error limits are shown in Fig. 1 along with the averaged vertical velocity. The latter was calculated on the assumption that the horizontal components of the apparatus descent velocity were negligible during the descent. The thin lines bracketing the velocity curve correspond to the possible errors in the descent velocity (V_d) determination. These do not exceed ± 1.5 m sec^{-1}.

The open-loop method was used to measure the descent velocity of the apparatus in the Venus atmosphere. The calculated velocity resulted from the deviation of the frequency of the signal received on Earth from the basic frequency f_0 of the on-board crystal oscillator. The frequency f_0 was calculated by extrapolating frequency calibration data obtained during the interplanetary phase of the mission. A comparison of velocity measurements made by both open- and closed-loop methods was used for the calibration. Corrections for the change in the frequency of the crystal oscillator produced by the temperature increase in the apparatus during descent and the frequency change produced by the refractivity of the Venus atmosphere were taken into account in deriving the values of Doppler frequency f_D. The refractivity effect on the velocity values was estimated at less than 0.3 m sec^{-1} to the end of descent.

The velocity of the apparatus with respect to the surface was obtained by subtracting all the components associated with the relative motion of Venus and the receiving station on earth from the measured values of total velocity.

A frequency recording of the received signal is shown in Fig. 2. The two curves, f_1 and f_2 correspond respectively to binary zeros and units of the telemetry data. After 08:37:32, the frequency f_2 and its sharp deviation caused by the abrupt deceleration of the apparatus is more distinctly visible than the frequency f_1. The lower horizontal line shows the fixed frequency of the ground-based receiver. The temperature increase in the apparatus after landing results in a small variation of frequencies f_1 (and f_2) with increasing time.

The parachute deployment at 08:02:50, when Venera 7 began its descent through the atmosphere, is indicated in Figs. 1 and 2 by the onset of a steady increase in temperature accompanied by a decrease in velocity. According to the program, at a temperature of ~470K (at 08:13:03) the parachute opened, causing a reduction of the descent velocity from 27 to 19 m sec^{-1}. A constant parachute descent associated with increasing aerodynamic drag persisted for 6 min.

At 08:19:08, a sudden increase of velocity from 15 to 26 m sec^{-1} occurred, followed by a decrease, with the mean velocity exceeding that anticipated. This increase in velocity gave rise to a more rapid increase in the measured temperature with time than had been anticipated. Because of the velocity increase, the total descent time was 35 min, rather than the predicted

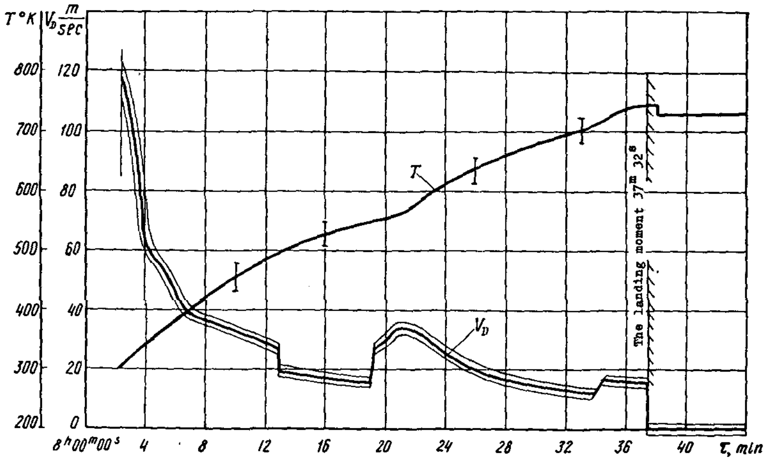

FIG. 1. Atmospheric temperature and probe descent velocity (Doppler frequency shift) measurements as a function of time. Tolerance ± 1.5 m sec^{-1}.

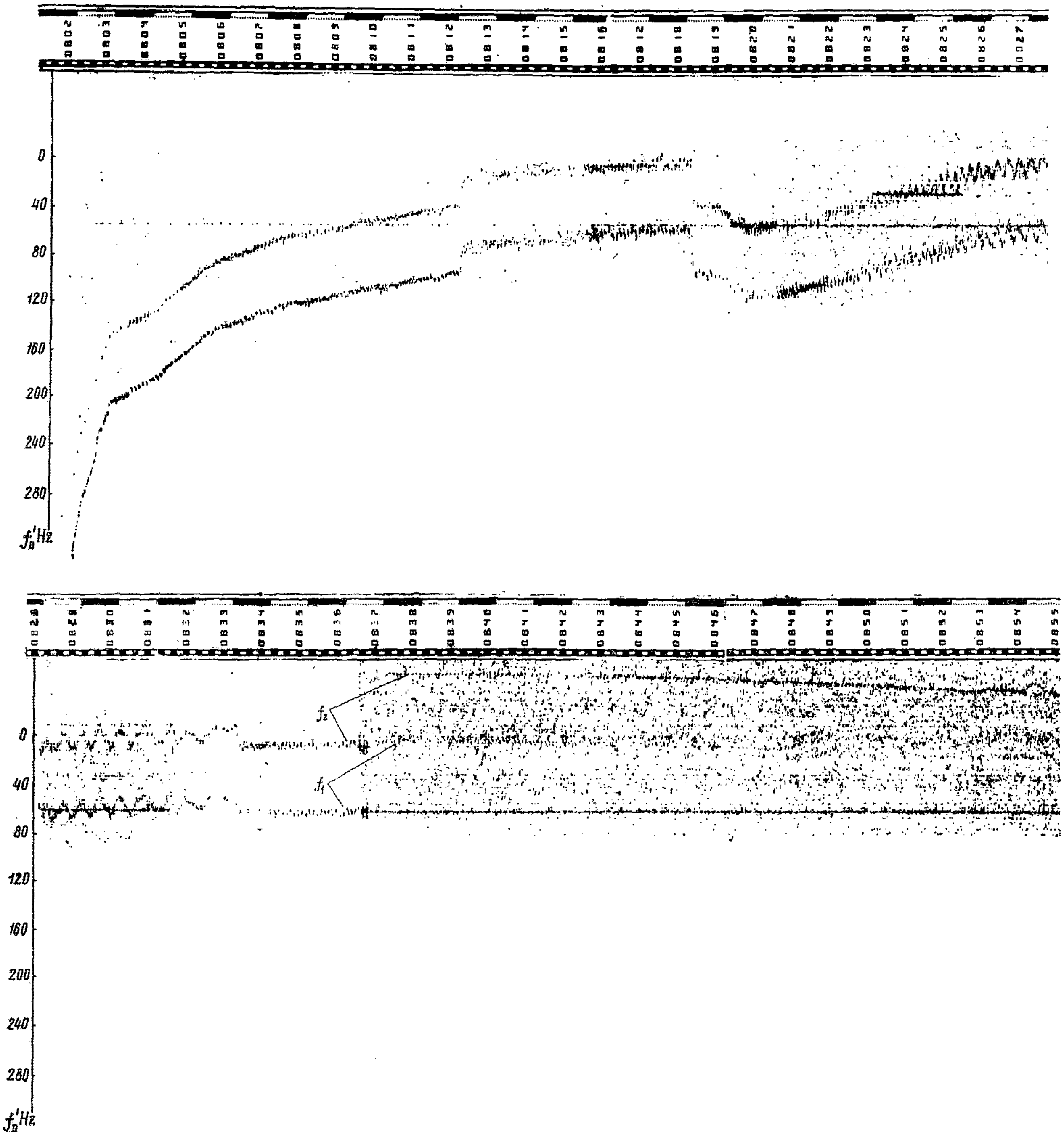

FIG. 2. Frequency of the received signal as a function of time, f_1 and f_2 being the binary zeros and units, respectively, of the telemetry data.

time of 60 min. The descending apparatus touched the Venus surface at 08:37:32, travelling at a velocity of ~16.5 m sec^{-1}. On landing, the frequency shift of the received signal due to the apparatus descent velocity dropped to zero. The fact of the landing was also established by the equality of the apparatus velocity with the velocity obtained independently by means of the frequency jump at the moment of touching the Venus surface.

After the surface had been reached, the power of the radio signal decreased by about a factor of 100, probably due to the inclination of the apparatus and the resulting orientation of the antenna axis with respect to the direction of earth. The reduced-power signal

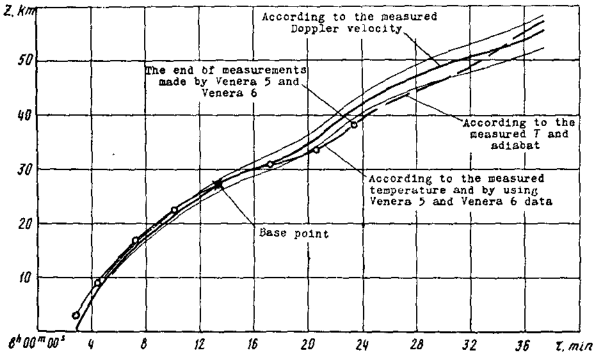

FIG. 3. Distance descended by the probe as a function of time.

received from the surface was subject to a harmonic analysis to determine its instantaneous spectrum, and then decoded according to a special program. The pertinent description of this procedure is given elsewhere.[2]

Signals were received until 09:00:30, with telemetry data on atmospheric temperature from the Venus surface being transmitted for ~20 min, until 8:57:00. The temperature measurement upon landing was 747K.

A constant temperature of 747K was transmitted during the first 50 sec after landing, and a temperature of 730K during the subsequent time. The difference between these two values is within the limits of telemetry sampling errors. The value recorded at the moment of touchdown should be taken as the most reliable figure. From this information, the temperature of the surface of Venus in the region of the Venera 7 landing 747K ±20 K.

3. Height distributions of temperature and pressure

In order to plot the height distribution of temperature above the planetary surface in the region of the Venera 7 landing, one must determine the distance covered by the descending apparatus as a function of time.

Using the dependence of measured descent velocity V_D on time τ, one obtains

$$z=\int_{\tau_1}^{\tau} V_D d\tau.$$

The curve $z(\tau)$ is shown in Fig. 3 (solid line). Calculations of the total distance covered by the apparatus during descent result in a value of $z=55.1\pm3$ km, where the uncertainty is due to the accumulation of V_D measurement error in the integration interval.

The temperature distribution as a function of altitude shown in Fig. 4 is based on the temperature measurements and the distance calculations. The horizontal bars superimposed on the curve indicate the error limits on the temperature measurements; the thin lines paralleling the temperature curve represent the uncertainty due to the errors in the determination of the distance descended because of errors in the V_D measurements.

As indicated by Fig. 4, the resulting temperature profile can be approximated by a straight line which corresponds to the average temperature profile in the atmosphere for convective equilibrium. Such an average temperature lapse rate falls within the limits of uncertainty and is close to the average adiabatic lapse rate $(\partial T/\partial h)_{ad}\approx 8.6\text{K km}^{-1}$. However, a noticeable deviation from a linear temperature variation appears between 27 and 5 km. This deviation corresponds to the period of time near 08:15:00 when the regular descent of the apparatus was interrupted. This region of descent requires further study.

The present results can be compared with data from Veneras 4, 5 and 6. For this purpose, the temperature measurements made by Veneras 4–6 should be related at some point to those made by Venera 7. The point corresponding to a temperature of 500K has been chosen as such a base point; in this region several measurements were made with different devices with good agreement among the results. The experimental points obtained by the Venera 5 and 6 measurements are shown in Fig. 4 by open and partially shaded circles; the data of Venera 4 are plotted as black circles.

Since pressure is the least variable parameter in the atmosphere at a given level, the data from Veneras 4, 5 and 6 were used by comparing temperatures at the same pressure levels, even though some discrepancy appeared in the single thermometer readings resulting from such a procedure. Height distributions of temperature as measured by Veneras 4, 5 and 6 above and below the 500K level were calculated using the hydrostatic law and the equation of state.

From a comparison of the data in Fig. 4 one comes to the conclusion that all measurements made by the Venera stations are in good agreement. For a given height distribution of temperature, the variation of pressure with height in the atmosphere can be easily obtained if the value of pressure at least at one point is known. Any value of p can be taken as a starting point in the region where all of the Venera measurements of temperature and pressure overlap. At the common point used in the comparison of the present results with those obtained earlier, the 500K level, the corresponding value of p is 10.1 kg cm^{-2}.

The height distribution of pressure (Fig. 5) was calculated from the Venera 7 measurements by using both the hydrostatic law and the equation of state, taking into account the real properties of the gas at high pressures.

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[2] A. M. Shakhovskoy, O. N. Rzhiga and Yu. N. Alexandrov: Private communication.

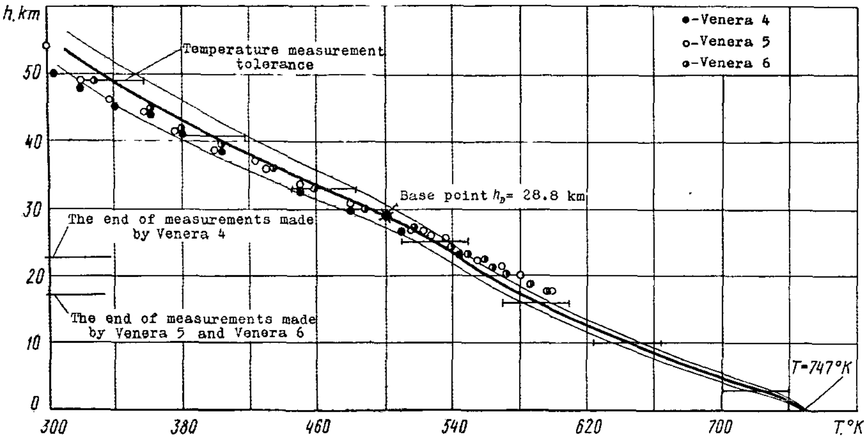

FIG. 4. Altitude distribution of temperature based on measured temperatures and calculations of distance descended based on Doppler frequency-shift observations.

The height distributions of temperature and pressure in the Venus atmosphere can be determined not only from the temperature and Doppler frequency measurements made by Venera 7 as a function of time, but also from the temperature measurements alone by assuming that the variation of temperature with height obeys the adiabatic law. In that case the distance which the apparatus descended can be easily calculated without velocity measurements. From the first law of thermodynamics we have

$$Tds = di - \frac{dp}{\rho},$$

where s is the entropy and i the gas enthalpy. If the adiabatic law is valid, $ds=0$ and $di=dp/\rho$. Assuming hydrostatic equilibrium in the Venus atmosphere, increments of distance covered in the vertical may then be written as

$$\Delta z_{ad} = \frac{1}{g}\Delta i,$$

where g is the acceleration due to gravity on Venus.

The results for the vertical distance (Δz_{ad}) descended as a function of time for an atmospheric abundance of 97% CO_2 and 3% N_2 are included in Fig. 3, with the calculated values plotted in such a way that both curves coincide at the base point. Despite the overall agreement of the $z(\tau)$ curves, some systematic disagreement is revealed in the region corresponding to the descent period between 08:15:00 and 08:35:00. The distance covered by the apparatus from the base point to the surface determined assuming adiabatic conditions proves to be 2 km greater than the mean value of the distance calculated from the measurements of V_D.

The height distribution of temperature based on the adiabatic law is plotted in Fig. 6. The curve essentially corresponds to a Venus atmosphere model with a surface temperature $T=747$K. Comparison of this curve with that obtained from the $T(\tau)$ and $V_D(\tau)$ measurements confirms the conclusion made in the analysis of Fig. 4 that the temperature profile deduced from the Venera 7 data is close to adiabatic. However, this comparison also shows that in the case of the explicit assumption of the adiabatic law for a CO_2 atmosphere, the effective depth of the atmosphere counted below the base point is 2 km greater than the mean depth value derived from the V_D measurements. It is worthwhile to note that this discrepancy falls within the measurement errors.

The height distribution of pressure corresponding to the $T(h)$ data in Fig. 6 is shown in Fig. 7. In this case the pressure profile was determined from the corresponding potential temperature isopleth on an adiabatic chart for 97% CO_2 and 3% N_2. From a comparison of the $p(h)$ curves in Figs. 5 and 7, it follows that pressure-height distributions above and below the base point generally coincide in both cases. However, the surface pressure in the first case proves to be equal to 86 kg cm^{-2}, and in the second to 97 kg cm^{-2}. This discrepancy is mainly due to the disagreement in the distances descended in the two cases (Fig. 3) and to the

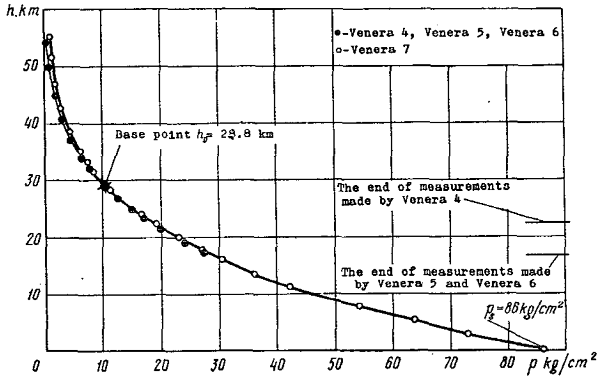

FIG. 5. Calculated height distribution of pressure.

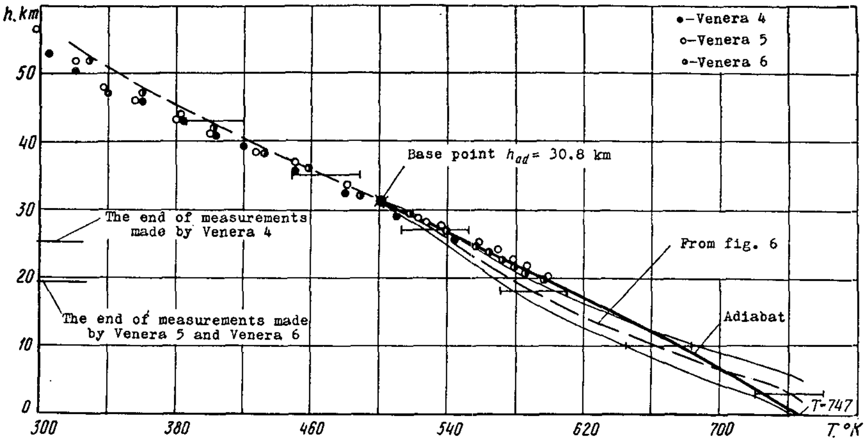

FIG. 6. Height distribution of temperature based on the adiabatic law, using data from Veneras 4, 5, 6 and 7.

differences in the estimates of the total depth of the atmosphere.

4. Further analysis of the data

The dependence of log$p$ on log$T$ is shown in Fig. 8. A superadiabatic condition is found in the final stage of descent corresponding to the height range from 16 to 3 km in Figs. 4 and 6. Since the superadiabatic conditions cannot be considered as steady, an adiabatic atmosphere is more likely in this region.

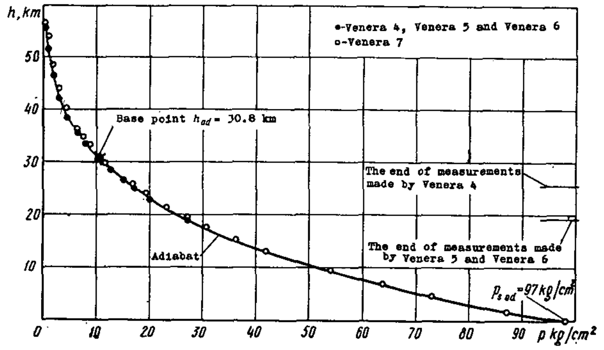

FIG. 7. Height distribution of pressure corresponding to the temperature data of Fig. 6.

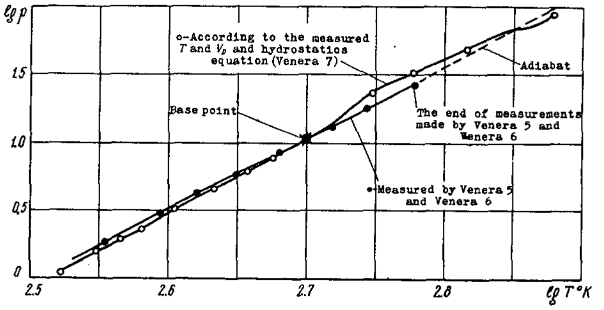

FIG. 8. Log p as a function of log$T$.

The dependence of $p^{\frac{1}{2}}$ on $\int T^{-\frac{1}{2}}d\tau$, which is obtained by combining the assumption of quasi-uniform motion of the apparatus with the equation of state and the hydrostatic equation, is plotted in Fig. 9. For steady descent at constant aerodynamic drag, and assuming the absence of vertical atmospheric currents, this dependence must be linear, i.e.,

$$p^{\frac{1}{2}} = A\int_0^{\tau} T^{-\frac{1}{2}}d\tau.$$

The aerodynamic drag is related to the factor of proportionality A (or tanϕ, where ϕ is the angle of inclination to the curves of Fig. 9) by the expression

$$C_xS \approx A^{-2},$$

where C_x is the coefficient of aerodynamic drag, and S the cross-sectional area.

Two phases of quasi-uniform parachute descent are evident in Fig. 9: 1) before the cross-sectional area change, with a small value C_xS, and 2) after this change, when C_xS became larger. In both these phases the experimentally determined and calculated aerodynamic values generally coincide. After 08:18:00 the value of

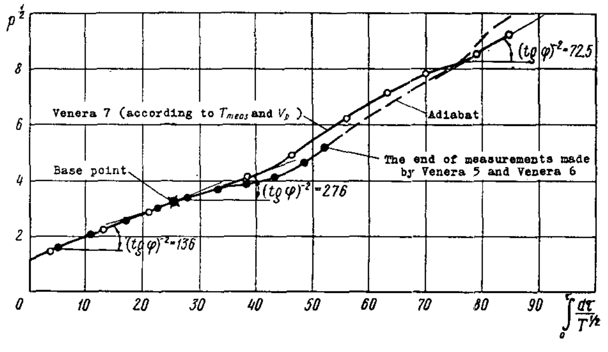

FIG. 9. Analysis of the descending motion of the probe.

C_xS sharply decreased and in this dynamically complicated region of descent (as is evidenced by the character of the tanϕ variation in Fig. 9), the observed C_xS value was considerably lower than the calculated one.

5. Conclusion

As a result of the Venera 7 flight, the first landing of a spacecraft on the planet Venus was achieved, and the temperature of the atmosphere was measured from a height of 55 km to the planetary surface. Temperature measurements continued to be taken for 20 min after the landing. The temperature-height profile $T(h)$ in the Venus atmosphere was obtained by combining temperature measurements with apparatus descent velocity measurements, the latter defined by means of Doppler shift frequency. The height-pressure profile $p(h)$ was then obtained by using the distribution of $T(h)$ indicated by Venera 7 and the results of measurements taken by Veneras 4, 5 and 6.

The distribution of temperature with height above the surface is close to adiabatic, apparently strengthening the hypothesis of strong convective mixing in the Venus atmosphere, and reducing the probability of the greenhouse mechanism for trapping solar radiation near the surface. Temperature on the surface of Venus in the region of the Venera 7 landing (at a distance of 2000 km from the sunrise terminator) is 747K ±20K. The height distribution of pressure was calculated by two methods, verifying that atmospheric pressure at the surface is between 86 and 97 kg cm^{-2}. Taking into account the errors of the T and V_D measurements and the $p(h)$ calculations, the most probable value of pressure at the surface is 90 ± 15 kg cm^{-2}.

The data obtained in the present experiment in the overlapping region agrees with the results of previous measurements made by Veneras 4, 5 and 6. The model of the Venus atmosphere that was calculated on the basis of the former measurements, assuming an adiabatic lapse rate in the regions of extrapolation to the planetary surface, is also in agreement with the data obtained. The surface level in the region of the Venera 7 landing coincides within 1–2 km of the mean surface level in the region of the Venera 5 and 6 probes. The results of Veneras 4–6 agree within 2–3 km with Mariner 5 atmospheric profiles (Kliore *et al.*, 1969) deduced from refractivity measurements above the level of critical refraction in the Venus atmosphere ($p\approx4.5$ kg cm^{-2}). This comparison leads to a mean value of the Venus radius that is in reasonable agreement with the radar data [$R_{♀}=6050\pm5$ km (Ash *et al.*, 1968)].

From the analysis of the signal transmitted by Venera 7 at the moment of impact, it seems fairly certain that the surface of Venus is hard enough to bring a spacecraft to an abrupt stop.

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REFERENCES

Ash, M. E., R. Ingalls, G. Pettengill, Y. Shapiro, W. Smith, M. Slade, D. Campbell, R. Dyce, R. Jurgens and T. Thompson, 1968: The case for the radar radius of Venus. *J. Atmos. Sci.*, **25**, 560–563.

Avduevsky, V. S., M. Ya. Marov and M. K. Rozhdestvensky, 1970: A tentative model of the atmosphere of the planet Venus based on the results of measurements of space probes Venera 5 and Venera 6. *J. Atmos. Sci.*, **27**, 561–568.

Kerzhanovich, V. V., B. N. Andreev and B. M. Gotlib, 1970: Investigation of Venus atmosphere dynamics by the automatic interplanetary stations Venera 5 and Venera 6. *Dokl. Akad. Nauk SSSR*, **194**, No. 2.

Kliore, A., D. Cain, G. Fjeldbo and S. I. Rasool, 1969: Structure of the atmosphere of Venus derived from Mariner V S-band measurements. *Space Research IX*, Amsterdam, North-Holland Publ. Co.

Marov, M. Ya., 1971: A model of the Venus atmosphere. *Dokl. Akad. Nauk SSSR*, **196**, No. 1.

Pravda, 1971: Soviet interplanetary station on the surface of Venus. No. 27, 27 January.