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EFFECT OF RAWINSONDE ERRORS ON ROCKETSONDE DENSITY AND PRESSURE PROFILES - AN ERROR ANALYSIS OF THE RAWINSONDE SYSTEM

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ABSTRACT

An initial value of pressure is required to derive the density and pressure profiles of the rocket-borne Rocketsonde sensor. This tie-on pressure value is obtained from the nearest rawinsonde launch at an altitude where overlapping rawinsonde and Rocketsonde measurements occur. An error analysis has been performed of the error sources in these sensors that contribute to the error in the tie-on pressure. It was determined that significant tie-on pressure errors result from radiation errors in the rawinsonde rod thermistor, and temperature calibration bias errors. To minimize the effect of these errors radiation corrections should be made to the rawinsonde temperature and the tie-on altitude should be chosen at the lowest altitude of overlapping data. Under these conditions the tie-on error, and consequently the resulting error in the Datasonde pressure and density profiles will be less than 1%. The effect of Rawinsonde pressure and temperature errors on the wind and temperature versus height profiles of the rawinsonde was also determined.

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SECTION 1
INTRODUCTION

The rocketsonde sensor provides upper atmospheric thermodynamic and wind data by use of a thermistor to sense the temperature profile. A tracking radar provides the coordinates of the <u>Starute</u>-borne sensor from which the wind profile is derived. By using the hydrostatic equation and the equation of state, pressure and density are calculated from the excellent approximation

$$P = P_o \exp \left[-\sum g \frac{\Delta h}{RT}\right] , \tag{1}$$

and

$$\rho = P/RT , \tag{2}$$

where

P_o = initial value of pressure at height Z_o ,

g = gravitational acceleration,

Δh = height interval between temperature measurements,

R = gas constant for dryair, and

T = average temperature for the interval Δh.

The integration process inherent in Equation 1 requires an initial value of pressure, P_o. This initial pressure value has traditionally been obtained from the most recently launched rawinsonde flight at some tie-on altitude near 24 km where overlapping data from both sensors exist. An error in the tie-on pressure obtained from the rawinsonde produces an error in all succeeding calculations of density and pressure at rocketsonde levels. As seen by Equation 1, P_o is a multiplier of the entire profile. Thus, a given percent error in the initial pressure will produce that same percent error in all succeeding calculations of pressure. For example, if the tie-on pressure from the rawinsonde is in error by 5%, a 5% pressure error will be calculated at all altitudes for the rocketsonde sensor. The effect of these errors in pressure are also significant on density computations since, from Equation 2, a given percent pressure error results in approximately the same percent density error. Because of these effects, it is imperative that maximum percent accuracy in the initial pressure tie-on value be obtained.

SECTION 2

DISCUSSION OF ROCKETSONDE AND RAWINSONDE SYSTEM

The rawinsonde system contains three sensors; a baroswitch which provides pressure measurements, a thermistor which measures temperature, and a hygrister which measures relative humidity. The height profile, H, for the rawinsonde is generated from these measurements by use of Equation 3, the hypsometric equation.

$$H_N = \sum_{i=1}^{N} \frac{R}{2g} (T_i^V + T_{i-1}^V) \ln (P_i/P_{i-1}) \qquad (3)$$

where T^V = virtual temperature. Thus, temperature, humidity and pressure errors introduce error in the height derived from the rawinsonde system. For simplicity, and because the affect applies mostly in the lower 8-10 km of the atmosphere, the humidity will be ignored.

The rocketsonde measures temperature using a thermistor and provides a height profile from radar tracking of the sensor. The region of best agreement between the temperature profiles from the rawinsonde and rocketsonde in the 24-30 km overlap region has, as in the past, provided the criterion for defining the tie-on altitude. Agreement between these temperature profiles, however, is not sufficient to insure an accurate tie-on pressure from the rawinsonde since its pressure is measured independent of temperature.

The criterion for choosing a rawinsonde pressure value for tie-on should be to choose that initial pressure, P_o, at height H_o that will produce maximum accuracy in the density and pressure profiles derived from the rocketsonde. As previously noted, minimum error in density and pressure profiles occur when the <u>percentage</u> error in the tie-on pressure is a minimum. Thus, the rawinsonde tie-on problem reduces to choosing that altitude, H_o, of overlapping rawinsonde-rocketsonde profiles at which the percent pressure error in the rawinsonde is a minimum. The problem is complicated, however, by the fact that the rawinsonde altitude, H_o, may also be in error which effectively makes an additional contribution to the tie-on pressure error. Thus, in the analysis of the rawinsonde system, both errors in H_o and P_o must be considered. The following sections analyze the error sources in the rawinsonde and rocketsonde systems and the influence of each source on the tie-on pressure error.

SECTION 3
TIE-ON ERROR SOURCES

The tie-on pressure can be in error due to error sources found in both the rocketsonde and rawinsonde. The radar track of the rocketsonde will not give the exact altitude of the rocketsonde. Thus, even if the rawinsonde altitude and pressure were without error, an error would result because the initial pressure would be assigned to an incorrect height for the rocketsonde. The resulting bias in the rocketsonde pressure and density profiles would reflect the change in atmospheric pressure that existed in the height increment between the true height and the radar derived heights of the rocket instrument.

Errors in the tie-on pressure also result from errors in the rawinsonde pressure measurement and height calculations. Since the rawinsonde height is calculated from the hypsometric equation, both pressure and temperature errors contribute to errors in the pressure versus height profile. Of special interest is an intriguing interrelationship between pressure and height errors whereby significant pressure errors produce compensating height errors and the derived pressure versus height profile of the rawinsonde remains essentially correct. To explain this influence of pressure and temperature on the derived pressure versus height relationship, a discussion of the hypsometric equation used to derive height is in order.

3.1 DISUCSSION OF HYPSOMETRIC EQUATION

The hypsometric equation derived from the gas law and hydrostatic equation calculates height from independent measurements of pressure and temperature. The effect on the height calculation from each error source can be analyzed separately.

3.1.1 Temperature Errors

It can be seen in Equation 3 that a random temperature error will produce an error in the height. Thus, even if the pressure measurements are error free, the derived height profile will be in error because of this influence of the incorrect thermal field in Equation 3. Thus, correct pressures will be related to an incorrect height. Similarly the temperature versus height profile will also be in error because the temperature and calculated height are in error. A random temperature error will be shown to produce only a small height error. Thus, the error in the temperature height relationship is essentially the magnitude of the temperature error. Bias temperature errors, however, will be shown to produce an ever increasing height error. Of interest also, though not directly related to the tie-on problem, is the fact that the calculated winds will be assigned to an incorrect height.

3.1.2 Pressure Errors

Consider next the effect of a pressure error. Through Equation 3 a pressure error will directly result in the calculation of an incorrect ehight. It can be shown, however, that the derived pressure versus height relationship, may or may not be in error depending on whether there is a temperature gradient between the actual and calculated height of the rawinsonde. That is, if temperature is constant over the Δh interval for which a height calculation is being made; then the pressure error, and its height induced error are compensating so that the pressure is the correct value at the computed height. The proof is as follows.

Let the pressure at P_i be in error by e_i. Let the temperature T_i be error free. Assume, furthermore, that at the previous data point the pressure, P_{i-1}, temperature, T_{i-1}, and height, H_{i-1}, are error free. Let us determine the effect of the pressure error e_i on the pressure-height relationship. The calculated height at the point $(P_i + e_i, T_i)$ is

$$H^* = H_{i-1} + \frac{R}{2g} (T_i + T_{i-1}) \ln \left(\frac{P_i + e_i}{P_i}\right) \quad . \tag{4}$$

The true height at that point in space where the true pressure happens to equal the incorrectly observed pressure $P_i + e_i$ is

$$H' = H_{i-1} + \frac{R}{2g} (T' + T_{i-1}) \ln \left(\frac{P_i + e_i}{P_i}\right) , \qquad (5)$$

where T' is the temperature at the point in space where the true pressure equals $P_i + e_i$. Note that if the temperature is constant in the altitude region between pressures P_i and $P_i + e_i$, then the observed temperature T_i equals T'. Equation 5 thereby equals Equation 4 and thus, H' = H*. That is the calculated height H* is true height of the pressure surface $P_i + e_i$. The pressure-height relationship $(H^*, P_i + e_i)$ is therefore correct. Since, however, the rawinsonde balloon is not physically located at the height H*, the temperature and wind measurements will be assigned a height for which they are not representative. This difference between the assigned height and the actual balloon height often can be large - exceeding 1/2 km. Thus, the resulting temperature and wind versus height profiles can be severely effected.

3.2 RAWINSONDE PRESSURE ERRORS

The type and magnitude of pressure errors inherent in the rawinsonde pressure sensor has been established by various researchers. Lenhard (1973) estimates the rawinsonde pressure measurement accuracy to be ± 1.5 millibars. Other references (Clark, 1969; Viz, 1977) quote approximate pressure accuracy of ± 2 mb. These accuracy estimates relate to the absolute accuracy of the baroswitch measurement. They are not valid for hypsometer measurements from rawinsonde so equipped. However, it should be noted that none of the meteorological rocket network stations release hypsometer equipped rawinsondes.

An empirical estimate of pressure accuracy has been obtained from a series of eight launches of rawinsondes from

Wallops Flight Center in November 1977. Each of the eight balloons had two separate rawinsonde instrument packages attached. Transmission from the two sondes were received by separate GMD's. Comparisons of pressure and temperature profiles from each rawinsonde versus height and time were made to evaluate measurement accuracy. Figures 1 and 2 show the difference in pressure in mb and in percentage between two rawinsondes attached to the same balloon at time intervals of five minutes for the eight flights. In absolute units of mb the pressure differences between the two sensors (error) is largest at the lower altitudes, sometimes exceeding 3 mb and decreases at higher altitudes to, in most cases, less than 1 mb. In several flights a bias appears throughout the entire altitude range. Analysis of the individual flights indicates a typical bias to be on the order of zero to 0.5 mb with a random error of 1.5 mb between the surface and 70 minutes (approximately 20 km) reducing to approximately 0.5 mb random error above this altitude. Since these error values represent the difference between two sensors the error attributable to a single sensor would be smaller by a factor of $\sqrt{2}$.

The percent difference in the pressure measurements from the 8 flights as shown in Figure 2 increases with increased time (altitude). Percent differences in excess of 10% occurred on two of the flights at the higher altitudes.

Figures 1 and 2 are in substantial agreement with the pressure error estimates from References 1, 2, and 3. As a result of the above analyses, the mean bias and random pressure error profiles shown in Table 1 will serve as pressure error input for a simulation analysis to assess the influence of pressure errors on the calculation of the tie-on pressure.

3.3 RAWINSONDE TEMPERATURE ERRORS

Rawinsonde temperature measurement errors consist of both random component and various bias components due to baseline

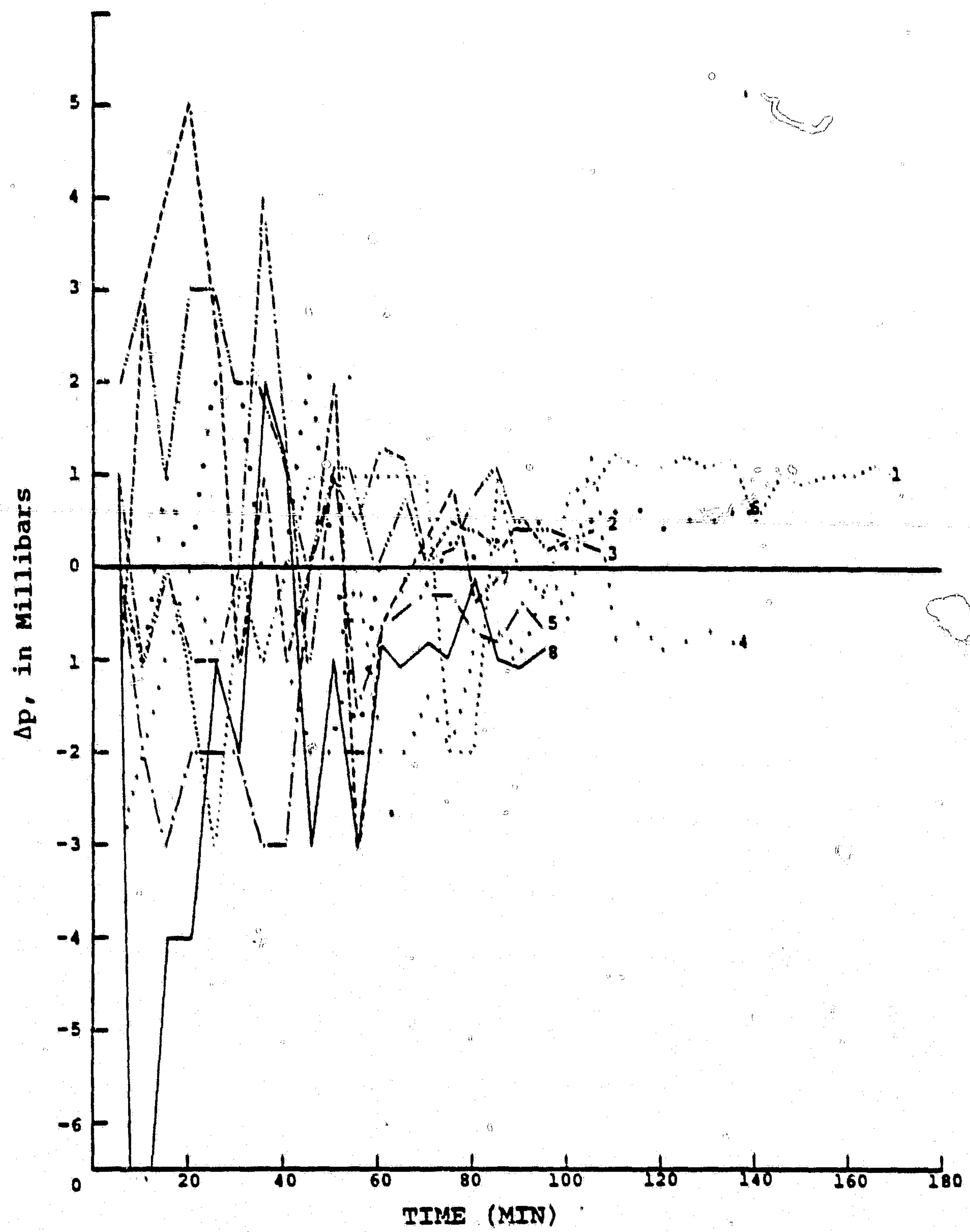

Figure 1. Difference in Pressure from Rawinsonde Flights With Dual Sensors

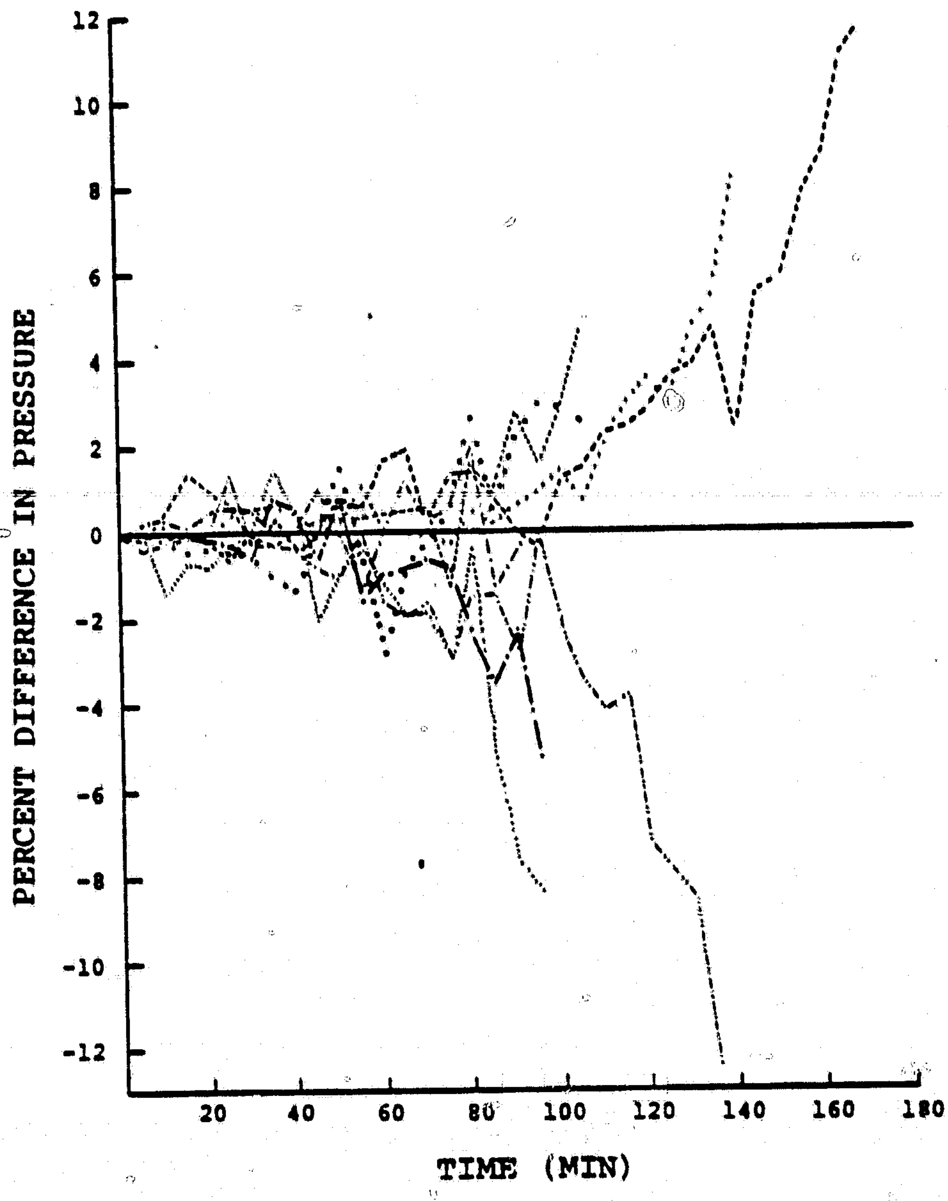

Figure 2. Percent Difference in Pressure From Rawinsonde Flight With Dual Sensors

TABLE 1

RAWINSONDE PRESSURE ERRORS

ALT (km)	RANDOM mb	BIAS mb
0	1.5	0.5
5	1.5	0.5
10	1.5	0.5
15	1.5	0.5
20	1.5	0.5
25	0.5	0.5
30	0.5	0.5

calibration, radiant heating of the thermistor, and the response time of the thermistor. The bias components bue to both radiant heating and time lag can be removed, if necessary, by improved data processing techniques. A measure of the random component of error has been obtained by Lenhard (1973) as approximately 0.2°C from the analysis of a series of 41 simultaneous launches of rawinsondes 10 miles apart. Other studies (Hodge and Harmantas, 1965; Lenhard, 1970) indicate random components of error as high as 0.5°C. Baseline calibration errors in the range of 0.2 to 0.75°C have been recorded by Williams 1976 and Cox 1968.

Empirical estimates of random and calibration types temperature errors (but not radiation or time lag errors) can also be derived from the eight Wallops rawinsonde flights. Figure 3 shows the temperature difference between two rawinsondes at each five minute intervals of flight time for the eight flights. Generally, the flights exhibit a small bias in temperature on the order of 0.2 to 0.6°K and a random temperature deviation on the order of 0.5°K about the bias. The bias error could result from an error in the preflight calibration of one of the rawinsondes. Bias errors appearing in both sensors such as those arising from radiation heating of the thermistor and the time lag of the thermistor should be identical in both profiles and thus should not appear in the differences.

Based upon the empirical results from Figure 3 and the studies of References 4-6, a typical bias calibration type error of 0.3°C and random errors of 0.2°and 0.5°C were chosen as representative of the rawinsonde system.

3.3.1 Radiation Error

In addition, bias components of temperature error exist due to the solar radiative heating of the thermistor and the time response of the thermistor. Presently, standard field procedures do not permit calculation of radiation corrections by the CMRN (Cooperative Meteorological Rocket Network) stations where rocketsonde pressure tie-on values are needed.

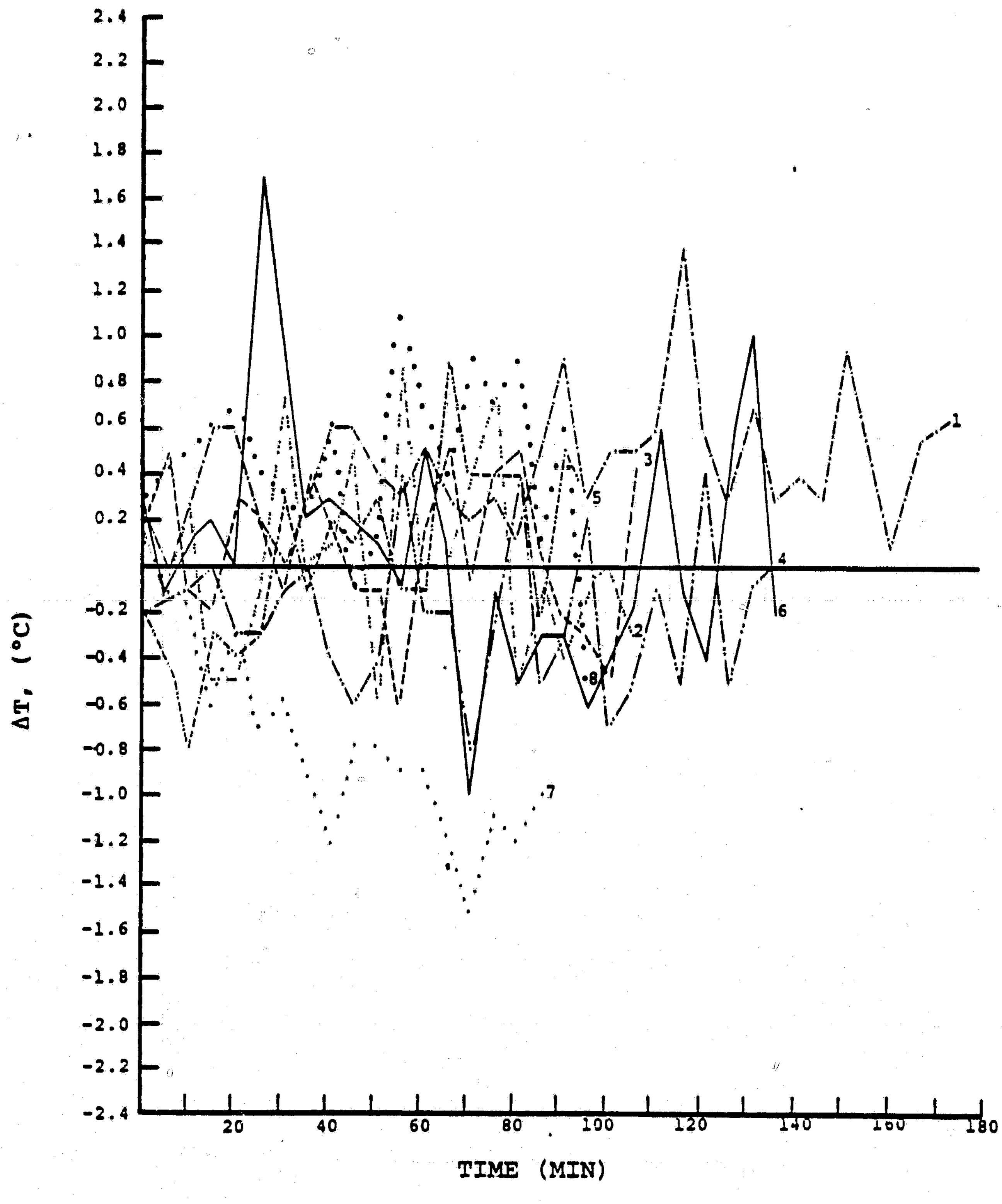

Figure 3. Difference in Temperature From Rawinsonde Flights With Dual Sensors

To estimate the magnitude of the radiant heating of the thermistor, a general examination of the heat transfer equation for the rawinsonde rod thermistor was undertaken. The total temperature correction that should be applied to the rod thermistor arises from three sources: aerodynamic heating; lead wire conduction; and solar radiation. Because of the relatively slow rise rate of the rawinsonde balloon (≈5 m/sec), aerodynamic heating of the cylindrical rod thermistor is negligible (Ballard and Rubio, 1968). The shape, size, and length of the lead wires makes the lead-wire conduction term also relatively insignificant. Significant correction to the rod thermistor temperature is primarily due to solar radiative heating of the thermistor and lead wires. The radiative heating, from Ballard and Rubio is given by:

$$\Delta T = \frac{J\varepsilon_s A_p}{S} + \frac{4\varepsilon_s JR}{pS} \ (\coth px - \operatorname{csch} px); \qquad (6)$$

where

S = dissipation factor = $4\sigma\varepsilon_\ell A T_e^{3} + (2k\beta/x)\ px \coth px + hA$,

J = solar constant,

ε_s = short wave absortion coefficient,

ε_ℓ = long wave emissivity,

A = thermistor surface area,

A_p = projected thermistor area,

p = $(2h/kR)^{1/2}$,

x = lead-wire length,

T_e = environmental temperature,

β = lead-wire cross-sectional area,

R = thermistor lead-wire radius,

σ = Stefan-Boltzman constant,

h = lead-wire convective heat transfer coefficient,

h_t = thermistor convective heat transfer coefficient, and

k = lead-wire thermal conductivity.

The first term reflects the radiative heating of the rod thermistor, while the second term reflects radiative heating of the lead wires. Evaluation of Equation 6 by Rubio and Ballard for the rawinsonde AN/AMT-4 instrument with the ML419 thermistor are shown in Table 2. The values shown are only approximate, based upon assumed values of albedo, absorption and emissivity coefficients, convective heat transfer coefficients, and solar angle dependence. Examination of this table shows that the solar irradiation of the thermistor accounts for the majority of the total temperature correction. For rawinsondes equipped with the ML405 thermistors, only a relatively small increase in radiation correction values would be expected.

The total temperature corrections from theoretical heat transfer calculations can be compared with empirically derived corrections as reported by McInturff and Finger (1968) and Johnson and McInturff (1978). In McInturff and Finger's (1968) study of the compatibility of day-night temperature observations, radiation temperature correction tables were generated as a function of altitude, solar elevation angle, and whether the dyatime observation was made in the morning or afternoon. Tables 3 and 4 list mean temperature corrections, obtained from temperature differences between day and nighttime observations, for the USA ESSA rawinsonde. The mean height corrections obtained from their study are also listed. Johnson and McInturff (1978) updated the earlier study for the U.S. rawinsonde using observations from 1974-1976. The day-night differences were also extended below 100 mb to the surface. Table 5 shows these differences by two classifications: the 0000GMT observation in sunlight and the 1200GMT observation in sunlight. For the U.S. this corresponds to the afternoon observation versus the morning observation

TABLE 2

RADIATION CORRECTIONS FOR RAWINSONDE TEMPERATURES (FROM BALLARD AND RUBIO, 1968)

Altitude (Km)	$(J\epsilon_s A_p/S)$ (^oC)	$(4\epsilon\ JR/pS)$ (coth px-csch px) (^oC)	Total (^oC)
30	1.5	.3	1.8
25	1.2	.2	1.4
20	1.0	.2	1.2
15	.8	.1	.9
10	.5		.5
5	.4		.4

TABLE 3

VALUES OF MEAN $\overline{\Delta T}$(a) AND MEAN $\overline{\Delta H}$(b) AS FUNCTIONS OF MEAN MORNING-DAYLIGHT SOLAR ELEVATION ANGLE AND OF PRESSURE LEVEL, FOR THE U.S.A. ESSA INSTRUMENT. UNITS ARE (a) DEGREES CELSIUS AND (b) METERS. (FROM MCINTURFF AND FINGER, 1968)

Solar Elevation Angle (Degrees)		Pressure Level (mb)				
		100	50	30	20	10
- 5°	a	-0.2	-0.3	-0.3	0.0	-0.2
	b	-7	-12	-18	-22	-28
0°	a	0.1	0.2	0.3	0.5	0.9
	b	-3	0	2	6	16
10°	a	0.4	0.5	0.8	1.1	1.6
	b	6	14	21	29	53
20°	a	0.6	0.8	1.1	1.3	2.0
	b	13	26	38	48	78
30°	a	0.8	1.0	1.2	1.5	2.1
	b	20	37	53	65	96
40°	a	0.9	1.1	1.4	1.7	2.3
	b	26	46	64	78	112
50°	a	0.9	1.2	1.5	1.7	2.3
	b	30	50	72	88	124
60°	a	0.9	1.2	1.5	1.7	2.3
	b	31	51	76	94	132
70°	a	0.8	1.1	1.3	1.6	2.1
	b	30	50	75	93	133
80°	a	0.7	0.9	1.1	1.2	1.8
	b	27	47	69	88	125

TABLE 4

VALUES OF MEAN $\overline{\Delta T}$(a) AND MEAN $\overline{\Delta H}$(b) AS FUNCTIONS OF MEAN AFTERNOON-DAYLIGHT SOLAR ELEVATION ANGLE AND OF PRESSURE LEVEL, FOR THE U.S.A. ESSA INSTRUMENT. UNITS ARE (a) DEGRESS CELSIUS AND (b) METERS. (FROM MCINTURFF AND FINGER, 1968)

Solar Elevation Angle (Degrees)		Pressure Level (mb)				
		100	50	30	20	10
- 5°	a	0.2	0.5	0.7	0.8	1.3
	b	12	23	32	43	66
0°	a	0.4	0.8	1.0	1.3	2.0
	b	23	36	50	65	106
10°	a	0.8	1.1	1.5	2.0	2.7
	b	35	53	74	98	146
20°	a	0.9	1.3	1.8	2.2	3.0
	b	45	67	90	117	170
30°	a	1.0	1.3	1.9	2.3	3.1
	b	50	72	97	124	180
40°	a	1.0	1.3	1.9	2.3	3.1
	b	50	74	99	126	181
50°	a	1.0	1.3	1.9	2.2	2.9
	b	47	72	97	123	175
60°	a	1.0	1.3	1.8	2.1	2.7
	b	42	65	92	116	163

being in the sunlight. Note that the differences shown in Table 5 result from not only radiation errors but are also influenced by diurnal heating, especially near the surface. For example the 1200GMT negative corrections, which indicate that the nighttime temperature was higher than the sunlight temperature, apparently resulted from nighttime observations shortly after sunset when the atmospheric temperature still reflected the day's heating and was warmer than the next morning's daylight measurement. The empirical observations from Table 3, 4, and 5 show reasonable agreement with the theoretical results of Table 2. Since the radiation correction varies somewhat from flight to flight an average radiation correction profile was generated based upon the 0000GMT sunlight values of Table 5 at the pressure levels above 500 mb and extended to the surface using the theoretical results of Table 2. These radiation temperature correction values are shown in Table 7, the summary table of temperature errors.

3.3.2 Thermistor Time Lag Error

An additional source of temperature bias error results from the time lag associated with the response of the rawinsonde thermistor to a temperature gradient. This temperature bias, is given by the equation,

$$\delta = -\lambda \cdot v \cdot \frac{dT}{dh} \quad \text{(Saunder, 1976)*} , \qquad (7)$$

where

λ = time constant (sec),

v = ascent rate of balloon, and

$\frac{dT}{dh}$ = rate of change of temperature with respect to height.

*Scott L. Williams and Donald G. Acheson's personal communication with Saunder, referenced in "Thermal Time Constant of U.S. Radiosonde Sensors Used in GATE", NOAA TM-EDS-CEDDA-7, May 1976.

TABLE 5

TEMPERATURE BIAS FROM DAY-NIGHT DIFFERENCES
(FROM JOHNSON AND MCINTURFF 1978)

Day-Night Differences (1974-1976)

P (mb)	Temp (°K) All	US Type 1 00GMT Sunlight	US Type 1 1200GMT Sunlight
1000	1.37	1.72	-0.92
850	0.76	0.88	-0.13
700	0.38	0.45	-0.02
500	0.31	0.37	-0.04
400	0.35	0.42	0.00
300	0.38	0.47	0.02
250	0.39	0.49	0.06
200	0.44	0.52	0.23
150	0.56	0.63	0.39
100	0.66	0.76	0.46
70	0.73	0.90	0.47
50	0.81	1.07	0.47
30	1.02	1.42	0.63
20	1.20	1.74	0.77
10	1.57	2.34	1.08

Since the lag error depends upon the temperature profile, several profiles were used in the estimation of the magnitude of the time lag error. Figure 4 shows representative and extreme case temperature profiles. Another parameter needed to solve Equation 7 is the time constant, λ, of the rod thermistor. This value, according to Williams and Acheson (1976), is a function of atmospheric density and balloon rise rate and is estimated by:

$$\lambda = 9.77\ (\rho v)^{-0.43} \quad ; \qquad (8)$$

where

ρ = density of air (kg/m^3), and

v = ascent rate of balloon (m/sec).

Figure 5 shows λ to vary from five seconds at the surface to 27 seconds near 30 Km. The evaluation of Equation 7, using the temperature profiles of Figure 4, a rise rate of 5 m/sec and time lag values from Equation 8, is shown in Table 6. This table reveals the temperature bias to be small in nearly all cases with a maximum time lag error of 0.37°C in profile 2. The various temperature error profiles shown in Table 6 served as input to assess the influence of time lag errors on the derived pressure/height relationship needed for obtaining the tie-on pressure.

3.4 ROCKETSONDE HEIGHT ERROR

Error in the rocketsonde height contributes to the tie-on pressure error because the tie-on height will not match for the two systems. Unlike the rawinsonde system, which computes height based on temperature and pressure measurements, the rocketsonde system uses a high precision radar, such as an FPS-16, to track the sensor. Therefore, errors in rocketsonde height result from inherent radar bias errors due to boresite calibration, time lag, alignment, etc., as well as random error components

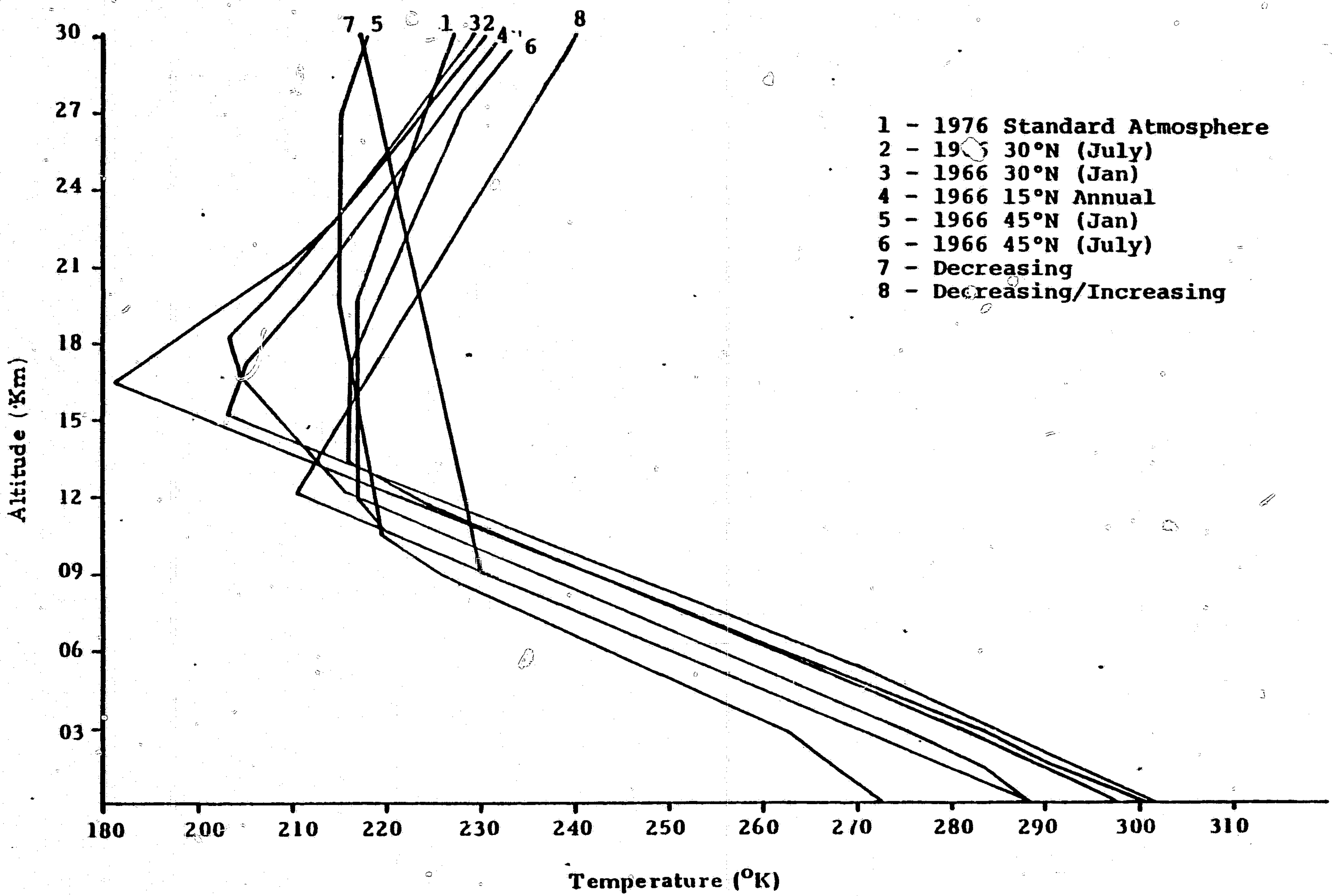

Figure 4. Temperature Profiles

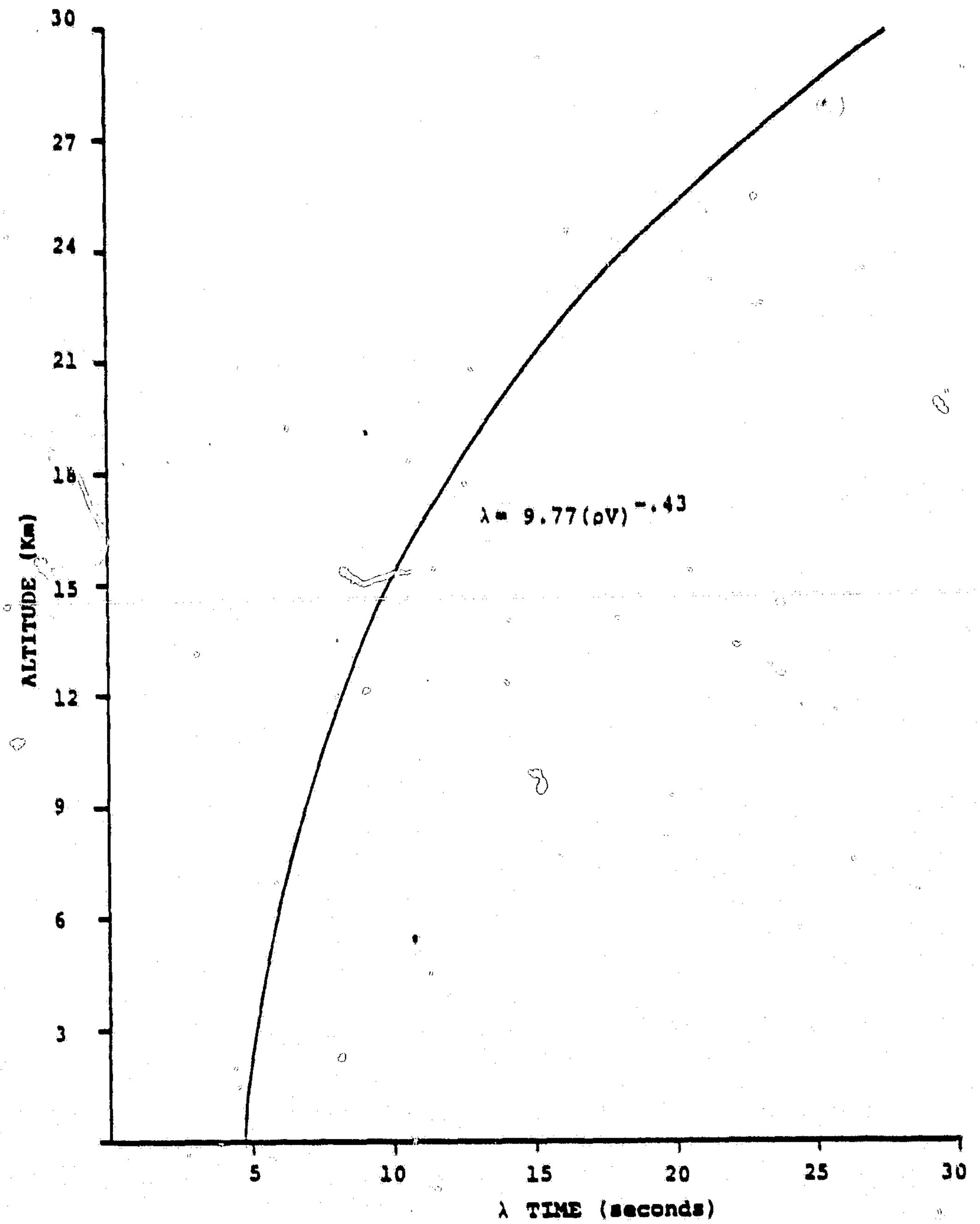

Figure 5. Rawinsonde Thermistor Time Lag Constant
(From Williams and Acheson, 1976)

TABLE 6

TEMPERATURE ERROR (^{o}C) DUE TO TIME LAG FOR DIFFERENT TEMPERATURE PROFILES

Altitude (Km)	Profile 1	2	3	4	5	6	7	8
0	-	-	-	-	-	-	-	-
1.5	.15	.16	.08	.19	.09	.12	.15	.15
3	.16	.14	.14	.15	.09	.15	.16	.16
4.5	.17	.19	.18	.16	.16	.17	.17	.17
6	.18	.19	.19	.16	.17	.17	.18	.18
7.5	.20	.21	.21	.22	.19	.21	.20	.20
9	.22	.23	.22	.24	.21	.22	.22	.22
10.5	.23	.24	.23	.25	.15	.23	.02	.23
12	.09	.27	.26	.28	.02	.26	.02	.26
13.5	.00	.30	.12	.31	.02	.19	.03	-.07
15	.00	.33	.13	.35	.02	.00	.03	-.08
16.5	.00	.37	.14	-.04	.03	.00	.03	-.09
18	.00	-.24	.05	-.13	.03	-.05	.04	-.10
19.5	.00	-.27	-.17	-.15	.02	-.08	.04	-.11
21	-.05	-.30	-.19	-.16	.00	-.09	.05	-.12
22.5	-.08	-.28	-.19	-.16	.00	-.10	.05	-.14
24	-.09	-.20	-.18	-.18	.00	-.11	.06	-.15
25.5	-.10	-.22	-.20	-.20	.00	-.12	.06	-.17
27	-.11	-.25	-.22	-.22	.00	-.13	.07	-.19
28.5	-.12	-.27	-.25	-.25	.00	-.26	.08	-.21
30	-.14	-.30	-.28	-.28	-.11	-.29	.09	-.23

due to thermal and electronic noise. In general, radar bias errors are nearly constant for a flight segment but vary from flight-to-flight thus making it impossible to remove the bias from a radar height profile. Estimates of the combined effect of random and bias errors have been obtained from a study of numerous flights tracked simultaneously by two FPS-16 radars (Miers and Avara, 1968). The best estimate from this study for the rocketsonde over the altitude range corresponding to pressure tie-on is approximately 10 meters. Other studies of FPS-16 radar tracking accuracy for balloon sensors (Engler et al., 1967 and Zartarian and Thompson, 1968) gave similar results. If lower precision tracking radars are used to track the rocketsonde radar tracking errors would be significantly larger.

3.5 SUMMARY OF ERRORS

The various components of temperature and pressure measurement errors of the rawinsonde and the height error of the rocketsonde is summarized in Table 7. Each of these error profiles were analyzed individually using a simulation procedure to assess the influence on the tie-on pressure error. The following sections discuss the results of this analysis.

TABLE 7

MAGNITUDE OF TEMPERATURE, PRESSURE, AND HEIGHT ERROR COMPONENTS

ALTITUDE (m)		TEMPERATURE ERRORS (°C) RADIATION	CALIBRATION	RMS	PRESSURE ERRORS (mb) RMS	BIAS	HEIGHT ERROR (m) DATASONDE
1500.		.38	0.3	±0.2 ±0.5	±1.5	0.5	-
3000.		.39	0.3	0.2 0.5	1.5	0.5	-
4500.		.40	0.3	0.2 0.5	1.5	0.5	-
6000.		.41	0.3	0.2 0.5	1.5	0.5	-
7500.		.43	0.3	0.2 0.5	1.5	0.5	-
9000.	PROFILES	.45	0.3	0.2 0.5	1.5	0.5	-
10500.		.50	0.3	0.2 0.5	1.5	0.5	-
12000.	(1-8)	.55	0.3	0.2 0.5	1.5	0.5	-
13500.		.65	0.3	0.2 0.5	1.5	0.5	-
15000.	FROM	.70	0.3	0.2 0.5	1.5	0.5	-
16500.		.75	0.3	0.2 0.5	1.5	0.5	-
18000.	TABLE 6	.85	0.3	0.2 0.5	1.5	0.5	-
19500.		.95	0.3	0.2 0.5	1.5	0.5	-
21000.		1.10	0.3	0.2 0.5	1.5	0.5	10
22500.		1.25	0.3	0.2 0.5	1.5	0.5	10
24000.		1.40	0.3	0.2 0.5	1.5	0.5	10
25500.		1.55	0.3	0.2 0.5	0.5	0.5	10
27000.		1.75	0.3	0.2 0.5	0.5	0.5	10
28500.		2.00	0.3	0.2 0.5	0.5	0.5	10
30000.		2.35	0.3	0.2 0.5	0.5	0.5	10

SECTION 4
EFFECT OF ERRORS ON TIE-ON

4.1 EFFECT OF PRESSURE ERRORS ON TIE-ON

The bias and random components of pressure error affect the pressure versus height profile from which the tie-on pressure at a designated height is obtained. The influence of rawinsonde pressure errors on the tie-on pressure-height relationship (P_o,H_o) has been calculated using the following technique.

Using the 1976 Standard Atmosphere profiles of pressure, P_{76}, and temperature, T_{76}, versus height, H_{76}, as a representative atmosphere, typical rawinsonde pressure errors from Table 7 were added to the Standard Atmosphere values. The resulting pressure is denoted as $P^*=P_{76} + \varepsilon$. Height was calculated from the error contaminated pressure profiles, P^*, and the Standard Atmosphere temperature profile, T_{76}, using the hypsometric equation. This calculated height profile is designated H^*. At any altitude H_o chosen for tie-on, the tie-on pressure error is the difference between the Standard Atmosphere pressure at H_o, that is P_{76} (H_o) and the rawinsonde pressure measurement at the calculated rawinsonde height of H_o, that is P^* (H_o). The percent tie-on error is obtained by dividing the tie-on pressure error by the Standard Atmosphere pressure. This is,

$$\%\varepsilon P_o = \frac{P_{76}(H_o) - P^*(H_o)}{P_{76}(H_o)} \tag{9}$$

Equation 9 gives the percent pressure error in the pressure versus height relationship resulting from errors in the rawinsonde pressure sensor. The evaluation of Equation 9 after introducing the bias and random pressure profiles of Table 7 into the Standard Atmosphere profiles, is shown in Table 8. In the case of introducing random error profiles

TABLE 8

EFFECTS OF PRESSURE ERRORS ON TIE-ON

ALT (Km)	Percent Error in P_o Resulting from Table 7 Pressure Errors	
0	RMS	Bias
1.5	.01(%)	<-0.1%
3.0	.01	<-0.1
4.5	.01	<-0.1
6.0	.02	<-0.1
7.5	.02	<-0.1
9.0	.03	<-0.1
10.5	.03	<-0.1
12.0	.03	<-0.1
13.5	.03	-0.1
15.0	.04	-0.1
16.5	.04	-0.1
18.0	.04	-0.1
19.5	.04	<-0.1
21.0	.05	<-0.1
22.5	.06	<-0.1
24.0	.07	<-0.1
25.5	.02	< 0.1
27.0	.02	< 0.1
28.5	.04	< 0.1
30.0	.05	+0.1

sampling was done from a normal distribution and the resulting calculations of Equation 9 were analyzed statistically. Table 8 shows the following. Both the random and bias components of error make negligible contributions to the tie-on error - less than 0.2 percent at all altitudes. In general, the tie-on error tends to increase slightly with increased altitude. Thus, even though the pressure measurement could be in error by as much as ten percent near 30 Km (1 mb error at 10 mb), the effect of this error on the pressure height profile and thus on the percent error in tie-on pressure is minimal.

4.2 EFFECT OF TEMPERATURE ERRORS ON TIE-ON

4.2.1 Random and Calibration Errors

Temperature errors effect the pressure-height relationship (and thus the tie-on error) by propagating through the hypsometric equation into a height error. The effect of the temperature error on the tie-on pressure was analyzed in a manner analogous to that for pressure errors. That is, temperature error profiles were added to the Standard Atmosphere temperature profile and the resulting percent pressure error calculated at each integration step, using Equation 9. The random and calibration bias error profiles used in the analysis consisted of random errors of $\sigma_T = 0.2°C$ and $\sigma_T = 0.5°C$ and a bias error of $\delta T = 0.3°C$ as shown in Table 7. The results are shown in Table 9. The 0.3°C bias error is shown to make a larger error contribution than the random error profiles. This is because a bias error profile produces a cumulative effect on the height error that results in increasingly larger errors in the pressure height relationships. Random errors on the other hand, have compensating positive and negative effects on the height error. Tie-on pressure errors, due to the 0.3°C bias are in excess of one-half percent at tie-on altitudes above 25 Km. For temperature bias errors in excess of 0.3°C (as apparently occurs in at least two of the 8 Wallops

TABLE 9

EFFECTS OF RANDOM AND BIAS TEMPERATURE ERRORS ON TIE-ON

ALT (Km)	Percent Error in P_o Resulting From Table 7 Temperature Errors		
	Calibration	RMS	
	0.3°C	0.2°C	0.5°C
1.5	.02%	±.01	±.03
3.0	.04	.01	.04
4.5	.06	.02	.05
6.0	.08	.02	.05
7.5	.12	.03	.06
9.0	.15	.03	.07
10.5	.19	.04	.08
12.0	.22	.04	.09
13.5	.26	.04	.10
15.0	.29	.05	.12
16.5	.33	.05	.13
18.0	.36	.06	.15
19.5	.39	.06	.17
21.0	.42	.06	.17
22.5	.45	.07	.18
24.0	.48	.07	.18
25.5	.51	.07	.19
27.0	.54	.08	.19
28.5	.56	.08	.20
30.0	.59	.08	.22

flights shown in Figure 3), the resulting tie-on error could approach or exceed one percent. Thus, careful and accurate procedures should be employed in calibrating the rawinsonde temperature sensor so as to maintain a calibration bias of less than 0.3°C. The random temperature errors are shown to be less important and in general contribute less than 0.2 percent to the tie-on error. For both bias and random errors the percent error in tie-on pressure is shown to increase with increased altitude so that with respect to these error sources the tie-on altitude should be chosen as low as possible.

4.2.2 Radiation Error

The temperature radiation error profile from Table 7 was used to perturb the Standard Atmosphere temperature profile and the resulting tie-on pressure error calculated in the same manner as previously employed. The resulting tie-on error is shown in Table 10. The effect of the radiation temperature error on the tie-on pressure results in an increasingly larger percent pressure error as the altitude increases. If the pressure tie-on value were taken at 30 Km, the 2.4 percent pressure error would directly produce the same percent error in the rocketsonde density and pressure profiles throughout its entire range (approximately 25 to 70 Km). Thus, from a consideration of radiation error alone, significant tie-on pressure errors can result. To eliminate or minimize this error source, radiation corrections can and should be made to the observed temperatures prior to the height calculation, or if corrections are not made, the tie-on should take place at the lowest possible altitude.

4.2.3 Time Lag Errors

An introduction of the various temperature lag error profiles of Table 6 into the simulation procedure resulted in the calculation of the tie-on pressure errors shown in Table 11.

TABLE 10

EFFECT OF RADIATION ERROR ON TIE-ON

ALT (Km)	Percent Error in P_o Resulting From Table 7 Radiation Error Profile
1.5	<.1
3.0	<.1
4.5	.1
6.0	.1
7.5	.1
9.0	.2
10.5	.2
12.0	.3
13.5	.4
15.0	.4
16.5	.5
18.0	.6
19.5	.8
21.0	.9
22.5	1.0
24.0	1.1
25.5	1.3
27.0	1.4
28.5	1.6
30.0	1.8

TABLE 11

EFFECT OF TIME LAG ERROR ON TIE-ON

Percent Error in P_o due to Thermistor Response Time for the Temperature Profiles Shown in Figure 4.

Altitude (Km)	Profiles 1	2	3	4	5	6	7	8
0	-	-	-	-	-	-	-	-
1.5	-.01	-.01	-.00	-.01	-.00	-.00	-.01	-.01
3.0	-.01	-.01	-.01	-.02	-.01	-.01	-.01	-.02
4.5	-.03	-.02	-.02	-.03	-.02	-.02	-.03	-.02
6.0	-.04	-.04	-.04	-.04	-.03	-.03	-.04	-.04
7.5	-.06	-.05	-.05	-.05	-.05	-.05	-.06	-.06
9.0	-.08	-.07	-.07	-.07	-.06	-.07	-.07	-.08
10.5	-.10	-.09	-.09	-.09	-.08	-.09	-.08	-.10
12.0	-.12	-.12	-.12	-.12	-.09	-.11	-.09	-.12
13.5	-.12	-.15	-.14	-.15	-.09	-.13	-.09	-.14
15.0	-.12	-.18	-.15	-.19	-.10	-.15	-.09	-.13
16.5	-.12	-.23	-.17	-.21	-.10	-.15	-.09	-.12
18.0	-.12	-.24	-.18	-.20	-.10	-.14	-.10	-.11
19.5	-.12	-.21	-.17	-.18	-.11	-.13	-.10	-.10
21.0	-.12	-.17	-.15	-.16	-.11	-.12	-.11	-.09
22.5	-.11	-.14	-.13	-.14	-.11	-.11	-.11	-.07
24.0	-.10	-.12	-.11	-.13	-.11	-.10	-.12	-.06
25.5	-.09	-.09	-.09	-.11	-.11	-.09	-.12	-.04
27.0	-.08	-.07	-.07	-.09	-.11	-.08	-.13	-.02
28.5	-.07	-.04	-.04	-.06	-.10	-.06	-.14	-.01
30.0	-.06	-.02	-.02	-.04	-.09	-.04	-.15	-.01

Note that the maximum percentage error in tie-on pressure for any profile occurs at 18 Km with Profile #2 and is less than one fourth of one percent. Thus, the time lag error produces a negligible error in the tie-on pressure calculation for any realistic type atmospheric temperature profile.

4.3 COMPARISON TO EXPERIMENTAL RESULTS

The eight experimental flights at Wallops with redundant rawinsonde sensors can assist in validating the simulation results for certain type error profiles. The standard reduction for each rawinsonde sensor was performed using the hypsometric equation to generate a height versus pressure profile. Similar bias errors that occur in both rawinsonde sensors will not be observed in the differences between the two profiles. The error sources that will be observed in comparing the pressure versus height profiles of the two rawinsondes are the random errors in pressure and temperature measurements, and the difference in bias errors between the two sensors. A comparison can therefore be made between the percent difference in pressure for the eight flights as shown in Figure 6 and the combined results of Tables 8 and 9 from the simulation. Only a general comparison, however, can be made. (Figure 6 overestimates the error due to a single sensor by a factor of $\sqrt{2}$. On the other hand, Figure 6 underestimates bias errors as the difference between the sensor biases rather than the absolute value of each sensor bias). What can be concluded from the comparison is as follows. In nearly all cases the percent difference in pressure increases with increased altitude in agreement with Tables 8 and 9. The largest percent difference in pressure for the eight flights is 1.6% and occurred at the highest altitude region of flights 1 and 7. The percent difference remained less than 1% for the remianing flights at nearly every altitude. The data shown in Tables 8 and 9 falls within the range of that shown in Figure 6 and is indicative of the type agreement one would anticipate between experimental and simulation results.

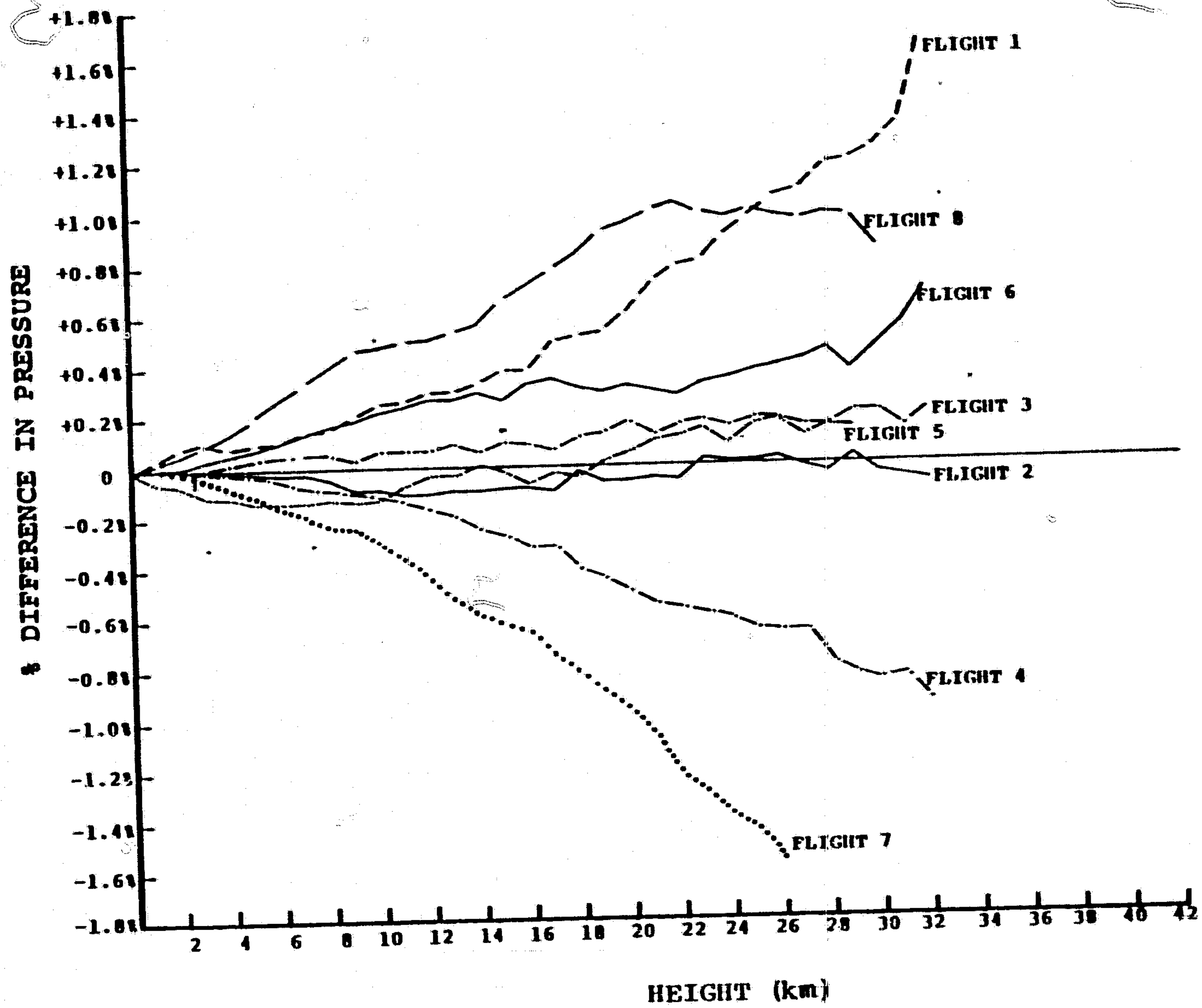

Figure 6. Percent Difference in Pressure Versus Height From Rawinsonde Flights With Dual Sensors. (Standard reduction technique used to obtain pressure profile from each rawinsonde.)

4.4 EFFECT OF ROCKETSONDE HEIGHT ERROR ON TIE-ON

The effect of a typical FPS-16 tracking error of 10 meter in height for the rocketsonde on the percent tie-on pressure error can be determined by calculating the percent change in pressure that occurs over the altitude error increment at the tie-on altitude. For a 10 meter height error the percent pressure change over this increment at tie-on altitudes between 20 and 30 km is less than 0.15%. Thus, this error source makes a negligible contribution to the tie-on pressure error.

4.5 SUMMARY AND RECOMMENDATIONS FOR TIE-ON

The primary source of error in the tie-on pressure is the radiation temperature error of the thermistor. This error increases with increased altitude and approaches 2% near 30 km. The radiation error could be corrected by using either empirical corrections or the radiation heat transfer equation. The other error sources of some significance are the random error and calibration bias errors in the rawinsonde temperature. Both of these errors also increase with increased altitude. Other error sources: the rawinsonde pressure measurement errors; the temperature time lag errors; and the rocketsonde height errors make an insignificant contribution (less than 0.25%) to the tie-on error.

The results of this analysis leads to the following recommendations.

(1) A correction should be made to the tie-on pressure (or the height) to account for the radiant heating of the rawinsonde thermistor. This can be done either by empirical correction tables or by solving the heat transfer equation of the rod thermistor.

(2) Care should be taken in the pre-launch calibration of the rawinsonde thermistor to minimize the calibration error. A calibration temperature accuracy of 0.3°C should be maintained.

(3) The tie-on altitude should be as low as possible, preferably approaching 20 km. This would insure rocketsonde pressure and density errors due to tie-on of less than 1/2% assuming radiation corrections are made to the tie-on pressure and less than 1% if no corrections are made.

SECTION 5

EFFECT OF ERRORS ON OTHER DERIVED RAWINSONDE PROFILES

The analysis of the rawinsonde tie-on problem has provided an understanding of the influence of measurement errors on the derived pressure versus height profile.

Though not related to the tie-on problem, results from this analysis can be utilized to understand the influence of rawinsonde measurement errors on the other height based profiles. The temperature versus height and wind versus height profiles are influenced by the same error sources that degrade the pressure versus height profile. The influence of the Table 7 errors on the temperature and wind profiles are analyzed in the following sections.

5.1 EFFECT OF PRESSURE ERRORS ON TEMPERATURE VERSUS HEIGHT AND WIND VERSUS HEIGHT PROFILES

Pressure errors can severely effect the temperature versus height and wind versus height profiles because of the error it introduces into height. The pressure error directly effects the calculation of height and consequently the rawinsonde is not physically located at the height of calculation. Even if the temperature and wind measurements were error free the temperature versus height and wind versus height profiles would be biased in altitude by an amount equal to the difference between the true height and calculated height of the rawinsonde. Thus, an analysis has been made of the effect of the Table 7 random and bias pressure errors on the height error of the rawinsonde. The analysis consisted of the following. The pressure error profiles of Table 7 were introduced into the 1976 Standard Atmosphere pressure profile and along with the 1976 S.A. temperature profile a calculation of height, H*, was made using the hypsometric equation. The true height at each integration step is the 1976 S.A. height associated with the corresponding 1976 S.A. temperature and pressure. The height error at any integration step is the difference between the calculated and Standard Atmosphere heights. That is, $\varepsilon_H = H_{76} - H^*$.

A calculation of the height error for the pressure error profiles of Table 7 is shown in Table 12. The bias pressure error is shown to produce an increasingly larger height error as altitude increases. A height error in excess of 200 m occurs at altitudes above 28 km. The affect of random pressure errors on the temperature versus height and wind versus height profiles is of the same order of magnitude as the bias error. RMS height errors in excess of 200 meters occur at the higher altitudes due to random pressure errors. Thus, both types of pressure errors significantly effect the height profile and can cause a typical height error on the order of 200 m to 400 m above 20 km. Extreme pressure errors can cause the height bias to even exceed 1 km at 30 km altitude.

This affect of pressure errors on the temperature and wind versus height profiles though not directly related to the tie-on problem, does assist in explaining the often observed discrepancies between overlapping rawinsonde and rocketsonde temperature profiles. An altitude offset in these overlapping profiles can be directly explained by a pressure bias in one of the rawinsonde pressure measurements.

5.2 EFFECT OF TEMPERATURE ERRORS ON WIND VERSUS HEIGHT AND TEMPERATURE VERSUS HEIGHT PROFILES

5.2.1 Wind Versus Height

An error in temperature introduces an error into the height calculation and thereby effects the wind versus height profile. An introduction of the various type bias and random temperature errors into the hypsometric equation and a calculation of the resulting height error has been made for the temperature error profiles of Table 7. The results are shown in Table 13. The largest height error results from the radiation bias of the thermistor. This error increases

TABLE 12

HEIGHT ERROR DUE TO PRESSURE ERRORS

Height Error in Meters Resulting From Random and Bias Pressure Errors Shown in Table 7.

ALT (km)	RANDOM	BIAS
1.5	10.4	4.9
3.0	13.1	5.9
4.5	15.3	7.1
6.0	18.1	8.5
7.5	22.4	10.3
9.0	26.3	12.4
10.5	30.7	15.1
12.0	34.2	18.5
13.5	40.8	22.8
15.0	53.1	28.2
16.5	73.6	35.0
18.0	98.0	43.6
19.5	135.3	54.5
21.0	188.4	68.1
22.5	221.9	85.2
24.0	272.6	106.7
25.5	80.0	133.5
27.0	94.8	167.4
28.5	136.5	213.2
30.0	207.3	259.2

TABLE 13

HEIGHT ERROR FROM TEMPERATURE ERRORS

Height Error in Meters Resulting From the Temperature Error Profiles Shown in Figure 7.

ALT (Km)	CALIBRATION (0.3)	RMS (0.2)	RMS (0.5)	RADIATION PROFILE	LAG PROFILE #4
1.5	- 1.6	1.1	2.1	- 1.6	0.5
3.0	- 3.2	1.5	2.9	- 3.5	1.4
4.5	- 4.9	1.8	3.8	- 5.6	2.2
6.0	- 6.7	2.0	4.1	- 7.8	3.1
7.5	- 8.5	2.3	4.6	- 10.4	4.2
9.0	-10.5	2.6	5.2	- 13.1	5.5
10.5	-12.4	2.8	5.8	- 16.2	7.1
12.0	-14.5	3.0	6.2	- 19.6	8.8
13.5	-16.6	3.3	6.9	- 23.4	10.8
15.0	-18.6	3.9	7.3	- 28.2	13.2
16.5	-20.7	4.1	8.5	- 34.1	14.4
18.0	-22.8	4.6	9.6	- 40.6	13.7
19.5	-24.9	5.4	11.1	- 47.8	12.7
21.0	-26.9	5.9	11.4	- 55.7	11.6
22.5	-28.9	6.1	11.9	- 64.1	10.5
24.0	-31.0	6.2	12.1	- 72.7	9.4
25.5	-33.0	6.3	12.4	- 83.7	8.1
27.0	-35.0	6.5	13.1	- 92.8	6.7
28.5	-37.0	6.7	13.7	-112.6	5.1
30.0	-39.0	6.9	14.2	-117.3	3.4

with altitude and exceeds 100 meters near 30 Km. All the other sources of temperature error make contributions of less than 40 meters to the height error. Thus, the wind versus height profile will be biased on the order of 100 meters or less, due to temperature errors through most of the altitude range. This is at least a factor of 2 less than the height bias due to pressure errors. Thus, the various sources of temperature error have a lesser influence on the wind versus height profile.

5.2.2 Temperature Versus Height

Temperature errors effect the temperature versus height profile in two ways. A direct error results from the inaccuracy of the temperature measurement, as well as a height error, due to the temperature influence in the hysometric equation. The effect of these errors on the temperature versus height profile was evaluated for the bias temperature error profile of Table 7. This error profile was introduced into the Standard Atmosphere and using the hypsometric equation the height was calculated. The Standard Atmosphere temperature at this height was then compared to the error contaminated temperature measurement to determine the temperature error at the calculated height. Table 14 shows the results. Comparing these results to the input temperature error shows that the error in the temperature versus height profile is sometimes slightly smaller and sometimes slightly larger than the error in the temperature measurement itself, depending on the signs of the temperature gradient and temperature error. However, the largest contribution to the temperature versus height error is due to the temperature error itself. Thus, the error in the temperature versus height profile is essentially the error in the temperature measurement.

TABLE 14

TEMPERATURE ERROR IN DERIVED TEMPERATURE VERSUS HEIGHT PROFILE

ALT (km)	Thermistor Bias Error From Table 7 (°C)	Temperature Error From Derived Temperature vs. Height Profile (°C)
1.5	.30	.31
3.0	.30	.32
4.5	.30	.34
6.0	.30	.34
7.5	.30	.35
9.0	.30	.37
10.5	.30	.38
12.0	.30	.34
13.5	.30	.30
15.0	.30	.30
16.5	.30	.30
18.0	.30	.30
19.5	.30	.30
21.0	.30	.29
22.5	.30	.28
24.0	.30	.27
25.5	.30	.26
27.0	.30	.26
28.5	.30	.26
30.0	.30	.26

5.3 CONCLUSIONS

In addition to the conclusion drawn relative to the tie-on problem other significant results of this analysis are as follows:

(a) Rawinsonde pressure errors have a strong influence on the calculation of height. Representative random and bias error profiles for the rawinsonde can combine to produce height errors in excess of 400 meters above 25 km. This causes a serious bias in the temperature versus height and wind versus height profiles;

b) Temperature errors introduce only a small error on the height data. Radiation errors of the thermistor make the largest contribution - on the order of 100 meters above 25 Km. Height errors of this magnitude have little effect on the wind versus height profile since in general the wind changes are small over 100 meters in altitude;

c) Temperature errors effect the temperature versus height profile both directly through an inaccurate temperature measurement as well as through a height error. The height error effect, however, is relatively small. Essentially the error in temperature versus height profile is the error in the temperature measurement itself.