VEGA Balloon Dynamics and Vertical Winds in the Venus Middle Cloud Region

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The VEGA balloons provided a long-term record of vertical wind fluctuations in a planetary atmosphere other than Earth's. The vertical winds were calculated from the observed displacement of the balloon relative to its equilibrium float altitude. The winds were intermittent; a large burst lasted several hours, and the peak velocity was 3 meters per second.

BALLOONS PROVIDE AN EXCELLENT platform from which to measure the vertical component of the wind vector. With measurements of temperature, pressure, and the three-dimensional wind vector, we can estimate kinetic and potential energies, dissipation, and the vertical and horizontal transports of heat and momentum, which are basic elements in a description of the general circulation. We present a temporal record of the vertical winds encountered by the VEGA balloons as they floated in the Venus clouds.

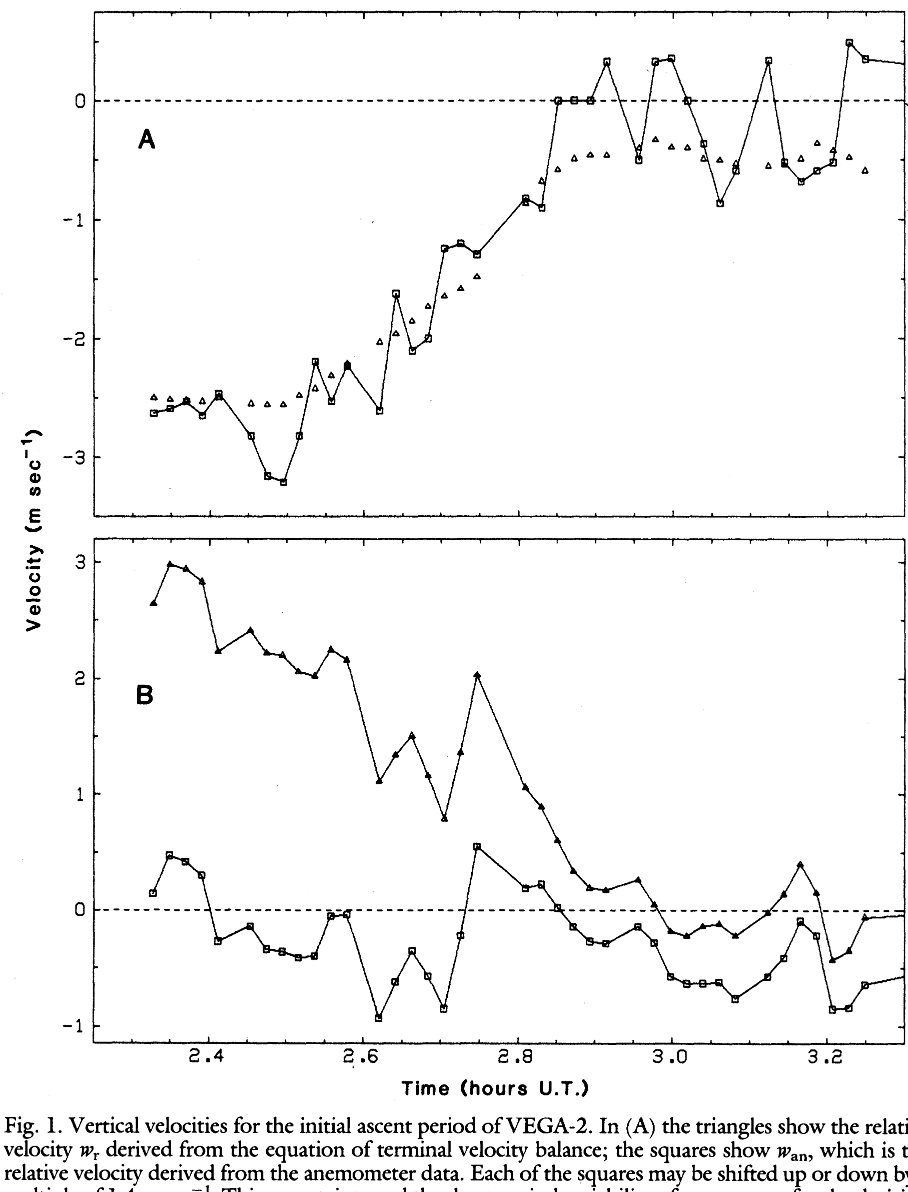

Fig. 1. Vertical velocities for the initial ascent period of VEGA-2. In (A) the triangles show the relative velocity w_r derived from the equation of terminal velocity balance; the squares show w_{an}, which is the relative velocity derived from the anemometer data. Each of the squares may be shifted up or down by a multiple of 1.4 m sec^{-1}. This uncertainty and the short-period variability of w_{an} account for the decision not to use the anemometer data except to identify EFA episodes. Such an episode occurred from 2.85 to 2.90 hours universal time (U.T.). In (B) the triangles show the balloon vertical velocity w_b, and the squares show the atmospheric vertical velocity w_a.

The quantity of interest for general circulation studies is the atmospheric vertical velocity w_a, defined as the rate at which an atmospheric parcel moves upward relative to constant-pressure surfaces (*1*). In a hydrostatic atmosphere, w_a is equal to $-\omega/\rho g$, where ρ is the atmospheric density, g is the gravitational acceleration, and ω is dp/dt, the rate of change of pressure measured by an observer moving with the fluid (*1*). The vertical velocity of the balloon relative to constant-pressure surfaces is w_b, which is equal to $-\dot{p}/\rho g$, where $\dot{p}$ is the rate of change of pressure measured by a sensor on the balloon (*2*). The upward velocity of the gas relative to the balloon is w_r. As outlined below, we determine w_b and w_r from the pressure and temperature record and then calculate w_a from the relation $w_a = w_b + w_r$.

The vertical acceleration of the balloon is the result of two forces: a drag force arising from the relative velocity w_r and a buoyancy force arising from the density difference $\Delta\rho$ between the balloon and its surroundings. To a good approximation, the vertical equation of motion is (*3*)

$$\frac{3}{2}\frac{dw_r}{dt} = -\frac{C_D}{2}\frac{3}{4r}|w_r|\,w_r - g\frac{\Delta\rho}{\rho} \quad (1)$$

where C_D is the drag coefficient for a sphere, r is the radius, and t is time. Drag on the gondola is negligible.

According to Eq. 1, the characteristic response time of the balloon is $4r/C_D|w_r|$, which is of order $15/|w_r|$ seconds, where w_r is in meters per second. For gas motions whose periods are long compared to this characteristic time, the equation reduces to a condition of terminal velocity balance, in which drag balances buoyancy. Similarly, the horizontal equation of motion reduces to a condition of zero drag, in which the balloon drifts with the horizontal velocity of the gas (*4*). These conditions are satisfied for the VEGA balloons, since $|w_r|$ is of order 1 m sec^{-1} and the periods are of order 1 hour.

Terminal velocity balance provides a means of determining w_r, since C_D is known and $\Delta\rho/\rho$ can be determined from p and T,

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which are the atmospheric pressure and temperature measured by the balloon:

$$\Delta\rho/\rho = 1 - (M_b + M_h)/(\rho V) \qquad (2)$$

Here M_b is the known mass of the balloon structure (18.807 kg for VEGA-1 and 19.060 kg for VEGA-2); M_h is the known mass of helium (initially 2.020 and 2.046 kg for the two balloons, respectively), and V is the volume of the balloon which is calculated from p and T.

To find V when the balloon is superpressurized, we use the elastic constants of the skin as measured in laboratory tests (*2*). Thus $V = A\ (p_h - p) + B$, where p_h is the helium pressure, A is 0.125 m^3 $mbar^{-1}$, and B is 19.4 m^3. Knowing M_h, T, and p, we can compute p_h and V by assuming that the temperature T_h of helium inside the balloon is equal to T (see discussion below). When p is greater than about 700 mbar, however, this method gives solutions with p_h less than p. Such solutions are spurious; they indicate that the balloon has lost superpressure. The correct solutions then are obtained by ignoring the elastic constants and setting p_h equal to p. The volume V is computed directly from the helium equation of state in these cases.

Loss of helium due to diffusion through the skin caused M_h to decrease by 3 to 4 percent during the course of the mission. This decrease was measured by observing the decrease in the equilibrium float altitude (EFA) as a function of time. The EFA is defined as the altitude where $\Delta\rho/\rho = 0$. The anemometer was used to identify periods when the balloon was close to this altitude—periods during which the propeller did not turn ($|w_r| < 0.25$ m sec^{-1}) for 5 minutes or more. Such episodes occurred frequently during the first 12 hours of VEGA-2 (Fig. 1) and tended to recur at intervals of order 10 hours during other periods. Having determined M_h during the EFA episodes, we calculated M_h at other times by linear interpolation.

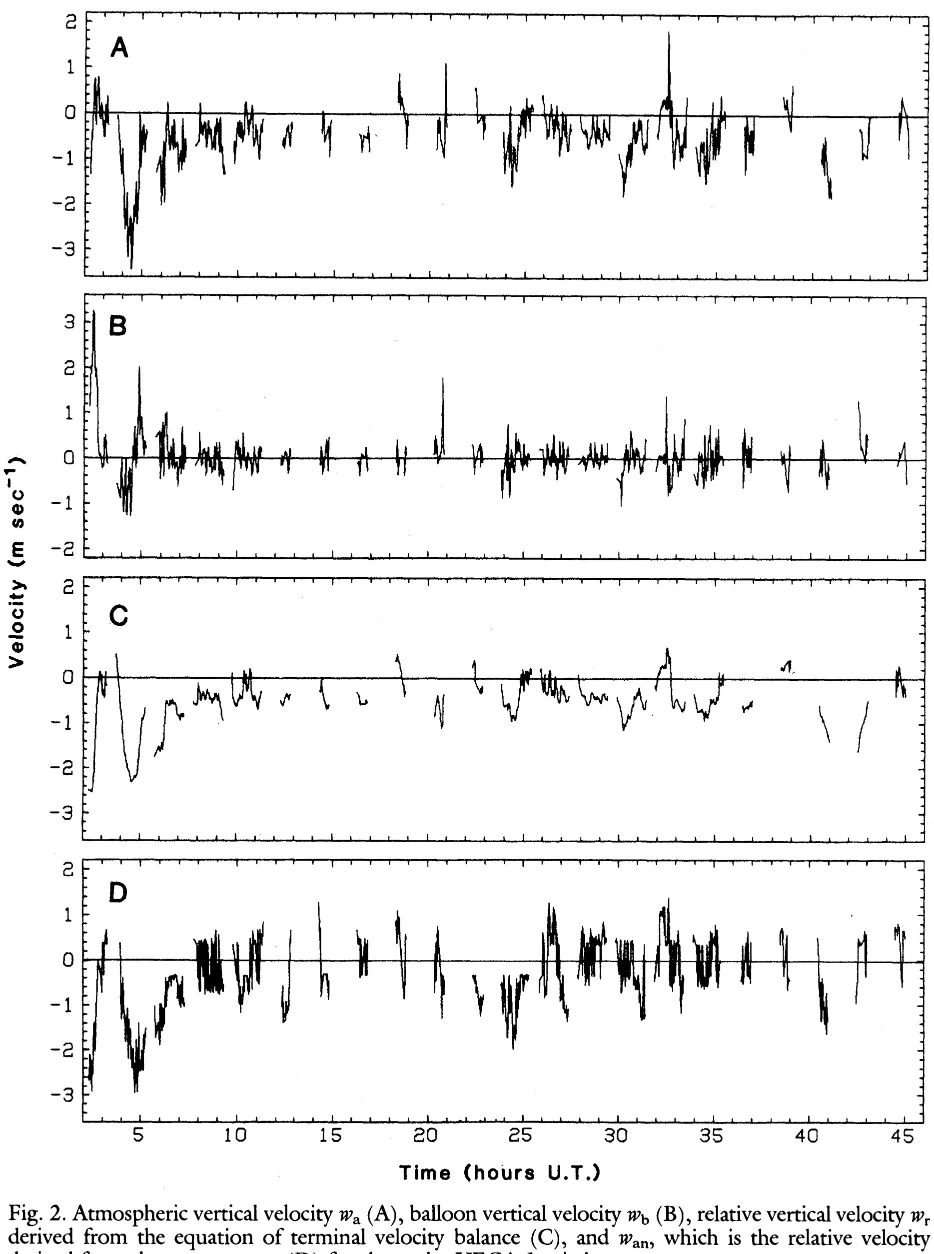

Fig. 2. Atmospheric vertical velocity w_a (A), balloon vertical velocity w_b (B), relative vertical velocity w_r derived from the equation of terminal velocity balance (C), and w_{an}, which is the relative velocity derived from the anemometer (D) for the entire VEGA-1 mission.

The drag coefficient C_D is treated as a known function of the Reynolds number Re, which is in the range 10^5 to 10^6. We represent C_D as a hyperbolic tangent in log(Re), which approaches 0.6 when Re is small and 0.3 when Re is large (*5*). Between these limits, the curve fits the data of Scoggins (*5*) obtained from observations of balloons rising in Earth's atmosphere. The curve does not fit an observation ($C_D = 0.2$, $w_r \geq 1$ m sec^{-1}) obtained for VEGA balloons in Earth's atmosphere, but it provides a good fit to the initial ascent data on Venus (see below). Dense falling spheres and fixed spheres in wind tunnels (*6*) do not exhibit the same dynamical behavior as balloons, and they yield different values of the drag coefficient.

Data from the first hour of each flight (Fig. 1) provide a check of the assumed drag coefficient and an upper bound on the error of w_a and w_r. During the initial ascent from $p \gtrsim 900$ mbar to $p \simeq 535$ mbar, the balloon's velocity w_b was of order 3 m sec^{-1}. The velocity w_r computed from the drag coefficient is approximately equal to $-w_b$, so that the computed value of w_a is less than 1 m sec^{-1}. Assuming that the atmospheric velocities are no larger than they are a short time later (<1 m sec^{-1}), then the degree of cancellation between w_r and w_b implies that the error in w_r is no larger than 33 percent. This error estimate is consistent with that obtained by comparing the different drag coefficient curves (*3, 5, 6*) with each other, and it is smaller than the scatter of w_r values derived from the anemometer (Fig. 1). Thus the anemometer, which was originally designed to measure w_r, was finally used only to identify those periods for which $w_r = 0$.

The VEGA-2 initial ascent also provides a check of the assumption that $T_h = T$. Less than 10 minutes after the ascent, a short EFA episode occurred at a pressure of 540 mbar (Fig. 1). Several hours later, many EFA episodes occurred at a pressure of 532 mbar. The difference can be attributed to the helium being 1.2 K colder after decompression during the ascent. Such a temperature difference has only a small effect on the determination of w_r. The EFA's that were reached several hours into the two flights provided estimates of M_h that are in excellent agreement with the initial masses determined before launch (2).

From 35 hours onward (Figs. 2 and 3) the balloons were in sunlight, and T_h may have been greater than T by as much as 10 K (7). Since our processing assumes that $T_h = T$, solar heating of the helium causes our estimate of w_a to be more positive than the true value. The large positive velocities ($w_a \gtrsim 1$ m sec^{-1}) that were inferred for VEGA-2 after 42 hours may therefore be unrealistic (Fig. 3).

The loss of helium is reflected in the decrease of altitude over the 45-hour life of the mission [Figs. 1 and 2 of the companion report by Sagdeev and co-workers (8)]. Short-period excursions away from the average altitude are mostly downward (Figs. 2 and 3). This fact is consistent with the balloon being near the top of a convection zone (9). Regions of horizontal convergence, into which the balloon drifts, are likely to be downdrafts rather than updrafts.

Loss of superpressure when the balloon is below 700 mbar tends to amplify the balloon's response to downdrafts, as demonstrated in the extreme excursion of VEGA-2 that began at 36 hours. Figure 5 of the report by Sagdeev and co-workers (8) shows this event in detail. Without superpressure the balloon's buoyancy no longer increases with depth, and the downward excursion continues until the balloon either moves out of the downdraft or the downdraft ceases. Thus the event at 36 hours was characterized not only by large negative values of w_a but also by the long duration of the downdraft (Fig. 3).

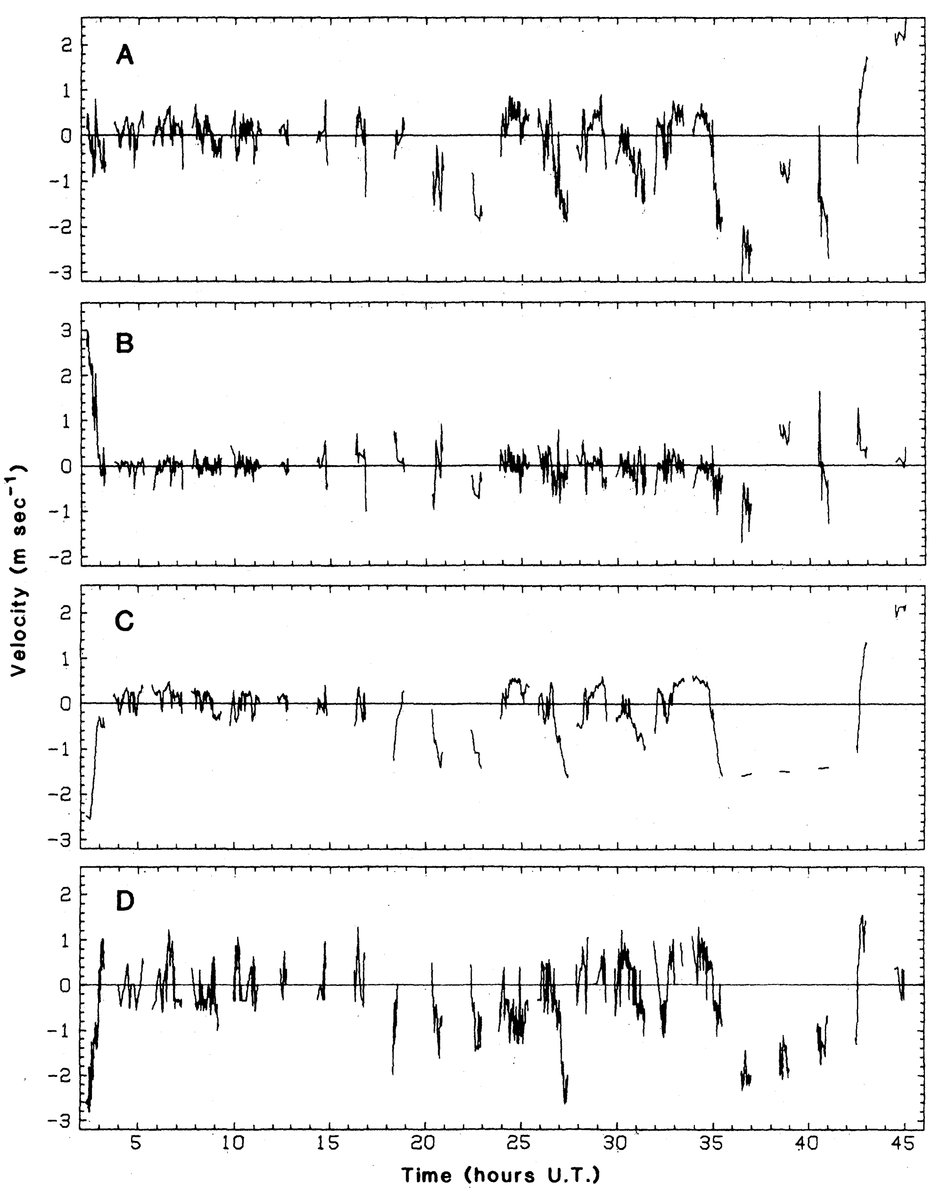

Fig. 3. As in Fig. 2, but for VEGA-2. The three flat sections of the w_r curve from 36 to 41 hours U.T. are real. This behavior occurred because the balloon lost superpressure during this period.

Figures 3 and 4 of Sagdeev and co-workers (8) show oscillations with periods of order 15 minutes. The phase relations among variables are consistent with the balloon moving up and down in an adiabatic atmosphere. The question is whether the motions are a thermally induced free oscillation of the balloon (10) or a forced response of the balloon to oscillations of w_a. The oscillations seem to reflect real oscillations of w_a. First, the observed 15-minute period is a poor fit to the 7.5-minute period of free oscillations calculated from Eq. 1. Also, the amplitude of 0.3 m sec^{-1} is incompatible with the value, computed to be 0.15 m sec^{-1}, above which the free oscillations are critically damped. Finally, there seems to be no energy source to maintain the balloon's free oscillations during the night in the optically thick clouds of Venus.

Oscillations at even higher frequency are apparent in the Doppler data (4). Amplitudes of 1 m sec^{-1} and periods of 1 to 2 minutes occur when $|w_r|$ is large, as it is during the large events. These high-frequency oscillations could be related to the self-induced oscillations of rising balloons observed by Scoggins (5). The oscillations could account for much of the noise in w_r derived from the anemometer (Fig. 1) and in w_b derived from $-\dot{p}/\rho g$.

The most significant findings of the experiment are the magnitude of the atmospheric vertical velocities (up to 3 m sec^{-1}), the duration of the bursts (up to 4 hours), and their intermittency. The bursts (episodes during which $|w_a|$ is larger than 1 m sec^{-1}) lasted long enough to allow at least two or three VLBI measurements of horizontal velocity to be made per burst (4). The VLBI sampling frequency is therefore adequate to determine the contribution of the bursts to the vertical and horizontal transports of heat and momentum.

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11. Funded partially by National Aeronautics and Space Administration Ames Research Center and the Jet Propulsion Laboratory.

23 October 1985; accepted 24 January 1986