CHAPTER 6

(Chapter was not revised since the six edition)

ROCKET MEASUREMENTS IN THE STRATOSPHERE AND MESOSPHERE

6.1 General

This chapter is concerned mainly with wind and temperature measurements made with small meteorological rockets. The wind data are obtained from the radar tracking of the drift of a falling sensor package which, either alone or with temperature sensors, makes *in situ* observations. The temperature observations are transmitted to a ground station. The techniques described here are applicable to the stratosphere and mesosphere, generally, between 20 km and 90 km.

Typically, meteorological rocketsonde measurement systems consist of:

(*a*) An instrument ejected from a rocket near its maximum height (apogee) which then descends on a decelerator device, similar to a parachute, and transmits measurements of temperature to the ground, while high precision radar tracking of the decelerator provides wind information;

(*b*) A free-falling inflatable balloon, called a ‘falling sphere’ tracked by a high precision radar to provide atmospheric density and wind data; or,

(*c*) A high precision radar track of clouds of foil dipoles, called chaff, which are ejected near the rocket’s apogee enabling only winds to be determined.

The elements to be measured are very diverse. Most important are wind and temperature, but others include solar radiation, electrical variables, turbulence, and chemical constituents. Among the latter are ozone, water vapour, oxides of nitrogen, atomic oxygen and hydrogen, chlorine and the hydroxyl radical.

A central body, the World Data Center-A (WDC-A), undertakes collection and the various exchanges of the data. By means of these data, systematic studies are undertaken, e.g. studies of the general circulation, solar/high-atmosphere relationships, correlation between geomagnetism and meteorological parameters, composition of standard atmospheres, checking of satellite data, and stratospheric warmings. For each launching, a report, known as a ROCOB, is compiled and disseminated by means of the Global Telecommunications System.

The measurement techniques are in a state of constant evolution as regards both the methods used and the constituents measured. The measurements are mostly carried out non-routinely at a single location. Only the thermodynamic and the ozone measurements have been widespread and frequent, with use being made of semi-operational methods. Several other meteorological measurement methods, not to be discussed further since these go beyond the realm of small meteorological rocketsonde techniques are:

(*a*) Chemical tracers, e.g. sodium or potassium, that provide information on wind, turbulence, and temperature: special tracking cameras are required with which to triangulate the chemical trail;

(*b*) Pitot probes;

(*c*) Active accelerometers;

(*d*) Acoustic grenades that, upon exploding emit sound waves to a system of highly sensitive microphones on the ground and provide wind and temperature data.

A comprehensive survey of earlier contributions to meteorological rocket soundings is given in Bollermann (1970).

6.2 Wind measurement

6.2.1 *Methodology*

After the rocket reaches its apogee, an expulsion device (usually pyrotechnical) separates the payload from the propulsion system, or rocket motor. Wind and temperature sensors are deployed along with a telemetry unit used to transmit the temperature information to the ground. During the ensuing descent, the motion of the sensing system is tracked with a radar. Thus, the trajectory of the falling target is determined, whether a parachute, a temperature sensor/parachute system, or an inflatable sphere. Corrections to the trajectory are usually made to insure correct wind data. Chaff is another wind sensing system which falls very slowly and which follows the wind quite well, thus corrections to its motion are not usually required. Chaff, however, is no longer routinely used.

6.2.2 *Wind sensors*

The quality of the wind measurements depends on how well the wind sensing system responds to atmospheric movements. The following factors influence this response:

(*a*) Inertia, accelerations, and fall velocity of the wind sensing system;

(*b*) Dynamic stability and oscillation of the decelerator system;
(*c*) The sensor shape as it affects the drag coefficient along the three axes.

6.2.3 *Tracking method*

After the payload has been ejected, its trajectory is usually tracked by a radar using the echo from the metal-coated sensor. This enables wind variations with height to be determined and the components of the wind velocity to be obtained. The required accuracy of azimuth and elevation tracking angles is of the order of 2×10^{-4} radians (approximately 0.011°), and of the order of 10 m for slant range; this is achieved by the use of high-performance radars or transponder transmitters. The raw data are sampled at a rate of 10 or more points per second and are then smoothed by the method of least squares in a manner that varies with target height and the fall speed.

6.2.4 *Corrections and computations of wind*

The horizontal velocity vector V_p of the sensor, relative to the observer is often mistaken as the horizontal velocity V of the true wind. However, high ejection speeds, fluctuations in the drag coefficient, and the force of inertia of the sensor lead to differences between these two vectors at heights above 50 km and make it necessary to apply corrections, the magnitude of which increase rapidly with increasing fall speed or height.

A technique for correction, developed by Eddy, *et al.* (1965) and by Ballard (1966) enables the horizontal wind components to be obtained at all levels from the tracking data, if the following assumptions are made:
(*a*) The sensor is subjected solely to the forces of gravity and of air resistance;
(*b*) The force of gravity remains constant;
(*c*) The magnitude (D) of the resistance to motion is proportional to the square of the speed of the sensor relative to the air.

From Newton's second law, we may write, as a first approximation:

$$m \frac{dV_s}{dt} = mg + D \tag{6.1}$$

$$|D| = \rho \cdot s \cdot \frac{C_d}{2} \cdot (V - V_2)^2 \tag{6.2}$$

where C_d is the drag coefficient; g is the gravity constant; m is the mass of the descending payload (i.e. wind sensor and/or transmitter); S is the cross-sectional area of the sensor; t is time; V is the wind velocity; V_s is the velocity of the wind sensor; and ρ is the air density.

We obtain an expression for the corrections to be applied to the horizontal components of the velocity of the wind sensor, Δu and Δv, to obtain the components of the vector wind. This expression is valid if the wind component is much less than the speed of the sensor, and if we assume that $S \cdot C_d$ is isotropic, i.e. independent of the direction of movement, we obtain:

$$\Delta u = -w_s \frac{\dot{u}_s}{|\dot{w}_s - g|} ; \Delta v = -w_s \frac{\dot{v}_s}{|\dot{w}_s - g|} \tag{6.3}$$

where $\dot{u}_s$ is the west-east acceleration of the wind sensor; $\dot{v}_s$ is the south-north acceleration of the wind sensor; w_s is the vertical speed of the wind sensor; and $\dot{w}_s$ is the vertical acceleration of the wind sensor.

The corrections are considered to be significant at altitudes above the level at which the sensor becomes sensitive to the wind, i.e. when the resistance to motion becomes sufficiently large. This altitude is usually defined as the level at which the vertical acceleration of the sensor becomes less than 5 m s^{-2} (on average 5 km below apogee).

The value of the terms Δu and Δv may reach 100 m s^{-1} at the highest levels and then decrease very rapidly to become less than 1 m s^{-1} below 50 km. The performance of the best radars used makes it possible to achieve an accuracy of 3–5 per cent for winds at levels above 70 km and of the order of 2 per cent at lower levels. This method of correction cannot take into account abnormalities in the behaviour of the wind sensor. In such cases, the data must be considered as doubtful.

6.3 Temperature measurement by immersion thermometry

6.3.1 *General*

In order to measure high-altitude temperatures by means of small rocketsondes, two methods are employed. The first uses immersion thermometry, i.e. a sensor/telemetering unit which is ejected from the rocket at apogee and then descends by parachute, which measures wind and temperature data during the payload's descent through the atmosphere. The second uses a passive inflatable falling sphere measuring primarily the density and wind profiles. Temperatures are derived from the density profile (see section 6.4). Both types of payloads must be radar tracked to obtain position information. This section discusses the first technique.

6.3.2 *Immersion thermometry*

The extreme difficulty of *in situ* measurements at high altitudes makes it a vital requirement that an instrument design be selected that minimizes the need for corrections. In this way, corrections may be either neglected completely or computed by using standard parameters up to the highest levels. Corrections are important at the highest levels and were developed for use by Henry (1967) and quantified by Krumins and Lyons (1972). Corrections are discussed further in section 6.3.3.

In these measurements, exchanges of energy between the sensing element and the surroundings rapidly become very small at great heights due to the very low air density, while the high speeds of descent result in rapid variation of the temperature measured. At a height of 70 km these speeds vary from 250 to 500 m s^{-1} depending on the system used. Unfortunately, the effect of the high fall speed and the thermistor thermal inertia expressed by its time constant of response, taken together, acts to dampen the amplitude of the temperature variation.

We are thus led to select sensors having a very low thermal capacity on mountings reducing the effects of heat conduction to a minimum. The sensors should be located as far away as possible from those regions aerodynamically disturbed by the body of the payload package and, in addition, must also be insensitive to oscillations of the sensor/parachute package which will cause variations in the effects of the incident air flux and direct solar radiation.

Three different types of sensors, based on a change in electrical resistance with temperature, are used:

(*a*) Thermistor: A bead thermistor, approximately 0.25 mm in diameter, is supported by two fine wires soldered to supports formed of metal-coated mylar film which are very thin compared to their area, in order to facilitate dissipation of the heat due to conduction from the main body of the payload. The thermistor's electrical resistance increases exponentially with decreasing temperature. At a height of 70 km, for a speed of descent of 250 m s^{-1}, the time constant of response is of the order of 15–20 sec and the magnitude of the corrections may be approximately 40–50 K for some types of instruments (Krumins and Lyons, 1972), and more for other types (Kokin and Rusina, 1971; Schmidlin, *et al.*, 1980);

(*b*) Fine wire: The sensor comprises a fine wire, 5 to 20 μ in diameter, made of tungsten, tungsten-rhenium alloy, or nickel-iron alloy. The sensor is sometimes covered with a gold skin a few hundredths of a micron thin, to protect it from oxidization (a gold-palladium alloy makes it possible to decrease the influence of solar radiation). In order to reduce the effect of heat from conduction, two techniques are used: either the fine wire is short (a few centimetres), has a small diameter, and is soldered to two constantan (copper-nickel alloy) wires a few tenths of a micron in diameter; or the fine wire is very much longer, has a larger diameter and is soldered to terminals which have an appreciable thermal capacity, the wire being held in place at several points by very small supports.

    The variation of resistance with temperature is practically linear, and is of the order of 1 ohm per 5 K in the first case, or 1 ohm per 10 K in the second. At a height of 70 km, for a speed of descent of 250 m s^{-1} the time constant of a short fine wire five μ in diameter is of the order of one-half second and the magnitude of the correction is approximately 35 K, while these values reach 2 to 3 sec and approximately 40 K in the case of sensors with a long fine wire of 20 μ in diameter;

(*c*) Layered sensors: This type of sensor, which is less fragile than the preceding ones, has a larger thermal inertia, which limits its use to heights below 60 km.

    On a thin nylon substrate, an electrical circuit, consisting predominantly of nickel, is vacuum deposited by evaporation, the two faces of the sensor then being covered with a film of anodized aluminum with a thickness of five μ to minimize the effects of solar radiation.

    The variation of resistance of the circuit with temperature is practically linear and is of the order of 1 ohm per 5 K and the time constant is of the order of a few seconds at 60 km.

6.3.3 *General equation for temperature sensor corrections*

Knowing the temperature of the sensor T_t, the temperature of the ambient air T_∞ can be calculated. In a general way and for each type of sensor, the first law of thermodynamics, i.e. the law of conservation of energy, demands that the variations in the internal energy of the system be balanced by the sum of the amounts of energy absorbed from the environment, as well as the amount dissipated away.

In a general way, we may write:

$$mC\frac{dT_t}{dt} = A \cdot h\left[T_\infty + \frac{rV^2}{2C_p} - T_t\right] + \alpha_s \cdot J \cdot A_s + \alpha_s \cdot J \cdot Alb \cdot A_a + \sigma\alpha_1 \sum_1^i A_i \cdot T_i^4 - A \cdot \varepsilon \cdot T_t^4 + W_t + K_c \qquad (6.4)$$

where A is the area of the sensor; A_a is the effective area of the sensor with respect to radiation reflected by the Earth's surface; A_s is the effective area of the sensor with respect to direct solar radiation; A_i is the effective area of the sensor exposed to long-wave radiation from the Earth, atmosphere, and the main body of the sonde; *A1b* is the albedo of the Earth and atmosphere; C is the specific heat of the sensor; C_p is the specific heat of air at constant pressure; h is the convective heat transfer coefficient (function of density and speed of air relative to sensor, and of air temperature); J is the solar constant; K_c is the heat from conduction; m is the mass of the sensor; r is the recovery factor; T_i is the equivalent black-body temperature of sources emitting long-wave radiation towards the sensor; T_t is the temperature of the sensor; T_∞ is the temperature of undisturbed air; V is the speed of air relative to the sensor; W_t is the heating by Joule effect due to measuring current and absorption of electromagnetic radiation by the transmitting antenna; α_s is the absorption coefficient of the sensor for solar radiation; α_l is the absorption coefficient for long-wave radiation; ε is the emissivity of the sensor; and σ is the Stefan-Boltzmann constant.

The first term on the right-hand side of equation 6.4 represents the quantity of energy exchanged by convection, including kinetic heating, which is severe above 50 km because of the very fast fall speed encountered. The second and third terms represent solar radiation and radiation reflected from the Earth and/or cloud surfaces, respectively. The fourth term represents long-wave radiation reaching the sensor from the environment and from the sonde. The fifth term represents the energy emitted by the sensor due to its emissivity. The sixth term W_t is that part of the energy absorbed by Joule-effect heating, and the seventh term characterizes the conduction between the sensor and its mounting. The last two terms are specific for each system and must be applied to supports or leads of the sensor in order to calculate the correction for conduction. For details, see Krumins and Lyons (1972), Bulanova, *et al.* (1967), and Yata (1970).

The necessary coefficients for calculating the other terms are determined experimentally and by mathematic formulation, depending on the parameters available during the launch. In particular, the coefficient h, which is a function of density and temperature, is calculated from standard values and then more accurately by successive iterative processes by applying the general equations for calculating temperature and density (equations 6.4, 6.8, 6.9, 6.10).

6.3.4 *Telemetry*

Meteorological telemetry units enable the variations in the temperature of the sensor to be transmitted. The resistance of the sensor is usually converted to a frequency which directly modulates the transmitter in the case of multiple channel measuring systems, or uses a commutator to switch up sequentially to three or four channels, or subcarriers in the case of a two- or three-channel measuring system.

Rocket-borne telemetry systems operate under very severe conditions. During the powered phase of the rocket flight these systems are subjected to a very wide spectrum of large vibrations and to accelerations (g-forces) which may reach some tens of g for a period of several seconds. Low-air density at the beginning of the descent restricts heat dissipation. Later in the descent, the measuring package encounters denser air at temperatures which can be as low as 190 K, and which may cool the electronics.

In most cases, reference resistances or voltages are selected by means of a sequential switch in order that errors introduced by the measuring system as a whole and, in particular, those due to possible changes in performance of the telemetry devices as a result of environmental stress during flight, can be detected and corrected. Particular care is taken in designing and positioning the antenna relative to the sensors in order to avoid heating of the sensors due to the Joule effect caused by the electromagnetic energy radiated from the transmitter; the power of the latter should, in any case, be limited to the minimum necessary (from 200 to 500 mw). With the use of such low transmission power, together with a distance of the transmitter from the receiving station which may be as much as 150 km, it is usually necessary to use high gain directional receiving antennae.

On reception, and in order to be able to assign the data to appropriate heights, the signals obtained after demodulation or decoding are recorded on multichannel magnetic tape together with the time-based signals from the tracking radar. Time correlation between the telemetry signals and radar position data is very important.

6.4 Temperature measurement by inflatable falling sphere

The inflatable falling sphere is a simple 1 m diameter mylar balloon containing an inflation mechanism and nominally weighs about 155 g. The sphere is deployed at an altitude of approximately 115 km where it begins its free fall under gravitational and wind forces. The sphere, after being deployed, is inflated to a super pressure of approximately 10–12 hPa by the vaporization of a liquid, such as isopentane. The surface of the sphere is metalized to enable radar tracking for position information as a function of time. To achieve the accuracy and precision required, the radar must be a high precision tracking system, such as a FPS-16 C-band radar or better. The radar-measured position information and the coefficient of drag are then used in the equations of motion to calculate atmospheric density and winds. The calculation of density requires knowledge of the sphere's coefficient of drag over a wide range of flow conditions (Luers, 1970; Engler and Luers, 1978). Pressure and temperature are also calculated for the same altitude increments as density. Sphere measurements are only affected by the external physical forces of gravity, drag acceleration, and winds which make the sphere a potentially more accurate measurement than other *in situ* measurements (Schmidlin, Lee and Michel, 1991).

The motion of the falling sphere is described by a simple equation of motion in a frame of reference having its origin at the center of the Earth, as:

$$m\frac{dV}{dt} = mg - \frac{\rho C_d \ A_s \left|V_r\right| \cdot V_r}{2} - \rho \, V_b \ g - 2m\omega \times V \tag{6.5}$$

where A_s is the cross-sectional area of the sphere; C_d is the coefficient of drag; g is the acceleration due to gravity; m is the sphere mass; V is the sphere velocity; V_r is the motion of the sphere relative to the air; V_b is the volume of the sphere; ρ is the atmospheric density; and ω is the Earth's angular velocity.

The relative velocity of the sphere with respect to air mass is defined as $V_r = V - V_a$, where V_a is the total wind velocity. C_d is calculated on the basis of the relative velocity of the sphere. The terms on the right-hand side of equation 6.5 represent the gravity, friction, buoyancy, and Coriolis forces, respectively.

After simple mathematical manipulation, equation 6.5 is decomposed into three orthogonal components, including the vertical component of the equation of motion from which the density is calculated; thus obtaining:

$$\rho = \frac{2m \ (g_z - \ddot{z} - C_z)}{C_d A_s \left|V_r\right| \ (\dot{z} - w_z) + 2V_b g_z} \tag{6.6}$$

where g_z is the acceleration of gravity at level z; w_z is the vertical wind component, usually assumed to be zero; $\dot{z}$ is the vertical component of the sphere's velocity; and $\ddot{z}$ is the vertical component of the sphere's acceleration.

The magnitudes of the buoyancy force ($V_b g_z$) and the Coriolis force (C_z) terms compared to the other terms of equation 6.7 are small and are either neglected or treated as perturbations.

The temperature profile is extracted from the retrieved atmospheric density (equation 6.7) using the hydrostatic equation and the equation of state, as follows:

$$T_z = T_a \frac{\rho_a}{\rho_z} + \frac{M_o}{R\rho_z} \int_h^a \rho_h g dh \tag{6.7}$$

where h is the height; the variable of integration; M_o is the molecular weight of dry air; R is the the universal gas constant; T_a is temperature in K at reference altitude a; and; T_z is temperature in K at level z; ρ_a is the density at reference altitude a; ρ_h is the density to be integrated over the height interval h to a; and ρ_z is the density at altitude z.

Note that the source of temperature error is the uncertainty associated with the retrieved density value. The error in the calculated density is comprised of high and low spatial frequency components. The high frequency component may arise from many sources, such as measurement error, computational error, and/or atmospheric variability and is somewhat random. None the less, the error amplitude may be suppressed by statistical averaging. The low frequency component, however, including bias and linear variation, may be related to actual atmospheric features and is difficult to separate from the measurement error.

6.5 Calculation of other aerological variables

6.5.1 *Pressure and density*

A knowledge of the air temperature, given by the sensor as a function of height, enables atmospheric pressure and density at various levels to be determined. In a dry atmosphere with constant molecular weight, and making use of the hydrostatic equation:

$$dp = -g\rho dz \tag{6.8}$$

and the perfect gas law:

$$\rho = \frac{M}{R} \cdot \frac{p}{T} \tag{6.9}$$

the relationship between pressures p_i and p_{i-1} at the two levels z_i and z_{i-1} between which the temperature gradient is approximately constant may be expressed as:

$$p_i = a_i \cdot p_{i-1} \tag{6.10}$$

where:

$$a_i = \exp\left[\frac{-M}{RT_{i-1}} \cdot g_o \left\{\frac{r_T}{r_T + z_{i-1}}\right\}^2 \cdot \left\{1 - \frac{T_i - T_{i-1}}{2T_{i-1}}\right\}\left\{z_i - z_{i-1}\right\}\right] \tag{6.11}$$

and g_o is the acceleration due to gravity at sea level; M is the molecular weight of the air; p_i is the pressure at the upper level z_i; p_{i-1} is the pressure at the lower level z_{i-1}; r_T is the radius of the Earth; R is the gas constant (for a perfect gas); T_i is the temperature at the upper level z_i; T_{i-1} is the temperature at the lower level z_{i-1}; z_i is the upper level; and z_{i-1} is the lower level.

By comparison with a balloon-borne radiosonde from which a pressure value p is obtained, an initial pressure p_i may be determined for the rocket sounding at the common level z_i, which usually lies near 20 km, or approximately 50 hPa. Similarly, by using the perfect gas law (equation 6.9) the density profile ρ can be determined.

This method is based on step-by-step integration from the lower to the upper levels. It is, therefore, necessary to have very accurate height and temperature data for the various levels.

6.5.2 *Speed of sound, thermal conductivity, and viscosity*

Using the basic data for pressure and temperature, other parameters, which are essential for elaborating simulation models, are often computed, such as:

(*a*) The speed of sound V_s:

$$V_s = \left(\gamma R \frac{T}{M}\right)^{\frac{1}{2}} \tag{6.12}$$

where $\gamma = C_p/C_v$;

(*b*) The coefficient of thermal conductivity, κ, of the air, expressed in W m^{-1} K^{-1} is:

$$\kappa = \frac{2.650\,2 \cdot 10^{-3} \cdot T^{\frac{3}{2}}}{T + 2454 \cdot 10^{\frac{12}{T}}} \tag{6.13}$$

(*c*) The coefficient of viscosity of the air μ, expressed in N s m^{-2} is:

$$\mu = \frac{1.458 \cdot 10^{-6} \cdot T^{\frac{3}{2}}}{T + 110.4} \tag{6.14}$$

6.6 Networks and comparisons

At the present time, only one or two countries carry out regular soundings of the upper atmosphere. Reduction in operational requirements and the high cost associated with the launch operation tend to limit the number of stations and the frequency of launching.

In order that the results obtained by the various existing systems may be uniform, international comparisons have been conducted from Wallops Island, Virginia, in 1968, 1972, and 1977; and from Kourou, French Guyana, in 1973 and 1977 (Finger, *et al.*, 1975; Schmidlin, *et al.*, 1980).

Below 50 km, the data appear reasonably homogeneous. Above that height and up to 65 km certain differences appear in the *in situ* thermistor measurements, but by using compatibility tables prepared during the comparisons it is possible to apply the results for synoptic studies simply by adjusting for systematic differences.

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