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Radiation and lag errors of the F-type Radiosonde

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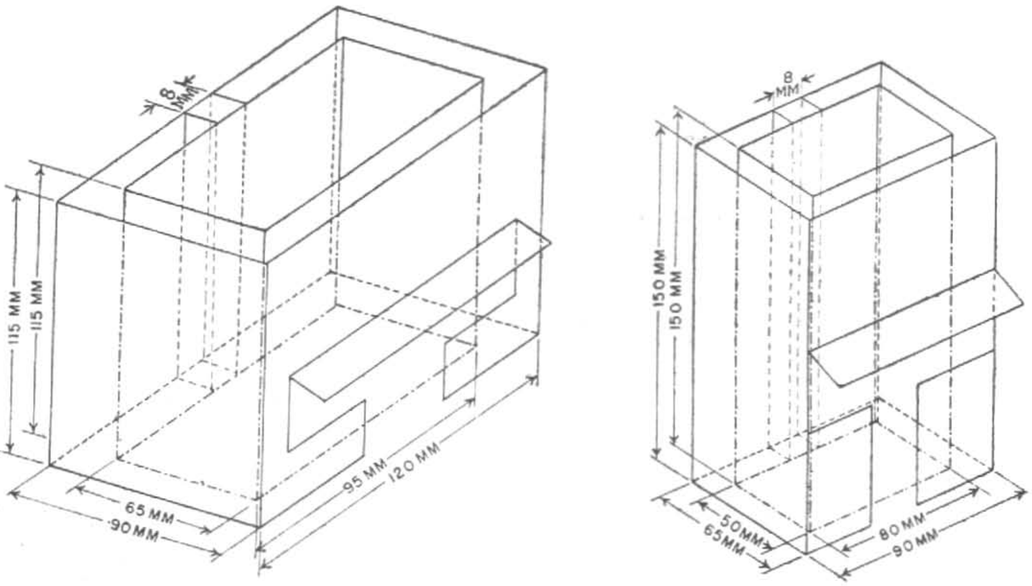
(*Received 13 July 1957*)

1. Introduction

Serious systematic errors in the measurement of upper air temperatures by radiosonde arise from the effect of solar radiation. These are generally small at lower levels due to the forced ventilation of air past the thermometric element, but become appreciable at higher levels on account of the thinness of the air and the resulting progressive reduction in the effective ventilation of the temperature element. The most direct and effective way of minimising radiation and lag errors is to use an element in which the heat exchange with the air is large compared with the radiation absorbed and in which the response to changes of air temperature is reasonably rapid. With very thin cylindrical elements, with diameters below 0·1 mm the effect of solar radiation is negligible even when fully exposed to the sun. The American sonde AN/AMT-4 uses a thin cylindrical thermistor element painted white, and the radiation and lag errors of this sonde are found to be extremely small, even when the element is fully exposed to the sun. Sondes using bimetallic elements necessarily have large radiation errors even with protective radiation shields and it is, therefore, necessary to determine accurately the errors due to lag and radiation under varying conditions, if upper air temperatures are to be determined with any degree of accuracy.

Radiation errors of various sondes in use in other countries have been determined by different methods and corrections are now applied to the observed temperatures in all routine ascents where these sondes are used. Till very recently, except for a short period in 1948, only one night sounding at 2030 IST used to be made at all radiosonde stations in India. With the progressive introduction of double ascents at all stations, with one sounding at 0530 IST and the other at 1730 IST, it became imperative to determine and apply corrections for radiation and lag errors to the radiosonde readings. The third meeting of the C.I.M.O. Working Group on the Comparison of Radiosondes at Zurich in October 1956 (WMO 1956), recommended that, "All Meteorological services, in which radiation corrections are not yet applied should undertake, as a matter of urgency, investigations to determine the radiation corrections, if any, which should be used for their radiosondes". The present paper reports the results of experimental investigations carried out at Poona, to determine the radiation and lag errors of the F-type radiosonde.



(a) (b)

Fig. 1. Radiosonde radiation shields—(a) Routine type and (b) 'Payerne' type

2. Theoretical considerations

(*a*) *Factors affecting radiation error*—The possible effects of radiation and lag on the temperature element of the F-type radiosonde will be more clearly understood by reference to Fig. 1 where the details of the shield are shown. The temperature elements themselves are made of nickel plated and polished steel-invar bimetal (Wilco Highflex 45), 1/8 inch wide and 0·025 inch thick, formed into spirals of one and a half turns each. The shield is made of aluminised paper and is double walled with a spacing of half an inch, the separators being of wood. The arrangement shown in Fig. 1(a) is in use at all F-type radiosonde stations, where two ascents are now taken daily at 0000 and 1200 GMT. Fig. 1(b) shows a very slightly modified shield used during the Second World Comparison of Radiosondes at Payerne in 1956.

The main factors affecting radiation errors are—

(*i*) Direct solar radiation which may reach the element from above directly or after multiple reflection inside the shield, at high solar elevations or due to the swinging of the sonde,

(*ii*) Radiation reaching the element from below in the form of (*a*) Short wave solar radiation reflected from the clouds and the earth's surface and (*b*) Long wave radiation emitted by the clouds, air and the earth's surface,

(*iii*) The shield itself may absorb sufficient radiation to warm appreciably the air flowing through it.

All these three factors may be expected to contribute to the radiation error of the sonde. Since the routine soundings are now made at

0530 and 1730 IST in India and solar altitudes are less than 35° at all F-type radiosonde stations during the early morning and late evening ascents, the effect of (*i*) may be expected to be small. A sonde at the end of a 50 metre suspension normally swings with an amplitude of ±30°. So, at extreme position of the swing, the sun may shine directly on the element and introduce additional errors. Since the shield is made of aluminised paper and the inner surfaces are of white card, the effect of multiple reflection in the shield can be assumed to be insignificant. The effect of (*ii*) and (*iii*) may, therefore, be expected to be more than that of (*i*). Since the shield is short and wide (95 × 65 × 115 mm), the ventilation is fairly efficient and the effect of warming by the air flowing through it may also not be as large as in sondes with narrower shields.

Scrase (1954, 1956) has shown from theoretical calculations that while the effect of the long wave radiation emitted from below is constant for all angles of solar elevation and very small (about 0·5 cal. sec^{-1} 10^{-3} for the temperature element of the British sonde and 8 cal. sec^{-1} 10^{-3}, for the shield, compared with a total rate of absorption of radiation of about 600 cal. sec^{-1} 10^{-3} for the shield and 12 cal. sec^{-1} 10^{-3} for the element), the effect of the short wave radiation reflected from below increases with solar altitude and can be as much as 20 per cent of the direct total radiation at 90° solar angles for the element and 30 per cent for the shield. But at low solar angles the largest contribution to the radiation error of the F-type sonde will be mainly from the warming of the air by the heated shield at great heights.

The magnitude of the radiation error of the sonde will be affected by the effective ventilation, the solar angle and the variation of solar radiation intensity with height. As shown later, the amount of effective ventilation is a product of the rate of ascent v and the air density ρ; and as the air density decreases with height, the rate of ascent remaining more or less constant, the radiation error will increase rapidly at higher levels.

The intensity of solar radiation which reaches the radiosonde at different levels with different solar angles is not constant and allowance must be made for this in applying corrections for radiation errors (Vaisala 1948).

(*b*) *Methods of computing radiation error*—The radiation errors of different sondes have been determined or estimated in various ways in different countries.

(*i*) Vaisala (1941) and Raunio (1951) used the statistical method, by comparing the soundings made in the daytime, with those made at night shortly after sundown. The diurnal variations in temperature were considered negligible above 200 mb for the purpose of the analysis and the difference between the day and night temperatures was taken as the radiation error and expressed as a function of the height angle h of the sun and the radiation error function $S(h)$ as follows—

$$\triangle T = S\,(h)\;.\;I\,(h,\,p)\sqrt{\frac{300}{v_{0\cdot1}}}\left(\frac{100}{p}\right)^{0\cdot852} \qquad (1)$$

where h = true elevation angle of the sun,

p = pressure (mb) at the radiosonde,

$v_{0\cdot1}$ = reduced rate of ascent (in gpm/min), as derived from

$$v_{0\cdot1} = -17220\;\frac{d}{dt}\;p^{\frac{1}{6}}\;,$$

t = time of ascent (min), and

$I\,(h,\,p)$ = relative radiation intensity at the sonde.

(*ii*) Scrase (1954, 1956), using heat transfer theory, has computed the radiation and lag errors of the British Meteorological Office sonde from theoretical considerations. From calculations of the rates of absorption of radiation and of heat loss by forced convection, he has calculated the errors due to direct solar radiation and to radiation reflected and emitted from below, of the ascending sonde for different solar altitudes and for heights up to 30 km.

(*iii*) Laboratory methods have been used in the U.S.A. (Serebreny—), Japan (Hayashi *et al.* 1956, Kitaoka *et al.* 1947), Germany (Gödecke 1949, Ulrich 1949, Abild 1949, Gröber 1953, Rossler 1953, Hinzpeter 1955), and Finland (Rossi 1954) to determine the magnitude of the radiation errors. The principle and methods used are the same, the sonde being irradiated in a wind tunnel with radiation from a light source of known intensity, and the increase in temperature of the sonde being measured at various wind speeds. The errors of the F-type sonde have been determined in the same way.

(*iv*) Relative values of radiation errors have also been calculated from the comparison of sondes with other sondes having little or no radiation errors or the errors of which are accurately known. Rossi (1957) first employed this method to compute the errors of the six sondes which took part in the First International Comparison of Radiosondes at Payerne in 1950. Vaisala (1957) has recently computed the radiation errors of all the 14 sondes, which took part in the Second World Comparison of Radiosondes held at Payerne in 1956. The values are in general agreement with each other and with values determined independently in various countries.

(*c*) *Theoretical basis of experiment*— In order to estimate the radiation errors of the sonde in actual flight from observations in the laboratory, actual flight conditions must as far as possible be reproduced in the laboratory. Since however, the density of air cannot be conveniently varied for the purpose of the study, different rates of ventilation are used, and this as shown below is justified by heat transfer theory.

The equation of heat balance of the thermometer be written as follows—

$$C.\frac{dT}{dt} = Q - H \qquad (2)$$

where, C = heat capacity of the temperature element,

$C.\frac{dT}{dt}$ = net rate of transfer of heat,

Q = rate of absorption of solar radiation by the element, and

H = net rate of transfer from the element by convection.

The effect of conduction to or from the element is relatively small, since the supports of the bimetal coils are of small cross-section. This was confirmed by insulating the support of the bimetal element from the frame of the unit and repeating the experiment. No appreciable difference was noticed in the rate of response.

Now $$H = q\,(T - T_a) \qquad (3)$$

where, q = heat transfer coefficient of the element,

T = temperature of the element, and

T_a = temperature of the air.

Equation (2) can then be rewritten as—

$$T - T_a = \frac{Q}{q} - \frac{C}{q}\cdot\frac{dT}{dt} \qquad (4)$$

The term Q/q is the temperature rise due to radiation. The last term is the lag error due to the thermal inertia of the body, the ratio C/q being the lag coefficient λ.

Neglecting the lag error for the moment,

$$T - T_a = \Delta T = Q/q \qquad (5)$$

i.e., the temperature rise due to radiation can be obtained if we know the rate of absorption of radiation Q and the heat transfer coefficient q. Q can be measured in the laboratory. q can be expressed as—

$$\frac{q}{k} = \text{Const.}\left(\frac{\rho v}{\mu}\right)^n\left(\frac{C_p\cdot\mu}{k}\right)^m \qquad (6)$$

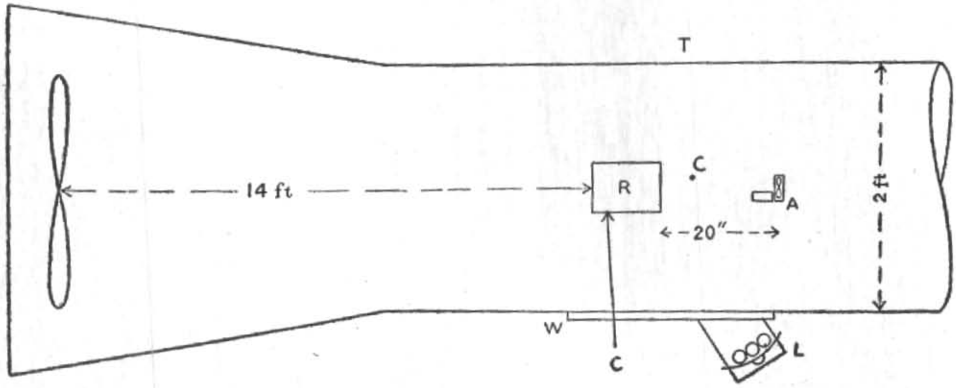


Fig. 2. Experimental arrangement

T — Wind Tunnel
R — Sonde with shield
A — Airmeter
W — Window
C — Thermocouples
L — Set of 3 lamps on adjustable stand

where, k = coefficient of thermal conductivity of the air,

ρ = density of the air,

μ = coefficient of viscosity of air,

v = rate of air flow, and

C_p = specific heat of air at constant pressure.

Since the increment $\triangle T$ is proportional to $(\rho v)^{-n}$ from equations (5) and (6), any change in either ρ or v will produce the same effect in $\triangle T$. Therefore, the temperature increments caused in actual flight by solar radiation at different levels can be produced in the laboratory by changing v and keeping μ and ρ constant. The variation of μ with temperature is small.

3. Experimental arrangement

The experiments were carried out in a wind tunnel, the diameter of the working portion being two feet (Fig. 2). The radiosonde was so mounted in the tunnel that the flow of air past the sonde was as it would be in an actual ascent. The wind speed was measured with a small vane anemometer and checked by a Pitot tube. The source of radiation was three 500 watt incandescent lamps (colour temperature about 3000°K), mounted side by side with a common metallic reflector. They were so arranged that the radiant energy would fall more or less uniformly on the radiosonde. The temperature of the bimetal element was measured by means of a copper-constantan thermocouple and potentiometer. A second thermocouple measured the temperature of the ambient air before and after the lights were switched on and off. The lights were put on for two minutes and the increase in the temperature of the bimetal was carefully measured after attaining a steady state. The experiment was repeated for wind speeds varying from 1–7 mph and for varying angles of incidence of radiation on the instrument. It was not possible to produce stable air flow at wind speeds below 1 mph. Consequently the temperature increments produced by solar radiation at the higher levels, corresponding to ventilation velocities of less than 1 mph have been extrapolated.

The intensity of the radiant energy emitted by the lamps was measured with a solarimetric thermopile and found to be of the order of 1·8 cal. per sq. cm per min., at a distance of 12 inches from the lamps. The temperature increments were multiplied by a suitable factor to correspond to the solar energy. Readings were taken at angles of incidence 0°, 15°, 35°, 45° and 60° above the horizontal position of the sonde and 25° and 80° below.

The following assumptions have been made in the above experiment—

1. That the errors introduced by the differences due to divergences in the non-parallelity of the incident beam and consequent non-uniformity of the illumination of the sonde, are negligible.
2. That the rise in temperature of the bimetal element is proportional to the radiant energy.
3. That the radiation with a colour temperature of 3200°K is equivalent to the solar radiation.
4. That the ventilation velocity is the same as the wind speed past the instrument in the wind tunnel.
5. That variations of the angle of incidence of the solar radiation on the sonde due to its swinging around the vertical, during ascent,and the consequent temperature variations of the sonde are negligible.

4. Results

The results are shown in Fig. 3, where the temperature increments in °C are plotted against the angles of incidence for varying wind speeds. It will be seen that while the increments in temperature increase with angles of incidence for all wind speeds, there is a change in the slope of the curve for angles of incidence grater than 35°—45°. This is probably due to the combined effects of radiation falling directly on the elements and reflection from the sides of the inner shield above this angle.

In Fig. 4, the temperature increments are plotted against ventilation speeds in miles per hour, for angles of incidence varying from –80° to +60°. Fig. 4 (a) refers to the routine shield and Fig. 4 (b) to the Payerne shield. The radiation errors for various pressure levels and for different solar angles were picked out from these curves as follows. Taking the values of air density for the International Standard Atmosphere for different pressure levels and assuming an average rate of ascent of 10 mph above 400 mb, ρv for the pressure levels 400, 300, 250, 200, 150, 100, 70, 50 and 30 mb was calculated. The radiation errors were then picked out from Fig. 4. These are given in Table 1. Table 2 gives the errors due to radiation for the sonde using the modified shield used during the Payerne Comparisons. The two values are of the same order of magnitude. In the last column in Table 2 are given the errors calculated by Vaisala from an intercomparison of the sondes at Payerne of the F-type sonde.

5. Comparisons with other sondes

(*a*) *Comparison with West German and British sondes*—To check the validity of the results obtained for the F-type sonde by the above method, the experiments were repeated in the wind tunnel with the West German Graw 50 sonde (DBR) and the British Meteorological Office sonde. Fig. 5 gives the temperature increments for the DBR, F-type and Kew sondes for different wind speeds. The errors of the F-type sonde will be seen to lie between those of the British and the German. The radiation errors for various angles of incidence and the different standard pressure levels are given in Tables 3 and 4 for the German and British sondes. The values obtained by Vaisala for the two sondes from a study of the 1956 Payerne data are given in the last column for purposes of comparison. The theoretical values obtained by Scrase for the British sonde are also given in Table 4. It will be seen that the values are comparable and that the experimental determination of the radiation errors in the laboratory, in spite of its limitations, gives reasonably good quantitative values of the radiation error.

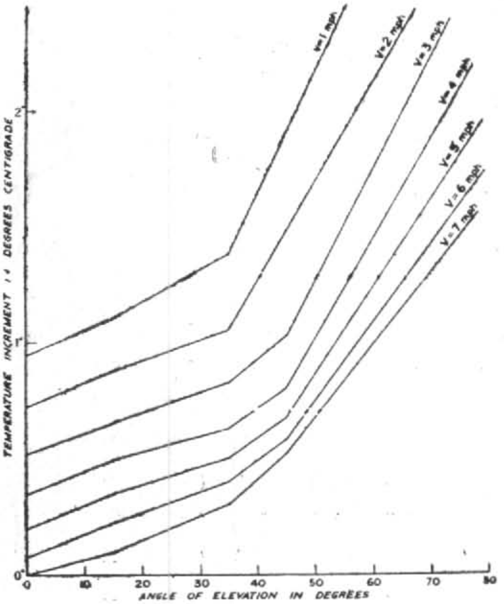


Fig. 3. Variation of temperature increment with solar altitude at different windspeeds

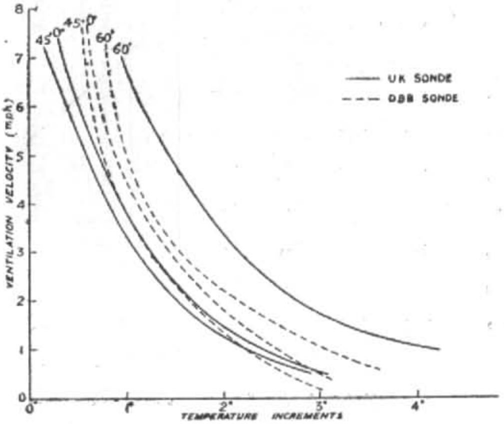
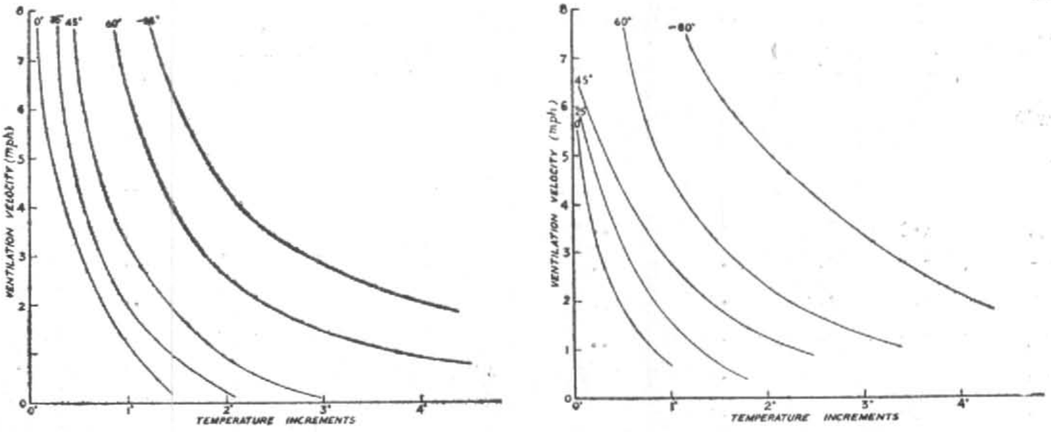


Fig. 5. Variation of temperature increment with ventilation velocity at different solar altitudes for UK and DBR radiosondes



(a) (b)

Fig. 4. Variation of temperature increment with ventilation velocity at different solar altitudes for the F-type radiosonde with (a) Routine and (b) 'Payerne' shields

Table 1

Radiation error of the F-type Radiosonde in °C (with routine shield)

Pressure level (mb)	Angle of solar elevation (degrees)						
	0	+15	+35	+45	+60	−25	−80
400	0·3	0·4	0·5	0·7	1·3	1·9	4·0
300	0·4	0·6	0·6	0·9	1·6	2·3	4·6
250	0·5	0·7	0·7	1·0	1·7	2·6	5·0
200	0·6	0·8	0·8	1·2	2·0	3·2	5·7
150	0·7	0·9	1·0	1·4	2·4	(4·0)	7·0
100	0·9	1·2	1·3	1·7	(3·1)	(5·0)	(>9)
70	1·1	1·4	1·5	2·0	(4·0)	(>6)	..
50	(1·2)	(1·6)	(1·7)	(2·2)	(>6)	..	..
30	(1·3)	(1·7)	(1·9)	(2·5)	..	..	..

The values in brackets are extrapolated

TABLE 2

Radiation error of the F-type Radiosonde in °C (with Payerne shield)

Pressure level (mb)	Angle of solar elevation (degrees)					Values from Payerne data (Vaisala)
	0	+25	+45	+60	−80	
400	0·1	0·2	0·4	1·0	2·2	..
300	0·2	0·4	0·7	1·3	2·8	..
250	0·2	0·5	0·8	1·5	3·1	..
200	0·3	0·6	1·1	(1·8)	3·5	..
150	0·5	0·8	1·4	(2·2)	4·1	..
100	0·7	1·1	1·9	(3·0)	(>5)	2·0
70	0·9	(1·3)	(2·4)	(3·5)	..	2·2
50	1·0	(1·5)	(3·0)	(>4)	..	3·1

The values in brackets are extrapolated

TABLE 3

Radiation error of Graw 50 Sonde in °C

Pressure level (mb)	Angle of solar elevation (degrees)			Values from Payerne data (Vaisala)
	0	45	60	
400	0·9	0·8	1·1	..
300	1·2	1·0	1·3	..
250	1·4	1·2	1·5	..
200	1·6	1·4	1·7	..
150	1·9	1·7	2·2	..
100	2·3	2·0	2·7	1·3
70	2·6	2·3	3·1	1·5
50	2·8	2·5	3·5	2·4
30	3·1	2·7	(3·9)	3·9

The values in brackets are extrapolated

TABLE 4

Radiation error of the British Sonde in °C

Pressure level (mb)	Angle of solar elevation (degrees)			Values from Payerne data (Vaisala)	Computed values (Scrase) 60° elevation angle
	0	45	60		
400	0·8	0·7	1·5	..	1·4
300	1·0	0·9	1·9	..	1·6
250	1·2	1·1	2·1	..	1·8
200	1·3	1·2	2·3	..	2·1
150	1·7	1·5	2·8	..	2·5
100	2·1	2·0	3·4	2·4	3·4
70	2·5	2·3	4·5	3·5	4·4
50	2·8	2·7	(>6)	5·7	5·6
30	(3·1)	(3·2)	..	6·9	8·4

The values in brackets are extrapolated

(*b*) *Analysis of Payerne data*—An analysis of the Payerne data was made following Rossi's method, and the radiation errors of all the 14 sondes which took part in the Second World Comparison of Radiosondes calculated. Though the number of ascents were very few, the day-night differences for each sonde were calculated, without applying radiation corrections for any sonde. The mean five minute interval values in Form 2 were used for the purpose. The results are of the same order as those obtained by Vaisala, who from the same data calculated the errors by taking, not the individual values, but the mean values of all the sondes in the train and plotting these against time for each flight.

6. Observed errors from day and night soundings

Some comparisons of temperatures obtained from soundings immediately before and after sun rise were made to study the actual observed errors. The differences between day and night observations at a number of stations in India were also examined. Observations above the tropopause are very meagre and it has not been possible from the data available to compute the radiation errors by Vaisala's method.

7. Lag errors

The lag in temperature of the element is represented by the last term $C/q \times dT/dt$ in equation (4), C/q being the lag coefficient, usually written as λ. It depends on the shape, size and material of the element and on the thermal properties and mass rate of flow of the air. In the laboratory it can be measured by observing the time required for an initial difference in temperature between the thermometer element and the air to be reduced in the ratio $1/e$. In such conditions,

$$T - Ta = (T_o - T_a)\exp.\left(\frac{-t}{\lambda}\right) \qquad (7)$$

where, $T = T_o$ at $t = 0$. In actual flight, the temperature of the environment changes with time and assuming T to be a linear function of time, it can be shown that—

$$T - T_a = \beta\lambda\left(1 - e^{-t/\lambda}\right) = \beta\lambda \text{ when } t \geqslant \lambda \quad (8)$$

where, β = change of temperature of the environment with time.

When the thermometer element is in the radiation shield, its lag behind the free air temperature will be affected by the lag of the shield itself and by the extent to which the shield heats the air reaching the element. The total lag error will in fact be the result of both. In the present computation the lag of the element in the shield has been taken roughly to be the same as that of the unshielded element and this is reasonably accurate except at the highest levels, as is shown by Scrase's computation.

The lag coefficients were determined in the wind tunnel at wind speeds varying from 1 to 13 mph. Cooling curves were drawn for the different wind speeds and the lag coefficients calculated assuming a rate of ascent of 5 metres per second. The values of the lag coefficients for the different pressure levels and the lag errors, assuming a lapse rate of 0·6°C are given in Table 5.

TABLE 5

Lag error of the F-type Radiosonde

Pressure (mb)	Lag coefficient (sec)	Error in temp. (°C)
1000	7·1	·21
900	7·5	·23
800	7·8	·23
700	8·3	·25
600	8·8	·26
500	9·5	·29
400	10·4	·30
300	11·6	·35
200	13·9	·42
100	19·7	·59

8. Conclusion

Radiation and lag errors of the F-type radiosonde have been determined experimentally in the laboratory for different solar altitudes and for heights up to 30 km. At solar altitudes of about 45°, the radiation errors amount to 1·2, 2 and 2·5°C at 10, 15 and 25 km. Lag errors amount to 0·4 and 0·6°C at 10 and 15 km respectively.

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NOTE—Rossi's (1957) article on 'A laboratory investigation on the radiation error of the radiosonde thermometer' was recently published in *Geophysica*, after the present paper was sent for publication. He has determined in the laboratory the radiation error of not only the Finish sonde but those of all the sondes, except the USA, Dutch and Swiss, which took part in the Payerne comparisons. Values of the radiation errors of the sondes for angles of solar elevation varying from 0-60° for the 100-mb level are given and these are compared with the values computed by Delver and Kuipers (1956), Kitaoka and Suzuki (1956), Perlat and Marc (1956), Malet (1956) and Vaisala (1957) from the Payerne data.