Temperature Error of the Vaisala RS90 Radiosonde

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ABSTRACT

The new F-Thermocap sensor used on the Vaisala RS90 radiosonde is a miniaturized capacitive sensor designed to decrease the solar radiation error and the time lag error that exists with the Thermocap sensor used on the RS80 radiosonde. The heating and response characteristics of the F-Thermocap sensor were evaluated by developing a heat balance model, RS90COR, that calculates the temperature of the sensor relative to the air temperature in various flight environments. The temperature of the F-Thermocap sensor was found to be essentially identical to that of the atmosphere in all nighttime environments. In daytime conditions solar heating of the sensor increases its temperature to slightly above that of the ambient air. The daytime error increases with altitude but remains less than 0.5°C to an altitude of 35 km. The time lag error of the miniaturized sensor is insignificant. The RS90COR modeling results were validated by using model-predicted errors to correct RS90 and RS80 temperature profiles from sondes flown on the same balloon. The corrected profiles agreed, except for a temperature bias of 0.1°–0.3°C that results from a calibration or electronics error in one or both of the sondes. A new source of temperature error in daytime flights of RS80, RS90, and VIZ radiosondes has been discovered that relates to the orientation of the sensor with respect to the impinging solar radiation. This orientation error is smallest in the RS90 sensor.

1. Introduction

A new radiosonde, the RS90, has been introduced by Vaisala Oy as an improvement to the RS80 instrument (Antikainen and Jauheainen 1995). The RS90 sonde contains an improved capacitive temperature sensor, F-Thermocap, and a cyclically heated humidity sensor. The temperature sensor is of much smaller size than that used on the RS80 radiosonde that has been in production since 1981. The reduced size of the F-Thermocap is designed to decrease the radiation error that exists with the RS80 sensor, and to make the time lag error negligible.

The F-Thermocap sensor consists of two 25-μm-thick platinum wires separated by a glass–ceramic dielectric, as shown in Fig. 1. The permittivity of the glass ceramic, and thus the sensor's capacitance, is a strong function of temperature (Turtiainen et al. 1995). The sensor, lead wires, and boom are insulated with a thin polymer coating and then covered with a reflective aluminum film. Operating on the same capacitive principle as the RS80 Thermocap sensor, its diameter is only one-tenth that of the Thermocap sensor.

All radiosondes have a history of temperature errors due to solar and infrared (IR) heating/cooling of the sensor and the time lag of the sensor in responding to a temperature gradient in the atmosphere (Johnson and Mcinturff 1978). For the Vaisala RS80 sonde, temperature corrections have been applied in the data reduction process to compensate for the radiation error. The RS80 correction table was updated in 1986 and again in 1993 to reflect an improved understanding of the magnitude of the radiation errors (Turtiainen 1993). These improvements resulted from the analysis of data collected during International Radiosonde Intercomparisons (Nash and Schmidlin 1987; Ivanov et al. 1991). Although corrections have been applied to remove radiation errors in the RS80 sonde, no correction is included in the Vaisala software to compensate for the time lag of the sensor (Antikainen and Turtiainen 1992). Other radiosondes in common usage, such as the U.S. VIZ sonde, also exhibit radiation and lag errors. For the VIZ sonde *no* radiation or lag corrections are applied in the data reduction software.

The purpose of this study of the RS90 radiosonde is to analyze the new F-Thermocap temperature sensor and determine its accuracy and response characteristics. Because this Vaisala instrument is likely to replace the widely used Vaisala RS80 radiosonde, it is essential that the user have a good understanding of the temperature accuracy and performance characteristics of the RS90 sonde.

The F-Thermocap sensor and its response characteristics are analyzed by developing a heat transfer model that calculates the temperature of the sensor as a func-

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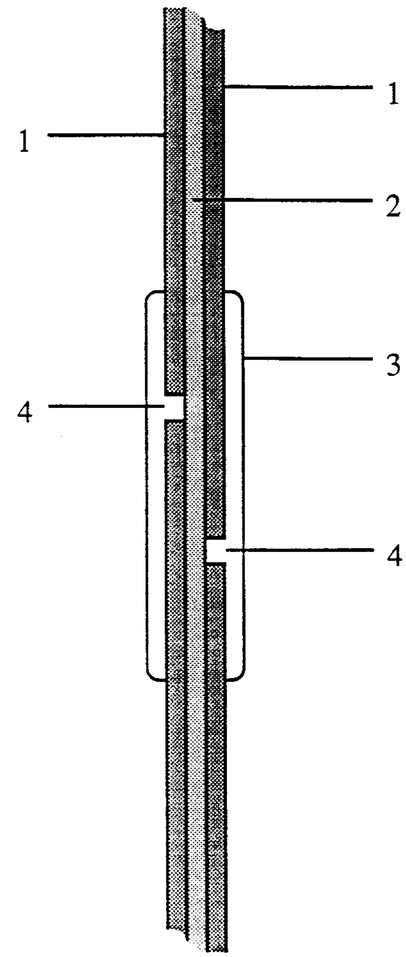

FIG. 1. Longitudinal section of the F-Thermocap: 1 = 25-μm-diameter, platinum wire, 2 = glass ceramic, 3 = glass, 4 = gaps in platinum wire (from Turtiainen et al. 1995).

tion of the temperature of the air and the heat transfer processes that link the air temperature with that of the sensor. Historically, estimates of the error in a radiosonde temperature sensor measurement due to solar heating, convection, IR cooling, and the time lag of the sensor were based on assumed solar and IR fluxes, using measured or estimated sensor emission properties and dimensions (Vaisala 1964; Ballard and Rubio 1968; Talbot 1972). These calculations provided mean estimates of the error in the temperature of the sensor but could not be used to estimate the temperature error for an individual flight because the solar and IR fluxes were only generic values not representative of an actual flight condition. The first model that calculated the temperature error for an individual radiosonde flight, VIZCOR, was developed for the VIZ radiosonde rod thermistor (Luers 1990). VIZCOR utilized the air force's LOWTRAN7 atmospheric transmission code to specify the radiational fluxes at each radiosonde altitude as a function of the atmospheric conditions prevalent at the time of the flight. Surface temperature, cloud cover, the atmospheric temperature profile (as measured by the sonde), solar angle, etc. were LOWTRAN7 inputs that corresponded to the actual sonde flight conditions. The calculated LOWTRAN7 radiational flux served as input to the heat balance equation for the sensor. The heat balance equation was solved for the temperature of the sensor. The difference between the air temperature and that of the sensor determined the sensor temperature error.

A slightly different approach was developed by McMillin et al. (1992) to estimate the VIZ temperature error for use with satellite temperature retrieval comparisons (McMillin et al.1988). McMillin and Uddstrom described a simplified heat balance equation that did not include the temperature lag term nor the heat conduction through the lead wire to the sensor. They also assumed a mean atmospheric transmission function for solar radiation and used the Elsasser solution for the IR transmission function. An assumed angular distribution of IR radiation was required to calculate absorption on the cylindrical surface of the temperature sensor. The model also required an estimate of the downwelling IR radiation above the sensor that was utilized in the model as a fitting parameter so as to make model results agree with those measured by the NASA multithermistor reference radiosonde.

Most recently the National Climatic Data Center, as part of the Comprehensive Aerological Data Set (CARDS) program has supported the development of temperature correction models for nine other radiosondes used throughout the world since the mid-1960s. The CARDS program is developing a database of raw, quality-controlled, and temperature-corrected radiosonde profiles suitable for use in climate studies (Eskridge et al. 1995). Using the same methodology developed by Luers (1990) for the VIZ sonde, heat balance models have been developed and validated for the Vaisala RS80 Thermocap temperature sensor (Luers and Eskridge 1995), the VIZ rod thermistor (Luers 1990), and temperature sensors used on Russian, Chinese, and Japanese radiosondes (Luers 1996). Because the solar and IR radiation changes with a changing environment, the LOWTRAN7 atmospheric transmission code (Kneizys et al. 1988) is used to predict the irradiation received by the sensor under a specified set of environmental conditions. This allows calculation of the temperature of the sensor, which then can be compared to the ambient air temperature under any environmental condition. The accuracy of the temperature correction models developed for the RS80 and VIZ radiosondes has been established by comparison with each other and with the NASA multithermistor reference radiosonde when all radiosondes are flown on the same balloon. The NASA multithermistor radiosonde utilizes three thermistors, each having different solar and IR absorption properties (Schmidlin 1992). Using the temperature of each sensor in a system of three heat balance equations allows the system to be solved for the unknowns: solar radiation, IR radiation, and atmospheric temperature. Agreement between the multithermistor temperature profile and the VIZCOR and RS80COR corrected profiles, when all radiosondes were flown on the same balloon, was used to validate the accuracy of the VIZCOR and RS80COR models. The models have been shown to be accurate within ±0.2°C (Luers and Eskridge 1995).

2. The RS90COR model

A temperature correction model, RS90COR, has been developed for the F-Thermocap sensor in the same manner used to develop the RS80COR model for the Vaisala RS80 sonde. The heat balance equation can be written as

$$mc\, dT_s/dt = q_{\rm abs} - \sigma\varepsilon_s A T_s^4 - AH(T_s - T) + 2\pi r_w^2 k_w\, dT_w/dl|_{l=0}, \qquad (1)$$

where

- A surface area of sensor (0.0063 cm^2),
- H convective heat transfer coefficient of sensor (cal s^{-1} cm^{-2} K^{-1}),
- T air temperature (K),
- T_s temperature of sensor (K),
- T_w temperature of wire (K),
- c specific heat capacity of the sensor (0.12 cal g^{-1} K^{-1}),
- k_w thermal conductivity of each lead wire (0.17 cal s^{-1} cm^{-1} K^{-1}),
- l length of each lead wire (cm),
- m mass of sensor (0.0001 g),
- r_w radius of lead wires (0.0065 cm),
- t time (s),
- ε_s emissivity of sensor ($\varepsilon = 0.02$), and
- σ Stefan–Boltzman constant (1.354×10^{-12} cal s^{-1} cm^{-2} K^{-4}).

The term on the left-hand side of the equation represents the rate of change of the temperature of the sensor, or time lag term, and $q_{\rm abs}$ accounts for the solar and IR radiation absorbed by the sensor. This term is calculated as

$$q_{\rm abs} = \int_\lambda \int_\theta \int_\phi I(\lambda, \theta, \phi)\alpha A(r, l, \theta)\, d\lambda\, d\theta\, d\phi,$$

where $I(\lambda, \theta, \phi)$ is the intensity of radiation of wavelength λ irradiating the sensor from the direction whose azimuth angle is ϕ and elevation angle is θ; $\alpha = 0.15$ is the laboratory-measured absorption coefficient for the aluminum coating used on the F-Thermocap sensor weighted over the solar spectrum, and $A(r, l, \theta)$ is the average presented area of the F-Thermocap sensor during one revolution of the sonde as viewed from the elevation angle θ. The average presented area is determined mathematically from the measured length and cross-sectional area of the aluminum-coated cylindrically shaped sensor (Luers 1989). The intensity of radiation $I(\lambda, \theta, \phi)$ is derived by running the LOWTRAN7 program under the specified environmental conditions. The integration is performed over the solar and IR spectrum from 0.25 to 28 μm.

The second term on the right side of Eq. (1) is the rate of IR emissions from the sensor. The third term is the rate of heat convection between the sensor and the air, and the final term is the rate of heat conduction to the sensor through the lead wires that attach to the sensor. The conduction term requires a knowledge of the temperature gradient in the lead wire at its attachment point to the sensor. This is established by solving a similar heat balance equation for the lead wire (see Luers 1989). The sensor and lead wires' dimensions, absorption and emission properties, and convective heat transfer coefficient are known, or are laboratory-measured quantities. The atmospheric temperature is assumed known, and Eq. (1) is solved for the temperature of the sensor. The difference between the sensor temperature and that of the atmosphere is the sensor temperature error.

Although the equations used in the RS90COR model are the same as those for the RS80, the dimension of the sensor and lead wires and the heat transfer coefficients differ. Because both the RS90 F-Thermocap and the RS80 Thermocap have the same aluminum coating over the sensors and mount, the solar and IR absorption properties are the same.

3. Sensitivity analysis

a. Night flight

A sensitivity analysis was conducted on the F-Thermocap temperature sensor, using the RS90COR model to simulate its performance under various environmental conditions. The reference dataset for the sensitivity analysis was the midlatitude spring standard atmosphere profiles of temperature, pressure, and trace constituents (Mcclatchey et al. 1972); a surface temperature of 280 K; clear sky; the LOWTRAN7 rural 5-km visibility tropospheric aerosol profile and background stratospheric aerosol profile; vegetation ground cover; and a balloon rise rate of 5 m s^{-1}.

The reference dataset represents a moderate atmospheric environment in that the extreme atmospheric conditions that occur in nature will be on either side of the reference profiles. In the sensitivity analysis the individual variables that influence the error in the radiosonde temperature sensor are perturbed about the reference values with a magnitude sufficient to include the extreme events that occur. For example, the reference midlatitude spring temperature profile is varied by ±20°C at all altitudes to encompass the range of upper-air temperature profiles likely to occur in nature. Since the error in the radiosonde temperature at a given altitude is (except for the lag component) dependent only

TABLE 1. RS90 temperature error for night reference dataset (T_{ref}) and change in temperature error ($T - T_{ref}$) from varying each sensitivity analysis parameter as indicated.

Night	Reference	Rise rate RR = 3 m s^{-1} RR = 7 m s^{-1} (reference = 5 m s^{-1})	No aerosols (reference = rural, 5 km visibility)	Surface snow (reference = vegetation)	Surface temperature T_{surf} = 265 T_{surf} = 310 (reference = 280 K)	Clouds 100% at 5 km (reference = no clouds)	Cirrus 3-km thick at 7 km (reference = no cirrus)	Background temperature $T + 20°$ $T - 20°$ (reference = midlatitude spring)	Humidity RH = 90% 5 km (reference = 20% RH)
SL	Temperature error for reference dataset	$T - T_{ref}$	$T - T_{ref}$	$T - T_{ref}$	$T - T_{ref}$	$T - T_{ref}$	$T - T_{ref}$	$T - T_{ref}$	$T - T_{ref}$
5 km	−0.00	0.00 0.00	0.00	0.00	0.00 0.00	0.00	0.00	0.00 0.00	0.00
10	−0.00	0.00 0.00	0.00	0.00	0.00 0.00	0.00	0.00	0.00 0.00	0.00
15	−0.00	0.00 0.00	0.00	0.00	0.00 0.00	0.00	0.00	0.00 0.00	0.00
20	−0.00	0.00 0.00	0.00	0.00	0.00 0.00	0.00	0.00	0.00 0.00	0.00
25	−0.01	0.00 0.00	0.00	0.00	0.00 0.00	0.00	0.00	0.00 0.00	0.00
30	−0.02	0.00 0.00	0.00	0.00	0.00 0.00	0.00	0.00	−0.01 +0.01	0.00
35	−0.02	0.00 0.00	0.00	0.00	0.00 0.00	−0.01	−0.01	−0.01 +0.01	0.00

on the environmental conditions at that altitude, it is not necessary to vary the shape of the vertical profiles in the sensitivity analysis. Thus, the sensitivity analysis need only use the limiting range of each variable that occurs in nature. The one variable that does relate to the shape of a profile is the temperature gradient that influences the lag term. This parameter is adjusted in the sensitivity analysis through varying the balloon rise rate. A change in rise rate reflects both the influence of a changing temperature gradient and a change in the convective heat transfer to the sensor. The range of variability in rise rate used in the sensitivity analysis encompasses both balloon rise rate and temperature gradient variability. Thus, the sensitivity analysis is performed using a reference dataset and varying the sensitivity analysis parameters to include extreme environmental conditions so that nearly any atmospheric–environmental profile that occurs in nature will fall within the range of the sensitivity analysis.

Two additional comments should be made about the sensitivity analysis. The first is that the LOWTRAN7 atmospheric transmission model allows for many other input parameters to be varied that have not been included in our discussion of the sensitivity analysis. Minor constituents such as ozone, carbon dioxide, etc.; stratospheric and marine aerosol profiles; surface vegetation, etc. all can be varied in the LOWTRAN7 input and their influence on the radiation environment determined. This assessment, however, has already been performed in the analysis of other type radiosonde sensors (VIZ, RS80, and others) with no discernible influence on any temperature sensor found. Thus, the sensitivity analysis parameters addressed in this research are only those parameters for which some influence on the radiosonde temperature error is possible. A second note is that the sensitivity parameters are essentially independent of one another and influence the temperature error in an approximate linear manner. This was established in the development of a linear regression model to estimate the temperature error of the VIZ thermistor as a linear combination of sensitivity analysis parameters (Luers 1994). Thus, varying of each sensitivity analysis parameter individually, while the remaining parameters retain their reference profile values, is a valid method of isolating an individual influence on the temperature error of the radiosonde sensor.

Using the reference dataset to specify the environment, the temperature of the RS90 sensor was calculated at all heights using the RS90COR model. The reference dataset, the sensitivity analysis parameters, and their incremental values are shown in Table 1. The difference between the sensor temperature and that of the atmosphere is the reference dataset temperature error T_{ref} in Table 1. The temperature error for the reference nighttime dataset is less than three-hundredths of a degree at all altitudes. This negligible error includes the influence of sensor lag. Because the mass and dimensions of the sensor are very small, little heat transfer is required to bring the entire mass of the sensor into thermal equilibrium with its surroundings. When each sensitivity analysis parameter is varied, the temperature error is recalculated and the incremental change $T - T_{ref}$, as shown in Table 1, is determined. All of the environmental parameters tested, as well as changes in the balloon rise rate, failed to significantly affect the temperature of the sensor. The reason for the insensitivity to

TABLE 2. RS90 temperature error for daytime reference dataset (T_{ref}) and change in temperature error ($T - T_{ref}$) from varying each sensitivity analysis parameter as indicated.

Altitude (km)	Reference	Rise rate RR = 3 m s^{-1} RR = 7 m s^{-1} (reference = 5 m s^{-1})	Solar absorbtivity α = 0.11 (reference = 0.15)	No aerosols (reference = rural, 5 km visibility)	Surface temperature T_{surf} = 265° T_{surf} = 310° (reference = 290 K)	Clouds 100% at 5 km (reference = no clouds)	Cirrus 3-km thick (7 km base) (reference = no cirrus)	Background temperature T + 20° T − 20° (reference = midlatitude spring)	Humidity 90% RH to 5 km (reference = 20% RH)
	T_{ref}	$T - T_{ref}$	$T - T_{ref}$	$T - T_{ref}$	$T - T_{ref}$	$T - T_{ref}$	$T - T_{ref}$	$T - T_{ref}$	$T - T_{ref}$
SL		0.00			0.00			0.00	
	0.03	+0.03	−0.03	0.02	0.00	—	−0.03	0.00	−0.01
		0.02			0.00			0.00	
5	0.09	−0.02	−0.04	0.02	0.00	0.01	−0.08	0.00	0.00
		0.03			0.00			−0.00	
10	0.14	−0.02	−0.05	0.02	0.00	0.00	−0.02	0.00	0.00
		0.04			00			−0.01	
15	0.18	−0.03	−0.06	0.03	0.00	0.01	−0.02	0.00	0.00
		0.05			00			−0.01	
20	0.25	−0.04	−0.08	0.04	0.00	0.02	−0.02	0.00	0.00
		0.05			00			−0.01	
25	0.32	−0.04	−0.10	0.05	0.00	0.02	−0.02	0.01	−0.01
		0.05			00			−0.01	
30	0.39	−0.04	−0.12	0.05	0.00	0.02	−0.03	0.01	−0.01
		0.04			00			−0.02	
35	0.42	−0.04	−0.14	0.06	0.00	0.02	−0.04	0.02	−0.01

environmental parameters results from the low emissivity property of the aluminum sensor coating. The emissivity of the aluminum coating has been measured to be $\varepsilon = 0.02$ by a commercial laboratory (DSET Laboratories, Inc. 1990). With this low emissivity, only minimal IR radiation is absorbed or emitted from the surface. Thus, the RS90 sensor provides excellent measurements of the nighttime temperature profile under all environmental conditions, balloon rise rates, and atmospheric temperature gradients (lag error). The difference between the sensor temperature and that of the air in which it is immersed is always considerably less than 0.1°C.

b. Day flight

The reference dataset for the daytime sensitivity analysis is the same as for the nighttime analysis except for the surface temperature that is increased to 290 K, and a solar elevation of 30° is assumed. The temperature error for the daytime reference dataset is shown as column 2 in Table 2. The temperature error increases with altitude reaching a maximum of 0.42°C at 35 km. The incremental change, $T - T_{ref}$, resulting from a change in environmental, sonde, and balloon parameters (other than solar angle) is also shown in Table 2. None of the environmental parameters, even cloud cover, produces a change in the temperature of the sensor by even 0.1°C. Likewise, a variation in the balloon rise rate between 3 and 7 m s^{-1} produces a change in the temperature of no more than 0.05°C. The sensitivity analysis also consisted in changing the solar absorptivity of the sensor from $\alpha = 0.15$ to $\alpha = 0.11$. Even though the laboratory-measured solar absorptivity of the aluminum coating is $\alpha = 0.11$, the laboratory measurements were made on a coated flat plate with a near vertical radiation impingement angle. For a cylindrically shaped metal surface, the solar absorption depends on the impingement angle, with more absorption occurring at low grazing angles. For this reason, the measured value of α was increased to $\alpha = 0.15$, based upon both theoretical geometric considerations as well as validation studies with the multithermistor radiosonde that found $\alpha = 0.15$ to provide best agreement. The sensitivity analysis determined the influence of α by running the model with the lower value. The resulting change in the temperature error was less than 0.15°C at all altitudes. If the value of α used in the model to derive the RS90 temperature correction is in error, then this error would essentially consist of a bias error that changes with height by the amount indicated. However, as seen from the results of the sensitivity analysis the magnitude of this bias is very small.

Since none of the environmental or balloon parameters (solar angle excluded) significantly affect the temperature of the sensor, it is not necessary that their influence be included in deriving a daytime temperature correction table for the RS90 radiosonde. The error resulting from neglecting these influences should cumulatively be no more than 0.1°C.

c. Solar angle

The influence of solar elevation angle on the temperature of the sensor is shown in Table 3. In place of the 30° solar angle used in the reference dataset, other

TABLE 3. RS90 temperature error vs solar elevation angle.

Altitude (pressure)	Night	−5°	−3°	0°	3°	5°	10°	20°	30°	45°	60°	80°
SL		0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.03	0.04	0.05	0.06
5 km (540 mb)	0.00	0.00	0.02	0.00	0.05	0.06	0.07	0.09	0.09	0.09	0.09	0.09
10 km (265 mb)	0.00	0.00	0.01	0.07	0.10	0.11	0.13	0.14	0.14	0.13	0.13	0.14
15 km (121 mb)	0.00	0.00	0.02	0.12	0.15	0.16	0.17	0.18	0.18	0.17	0.17	0.18
20 km (55 mb)	0.00	0.00	0.10	0.18	0.22	0.23	0.25	0.25	0.25	0.24	0.24	0.24
25 km (25 mb)	−0.01	0.00	0.16	0.26	0.30	0.31	0.32	0.32	0.32	0.30	0.30	0.31
30 km (12 mb)	−0.01	0.01	0.23	0.34	0.37	0.38	0.39	0.40	0.39	0.37	0.37	0.37
35 km (5.7 mb)	−0.02	0.13	0.30	0.39	0.40	0.41	0.42	0.42	0.42	0.39	0.39	0.40

solar elevation angles from −5° to 80° were substituted and the resulting RS90COR temperature error calculated. The temperature error profile with respect to altitude (or pressure) is nearly constant for all solar elevation angles above 3°. Because of the 45° tilt of the radiosonde boom that holds the cylindrical temperature sensor, the average exposed area of the sensor to solar radiation during a sonde revolution does not vary significantly with solar angle. For this reason the temperature error profiles remain nearly constant for all solar angles above 3°. At solar angles below 3° the sun's radiation passes through a considerable amount of atmosphere before arriving at the sensor. The absorption and scattering by the atmosphere decreases the amount of sensor heating. When the solar elevation reaches −5° the sensor is only irradiated at high altitudes, and the sensor heating, even at 30 km, is insignificant. Thus, the primary change in RS90 temperature error with solar angle occurs between solar elevation angles of −5° and +3°. If the solar angle is accurately calculated versus altitude throughout an RS90 radiosonde flight, then it should be possible to correct the measured temperature, using Table 3 to an accuracy well within ±0.1°C. The overall accuracy of RS90 corrected daytime temperature measurement under any environmental conditions should also be accurate to ±0.1°C. That is, the corrected temperature of the sensor is within ±0.1°C of the temperature of the atmosphere. This does not imply that the ground-recorded temperature is of the same accuracy, since other sources of error may be present. This does imply, however, that the sensor itself can provide an excellent measurement of the atmospheric temperature.

4. Analysis of Tenerife flights

A series of multiradiosonde launches, conducted at Tenerife in June 1995, were used to evaluate the temperature error model developed for the RS90 radiosonde and to verify the performance of the RS90 sonde. In June the sun nearly reaches its zenith in Tenerife, thus allowing the study of radiation errors at all angles up to 85°. Each balloon launch contained three radiosondes: an RS90, an RS80, and a third sonde that was either an experimental RS90 sonde with a titanium-coated F-Thermocap or a standard F-Thermocap RS90 sonde. Initial comparisons were made between sensors that should have provided identical results. For example, four flights contained two RS90 sondes and thus the difference between the measured temperatures is an indication of the error in the system. These flights with identical sensors uncovered easily observed temperature biases of up to 0.2° at all altitudes. A similar evaluation was made between the nighttime temperature measurements from the RS90 and RS90B (titanium coated) sondes. Both the titanium and aluminum sensors have very low emissivity and thus are essentially unaffected by IR radiation. Their nighttime temperature profiles should be identical except for random errors. In viewing four night flights, the titanium and aluminum sensors are often biased by 0.1° to 0.3°. Since the sign of the bias between the two different sensors is not consistent, it is unlikely that this results from a difference in the IR absorption properties of the two sensors. Thus, it appears that there can be up to a 0.3° bias in a sensor measurement at all altitudes due to some external factor such as calibration or electronic circuitry.

a. *Night flights*

The sensor temperature error for both the RS80 and RS90 sondes were calculated for six nighttime Tenerife flights using the RS90COR and RS80COR models. The models were run on each radiosonde using as input the environmental conditions for that flight (e.g., measured temperature profile, surface temperature, cloud cover, rise rate, etc.). The temperature error profiles are shown for night flight T1 in Fig. 2. The nighttime error for the RS80 sonde is essentially due to sensor lag. The high-frequency fluctuations in the profile results from lag error due to small-scale temperature gradients in the atmosphere, while the bias reflects the background lapse rate of the atmosphere. The lag error is positive up to about 15 km, indicating the sensor is warmer than the atmosphere in which it is embedded. At higher altitudes the atmospheric temperature gradient changes sign and the temperature error becomes negative. For the RS90 sonde the total error, including the sensor lag, is essentially zero at all altitudes. Corrections to remove the error have been applied to each sonde, and the difference in corrected temperatures between the RS80 and RS90 sondes is shown in Fig. 3. Similar calculations for other night flights are shown in Figs. 4 and 5. Ideally, the

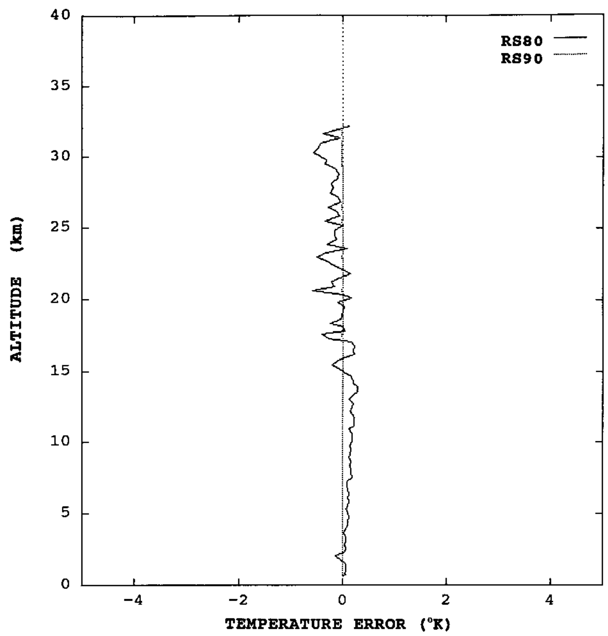

FIG. 2. Temperature error calculated by RS80COR and RS90COR for the night flight T1.

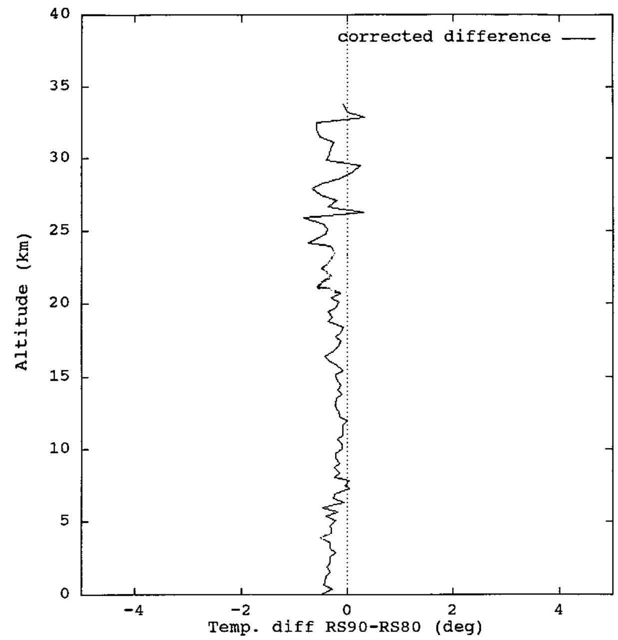

FIG. 4. Difference between the corrected temperature profiles for night flight T2 after the RS80COR and RS90COR corrections have been applied.

differences should oscillate about zero, with the oscillations due to noise in the data. As seen in the figures there appears to be a bias of about 0.3° between the two different sondes, with the RS90 sonde providing the colder temperatures. This bias appears to be constant with altitude and is in all six night flights. An attempt was made to explain this bias as perhaps not real, but rather due to inaccuracy in specifying sensor or environmental parameters used in the heat balance models. However, errors in environmental or sonde parameters, such as heat transfer coefficient, emissivity or absorp-

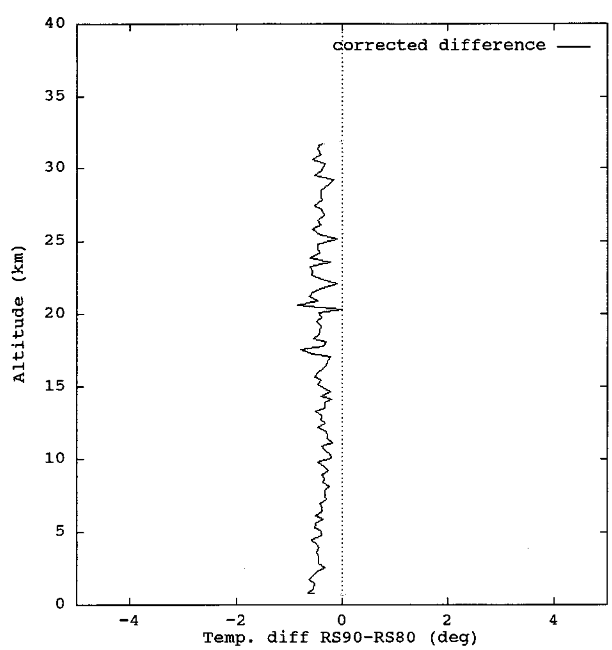

FIG. 3. Difference between the corrected temperature profiles for night flight T1 after the RS80COR and RS90COR corrections have been applied.

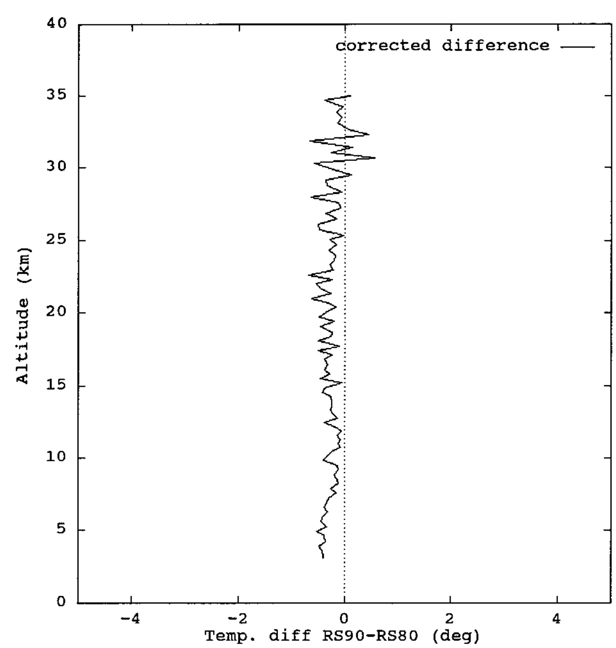

FIG. 5. Difference between the corrected temperature profiles for night flight T3 after the RS80COR and RS90COR corrections have been applied.

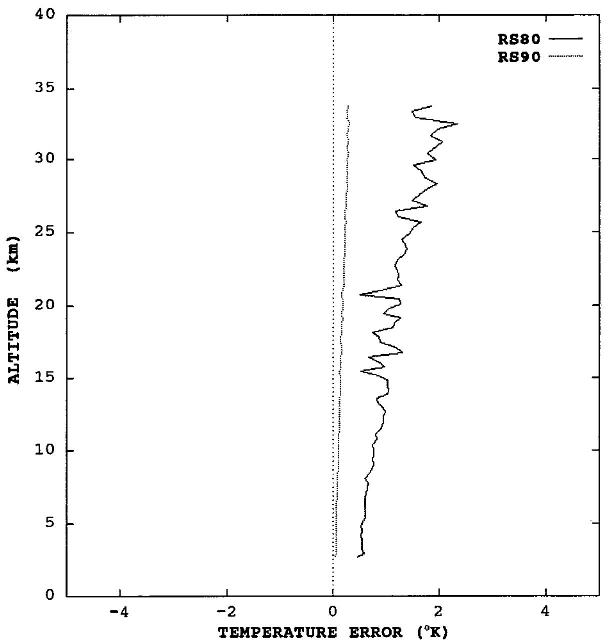

FIG. 6. Temperature error calculated by RS80COR and RS90COR for the day flight T4 with cloud cover and solar elevation 85°–65°.

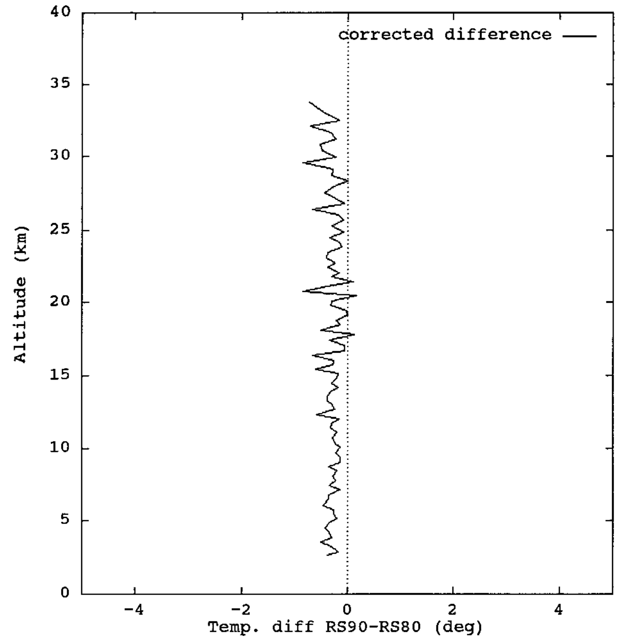

FIG. 7. Difference between the corrected temperature profiles for day flight T4 after the RS80COR and RS90COR corrections have been applied.

tivity of sensor, lag term parameters, cloud cover, rise rate etc., cannot produce a bias error in temperature that is constant with altitude. Because of the heat transfer characteristics of the atmosphere, temperature errors always vary in magnitude as the altitude changes. Thus, this small error of about 0.3° is believed to be a calibration of electronics error in either the RS90 or RS80 sonde.

b. Day flights

Approximately 10 Tenerife day flights were analyzed to determine the performance of the RS80 and RS90 sondes under various solar insolation conditions. Figure 6 shows the RS80COR and RS90COR model calculated temperature errors for the day flight T4. The solar elevation angle for this flight varied from 85° at launch to 65° at burst. The RS90 error is small, and consistent with Table 2, increasing to about 0.4°C at the top of the flight. For the RS80 sonde the temperature error is considerably larger increasing to 2.0°C above 30 km. This error profile includes the influence of reflected solar radiation from a cloud deck at 2 km. These measured profiles were then corrected and the difference between corrected profiles calculated. If the corrected difference profiles are near zero, one has confidence that the profiles are accurate and that the temperature correction models are performing properly. Figures 7–9 show the difference in the corrected RS80 and RS90 temperatures from flight T4, and from flights at other solar elevations. The corrected difference profiles for all flights are small. The random point-to-point variability in the profiles is system noise and is not of concern to this analysis. What one does observe in all 10 flights analyzed, however, is a nearly constant bias of about 0.1° to 0.3° with altitude. In all flights the corrected RS90 temperature is colder. This bias is consistent with that previously found in the

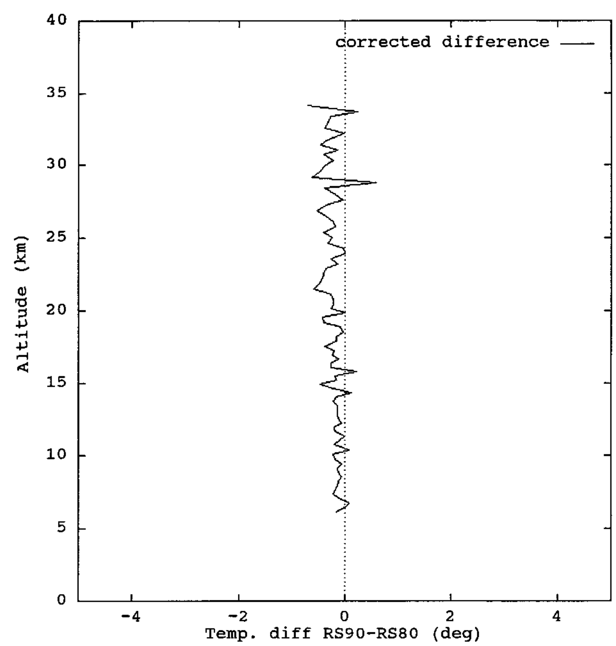

FIG. 8. Difference between the corrected temperature profiles for day flight T5 with Ac/As clouds and solar elevation 22°–2° after the RS80COR and RS90COR corrections have been applied.

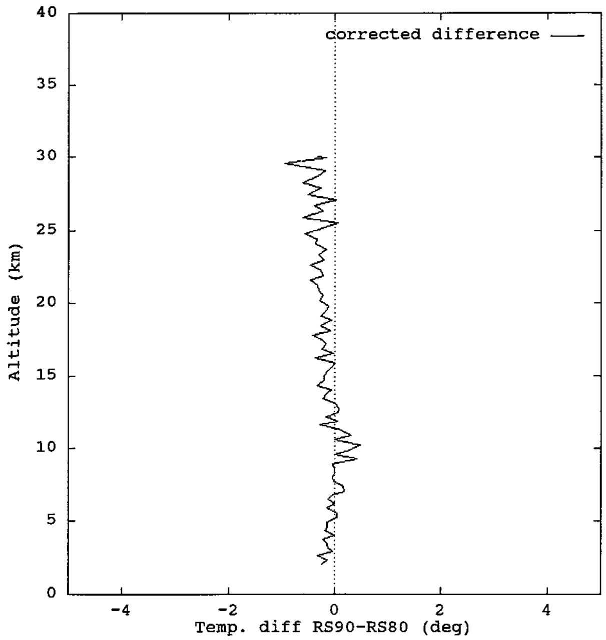

FIG. 9. Difference between the corrected temperature profiles for twilight flight T6, with solar elevation 15° to −3° after the RS80COR and RS90COR corrections have been applied.

analysis of nighttime flights. Thus, it appears that there is some sonde calibration or electronics problem that is causing a small bias in all flight data.

5. Sensor orientation error

The September 1995 launch program conducted at Wallops Island, Virginia, served as an international comparison of VIZ, RS80, RS90, and other radiosonde sensors. Even though the primary purpose of this launch program was to compare humidity sensors, the test series also provided temperature data at a rapid sample rate of 2 s. Analysis of the 2-s data has led to the identification of a previously undetected source of error in all radiosonde measurements.

The influence of solar radiation on the temperature error depends upon the orientation of the sensor with relation to the sun. The F-Thermocap, Thermocap, and VIZ sensors are cylindrical-shaped sensors whose exposure to solar radiation depends upon the impingement direction of the solar radiation. A sensor experiences maximum solar radiation when the sun's rays come from a direction perpendicular to the axis of the cylinder. Minimum exposure occurs when the sun's rays are parallel to the axis and thus irradiate only the ends of the cylinder. As the sensor rotates while rising through the air, its exposure to solar radiation varies considerably between the maximum and minimum extremes. At low altitudes the radiosonde rotation rate has been visually observed at several revolutions per minute, which allows the orientation effect to be removed by averaging data over a 1-min period (or longer). However, analysis of the individual Tenerife temperature profiles, at a 2-s sample rate, from the RS80, RS90, and VIZ radiosondes freely suspended below a single balloon, gives reason to believe that at higher altitudes the balloon rotation rate may slow to less than a revolution per minute, making the temperature of the sensor fluctuate because of its orientation. This orientation influence is observed by comparing temperature profiles from night and day flights. Figure 10 shows the difference in temperature profiles, as referenced to the RS90 sensor, for a VIZ, two RS80s, and an RS90 sensor all flown on night flight W1 balloon. The VIZ and RS80 sensors were differenced from the RS90 because the latter best represents the true nighttime temperature. The data are plotted at 10-s intervals to observe the finescale structure in the temperature data. The bias seen in the VIZ sensor (Fig. 15) is due to IR cooling, reflecting its high emissivity ($\varepsilon = 0.86$). The two RS80 sensors show excellent repeatability and exhibit the same temperature trends observed by the VIZ sensor. These temperature trends reflect real temperature variations in the atmosphere as seen by each sensor. Other night flights show the same consistencies. On the other hand, the situation is different for day flights in which the solar heating depends on the orientation of the sensor. Figure 11 shows temperature difference profiles (referenced to RS90) from a noon flight W2 at an altitude above 25 km. Note that even the two RS80 sensors do not agree on high-frequency temperature oscillations, nor do they agree with the VIZ oscillations. Several regions can be seen in which one RS80 sensor indicates a temperature warmer than the other by 1°C, and less than 2 min later the same sensor becomes more than 1°C colder. This obviously is not real atmospheric temperature variation, nor is it likely to be random temperature error in the sensor since it does not occur in the nighttime flights. Thus, there is strong reason to believe that slow rotation of the balloon provides a changing solar irradiation of each sensor that makes the temperature of an individual sensor fluctuate by up to 1°C (for the RS80) during a single revolution. The oscillations from the different sensors are not in phase because each radiosonde, with sensor, is attached to the balloon in a manner that allows it to rotate free from the other radiosondes.

This orientation error is less at lower altitudes where enhanced convective cooling makes the radiation error smaller, and the balloon rotation rate is believed to be more rapid. Figure 12 shows the temperature difference profiles for the same noon flight W2 at a lower altitude ($\approx$15 km). Although there is still more variability in the temperature profiles from the two RS80 sensors than for the night flight, the magnitude of the differences is generally 0.5°C or less. Both the VIZ and the two RS80 sensors show the same general temperature structure, indicating real atmospheric temperature variations.

The sensor orientation error could be alleviated by designing a spherical sensor whose presented area is

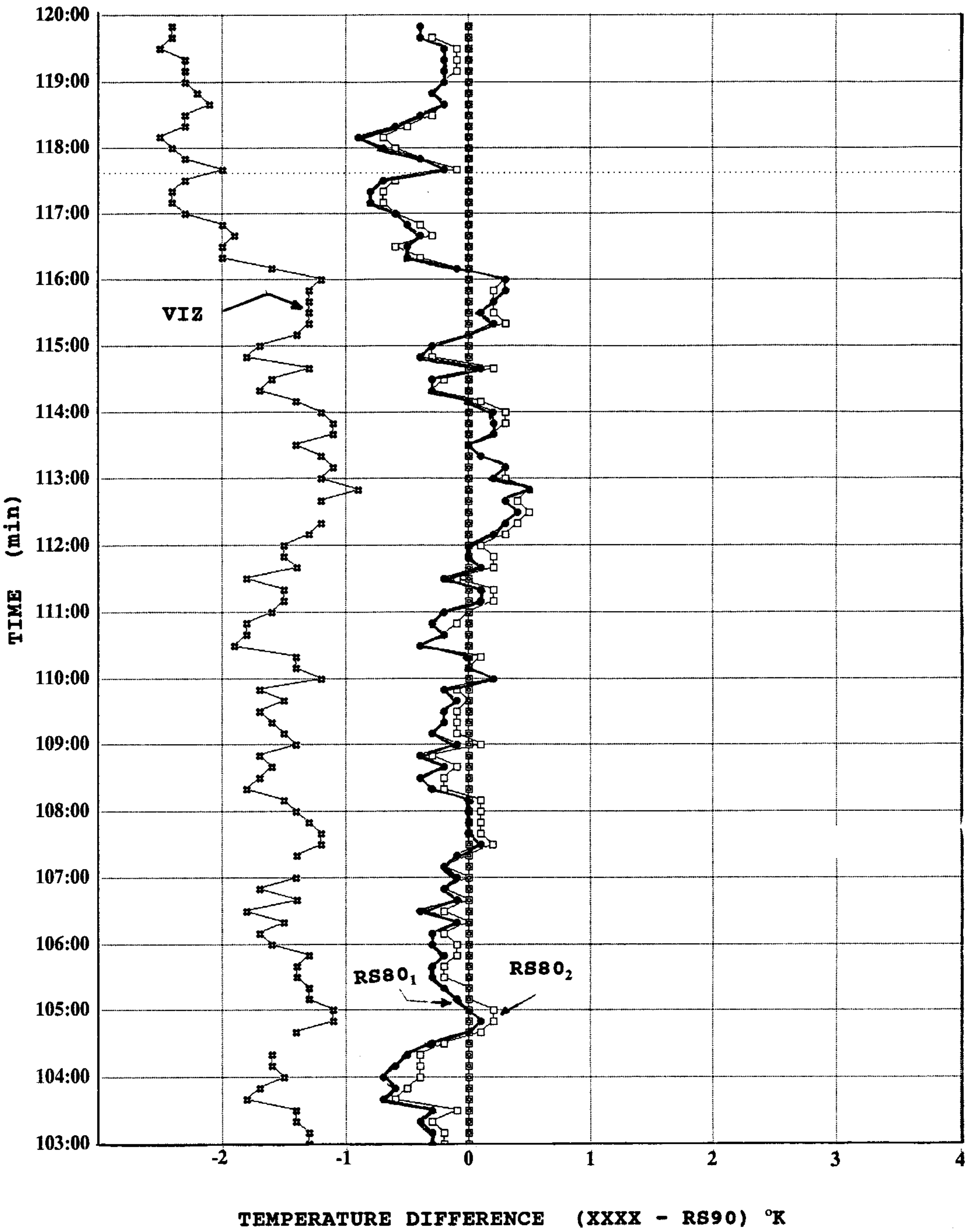

FIG. 10. Difference in temperature between RS90 and other radiosondes flown on the same balloon at 30-km altitude; night flight W1.

independent of direction. A second approach for existing sensors would be to mount the sonde on a swivel and add a fin to the bottom of the sonde that forces it to rotate during ascent. If the sonde rotated at least one revolution per minute, at all altitudes, the orientation error could largely be removed by 1-min averaging of the data. For present-day RS80 and VIZ sensors, the orientation error may affect the temperature of the sensor by as much as ±1°C at high altitudes. If the sonde temperatures are corrected for radiation error, the correction tables, which assume an average presented area of the sensor during one revolution, would not compensate for the orientation error. Thus, any corrected radiosonde temperature measurement at a high altitude may still be in error by up to 1°C due to orientation. Because of the cyclic nature of the error it will appear

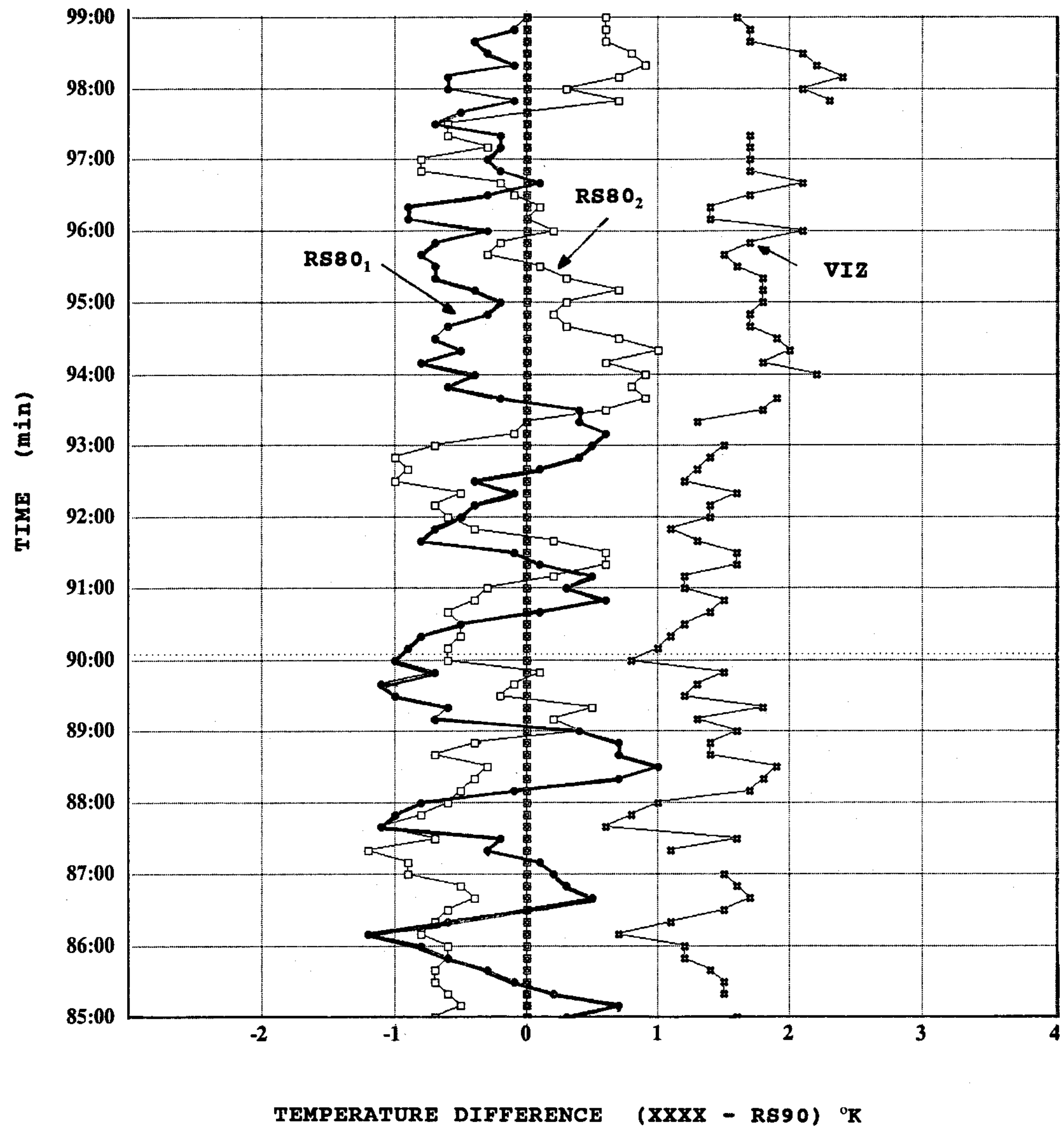

FIG. 11. Difference in temperature between RS90 and other radiosondes flown on the same balloon at 25-km altitude; day flight W2.

as an oscillation about the true atmospheric temperature. The RS90 sensor has a smaller orientation error (than the RS80 or VIZ) because of its reduced sensitivity to solar radiation. The maximum orientation error for the RS90 sensor is about ±0.3°C. Nevertheless, the orientation error is likely to be the largest error source in corrected data for any of the three sensors.

6. Summary and conclusions

The performance characteristics of the F-Thermocap capacitive temperature sensor used on the Vaisala RS90 radiosonde was established by developing the RS90COR model to estimate the temperature of the sensor in various flight environments. The F-Thermocap sensor, because of the low emissivity of its aluminum coating, shows no nighttime radiation error. The small size of the sensor also makes its response time sufficiently rapid to respond to temperature gradients in the atmosphere without significant error. At a given point in time the sensor temperature could be in error by a couple of tenths of a degree due to an extreme local temperature gradient, say at the top of a marine stratocumulus layer. However, when measuring a mean temperature gradient over a time interval of 1 min, typical of radiosonde observations, the lag error becomes insignificant. Thus, for a nighttime flight environment, the temperature of the F-Thermocap sensor is essentially identical (within 0.05°C) to that of the air in which it is embedded.

During the daytime, solar heating of the sensor makes its temperature rise above that of the air. At altitudes

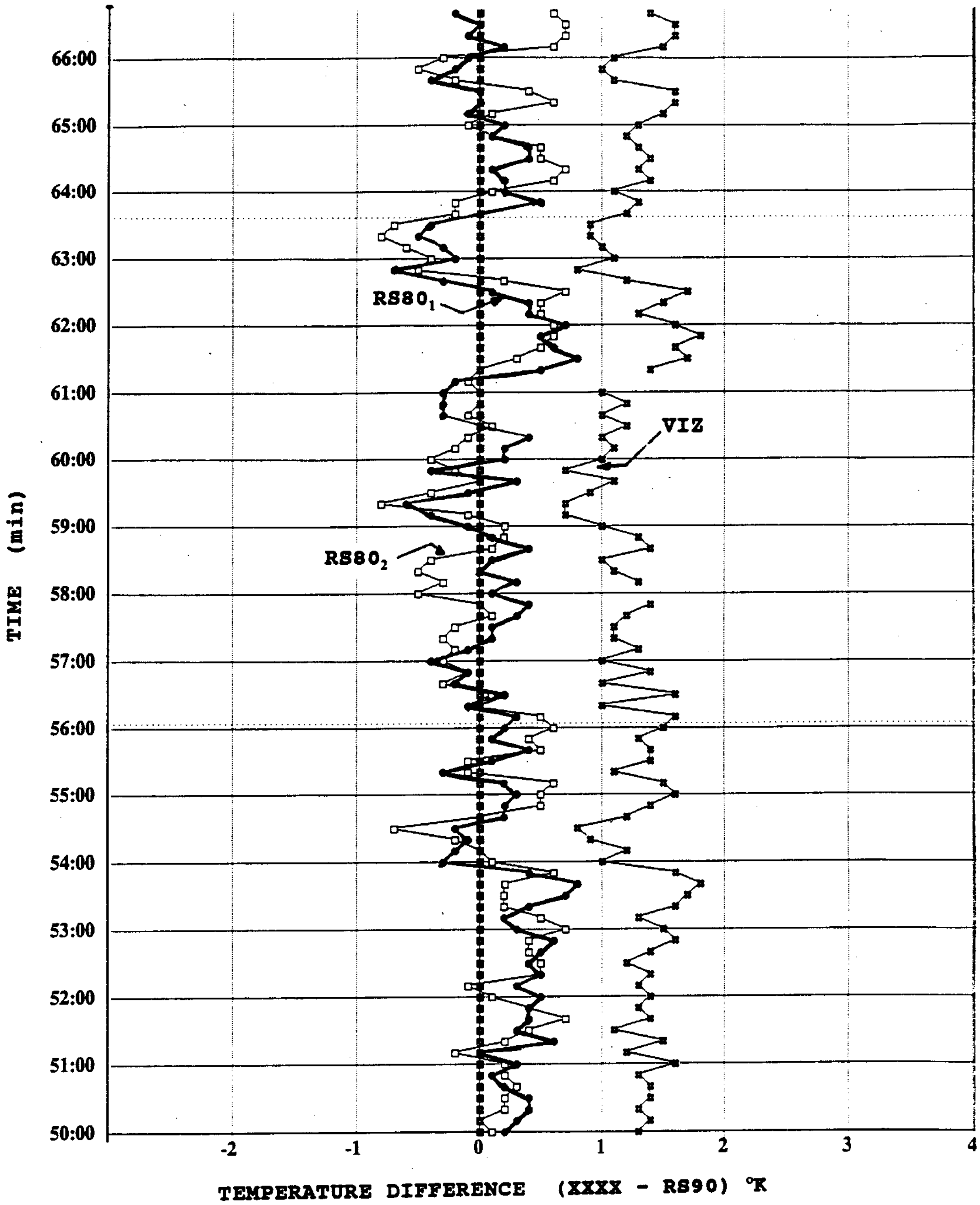

FIG. 12. Difference in temperature between RS90 and other radiosondes flown on the same balloon at 15-km altitude; day flight W2.

above 25 km and solar elevation angles above 3°, this temperature rise may approach 0.5°C. The F-Thermocap sensor has the shape of a cylindrical wire tilted at an angle of about 45° with the horizontal. Thus, the solar irradiation of the sensor and, consequentially, solar heating, depends on the orientation of the sensor relative to the sun. In modeling the temperature error, the average presented area of the sensor during one sonde rotation is used to estimate the solar irradiation. At high altitudes an instantaneous measurement from the F-Thermocap sensor may deviate from the temperature of the air by up to 0.3°C due to this orientation error. For normal radiosonde data reduction, an averaging time of 1 min appears adequate to filter fictitious high-frequency temperature oscillations at low altitudes, but at altitudes above 25 km the orientation error is likely to still be present.

The radiation error for the F-Thermocap remains nearly constant with solar angle for solar elevations above 3° but varies with altitude (or pressure). Below 3° the radiation error decreases rapidly as more of the sun's radiation is scattered and absorbed by passing through the atmosphere. The daytime radiation error, like the nighttime error, is essentially insensitive to changing environmental parameters, such as cloud cover, surface temperature, aerosols, etc. Thus, if the daytime F-Thermocap temperature is corrected as a function of altitude (or pressure) and solar angle, the average corrected temperature of the F-Thermocap during one sonde revolution should be within 0.1°C of the air temperature under any environmental condition. The sensor thus provides an excellent capability for measuring the mean atmospheric temperature. It must be emphasized, however, that this error analysis addresses only the temperature error due to the radiosonde temperature being different from that of the air in which it is embedded. Other error sources such as electronic noise, sensor calibration, transmission, and decoding errors may also be present.

An evaluation of the actual performance of the F-Thermocap sensor on an RS90 sonde was arrived at by comparing corrected temperature profiles from RS90 and RS80 sondes flown on the same balloon. Error sources other than that attributable to the temperature of the sensor are likely to be present when making such comparisons. In comparing corrected temperature profiles derived from RS80 and RS90 radiosondes flown on the same balloon, a bias error of 0.1°–0.3°C has been observed. In all of these cases the RS90 temperature is colder than that of the RS80. Because previous RS80 temperature profiles when compared with other sensors (Luers and Eskridge 1995) have not exhibited this bias, it is believed to be in the RS90 radiosonde. The Vaisala Oy Company believes the bias results when the humidity conditions under which the sonde is stored differ from those present during calibration. This affects the capacitance curve for the temperature sensor. Correction steps are being implemented by Vaisala to assure that RS90 sondes are both calibrated and stored in a low humidity environment. If this procedure eliminates the bias, then the temperature measurements from the RS90 radiosonde, when corrected for solar radiation as a function of altitude (pressure) and solar angle, will provide the highest degree of accuracy of any radiosonde currently in existence. The F-Thermocap sensor is superior to its RS80 (Thermocap) predecessor, as well as the VIZ, which possess daytime and nighttime errors as large as +1°C and −2°C, respectively.

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