Status of VAS Calibration after SBRC Engineering Model Vacuum Test

UW/SSEC

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1. Introduction

A review of the VAS Engineering Model Vacuum Test indicates a possible problem with the VAS in orbit calibration. Performing the calibration algorithm with coefficients determined from ray tracing yields results that do not meet the accuracy requirements. Adjustments of the coefficients can yield acceptable fits but several of the significant calibration coefficients are moved far outside the range defined by the calculated values and their estimated errors. Since no proven physical justification exists for these changes, the calibration data set was analyzed in an attempt to determine the coefficients uniquely from a regression analysis and to estimate errors.

2. Calibration of VAS

The VISSR Atmospheric Sounder (VAS) will expose photoconductive HgCdTe and InSb detectors to filtered and focused radiation emitted from the earth. The resulting detector output voltage must be converted to spectral radiance values by a reliable calibration procedure. The VAS detectors have a linear relationship between output voltage and input radiance which is determined by voltage responses to two known radiances. In flight evaluation of this linear response is implemented by determining the detector response to space and to an internal blackbody near 300°K.

To see this more clearly consider the voltage response of a linear radiometer

$$V = R\,N_T + V_0$$

where V is the output voltage, N_T is the input radiance, R is the responsivity of the radiometer, and V_0 is the system offset voltage. Calibration consists of determining R and V_0. A rigorous determination is made by exposing the radiometer to the two different external radiation targets of known radiance magnitude and measuring radiometer responses. Therefore

$$V_1 = RN_1 + V_0,$$

$$V_2 = RN_2 + V_0,$$

so

$$R = (V_2 - V_1)/(N_2 - N_1),$$

$$V_0 = (N_2V_1 - N_1V_2)/(N_2 - N_1);$$

and if N_1 = space view through VAS telescope = 0,

N_2 = external blackbody view,

we have

$$N_T = (N_2V - N_2V_1)/(V_2 - V_1)\ .$$

However this relationship assumes that there is a source of known radiance external to VAS. This is not so. Instead an internal blackbody is used for calibration from which an effective value for N_2 must be determined. The estimate for the effective value of N_2 is based on optical constants of the VAS telescope and temperature measurements of the optical components. The accuracy of the calibration is limited to the accuracy of the constants and temperatures used to estimate N_2.

A simplified description of the VAS and its radiation sources and targets is presented in Figure 1. There are three distinct measurements which must be considered in the VAS calibration.

space view $$V_1 = \alpha(1 - \gamma)B(T_A) + V_0 \tag{1}$$

internal blackbody $$V_2 = \alpha B(T_S) + V_0 \tag{2}$$

external target $$V_3 = \alpha(\gamma N_T + (1-\gamma)B(T_A)) + V_0 \tag{3}$$

where α is the responsivity of the detector, γ is the transmission of the VAS telescope, T_A is the weighted average temperature of the VAS telescope, T_S is the temperature of the internal calibration blackbody, and $B(T)$ is the Planck radiance of a blackbody at temperature T. We readily find that equations (1) and (3) imply

$$N_T = (V_3 - V_1)/\alpha\gamma \ . \tag{4}$$

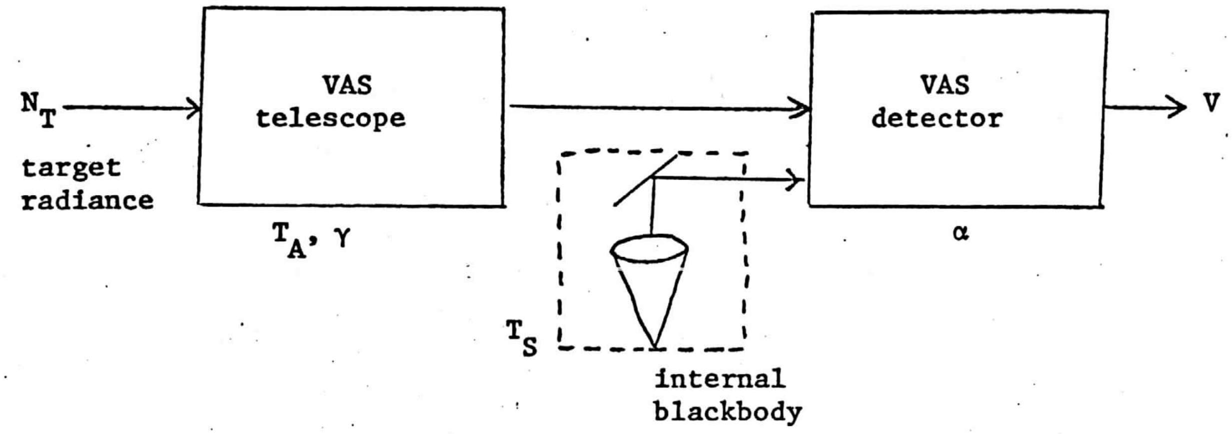
Determination of α, by estimating γ and T_A, comes from equations (1) and (2)

$$\alpha = (V_2 - V_1)\{B(T_S) - (1 - \gamma)B(T_A)\}^{-1} \ . \tag{5}$$

So we can rewrite equation (4) by inserting (5)

$$N_T = \frac{1}{\gamma}\{B(T_S) - (1 - \gamma)B(T_A)\}(V_3 - V_1)/(V_2 - V_1) \ . \tag{6}$$

SIMPLIFIED DESCRIPTION OF VAS



α = responsivity of detector

γ = transmission of telescope

T_A = weighted average temperature of telescope

T_S = temperature of internal blackbody

Figure 1

The $\frac{1}{\gamma}\{\}$ term is the effective value of N_2, the external blackbody radiance which produces the same response as the internal blackbody radiance $B(T_S)$. Define this to be $B(T_E)$, the effective blackbody radiance.

To determine T_A, we write the relations

$$(1 - \gamma)B(T_A) = \sum_i a_i \; B(T_i);$$
$$\sum_i a_i = (1 - \gamma), \tag{7}$$

where $\sum_i$ runs over all telescope components that contribute appreciably to the background radiation, and the a_i are constants determined from the reflectivities, emissivities, transmittances, and obscuration fractions of the various telescope components. Therefore

$$B(T_E) = \frac{1}{\gamma} \{B(T_S) - \sum_i a_i \; B(T_i)\}, \tag{8}$$

and if all component temperatures are a few degrees within T_S, then Taylor expansion is justified and

$$B(T_S) + \left.\frac{\partial B}{\partial T}\right|_{T_S} (T_E - T_S) = \frac{1}{\gamma}\{B(T_S) - \sum_i a_i [B(T_S) + \left.\frac{\partial B}{\partial T}\right|_{T_S} (T_i - T_S)]\}.$$

Thus

$$T_E - T_S = - \frac{1}{\gamma} \sum_i a_i \; (T_i - T_S),$$

which can be rewritten

$$T_E = T_S - \sum_i c_i \; (T_i - T_S) \; , \quad \text{where } c_i = \frac{a_i}{\gamma} \; . \tag{9}$$

So all together we find

$$N_T = B[T_S + \sum_i c_i \; (T_S - T_i)](V_3 - V_1)/(V_2 - V_1) \; . \tag{10}$$

The telescope components included in the sum are

i	symbol	component
1	SM	secondary mirror
2	PM	primary mirror
3	θM	scan mirror
4	BF	baffle tube, forward end
5	SC	shutter cavity
6	PAS	primary mirror aperture stop
7	SMS	secondary mirror shield
8	BA	baffle tube, aft end

and the relative locations of the components are shown in Figure 2.

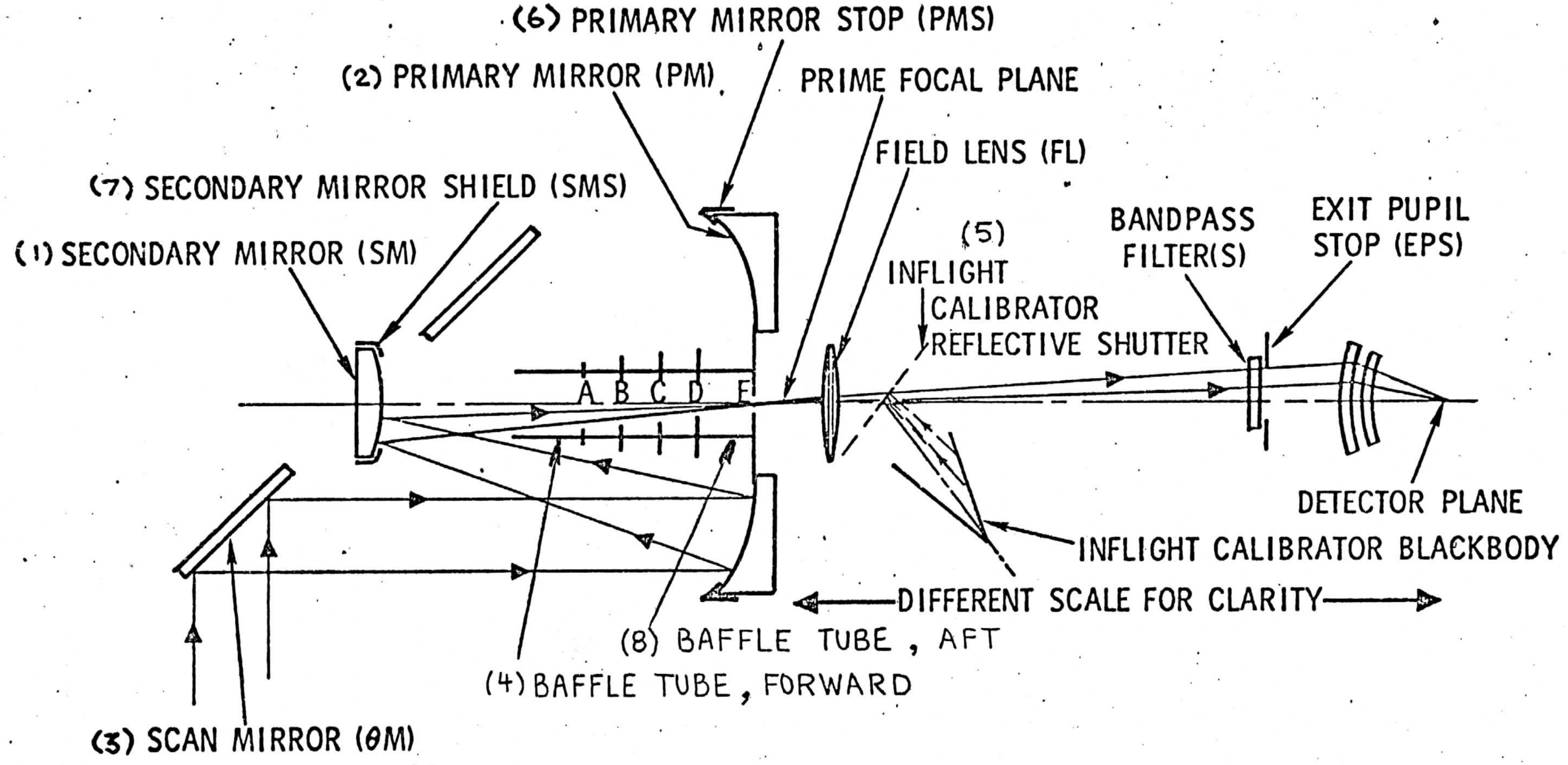


Figure 2. Optical Schematic for Inflight Radiometric Calibration Analysis

3. VAS Engineering Model Thermal Vacuum Test

The VAS Engineering Model Thermal Vacuum test attempted to verify that this calibration technique meets the accuracy requirements 1.5°K absolute error (mean error) and .5°K relative error (standard deviation). The evaluation of the calibration accuracy was somewhat obscured by preamplifier dc restore problems. However, it was possible to obtain a good data set of temperatures and voltages for spectral band 8. Band 8 calibration accuracy was evaluated for 20 different telescope temperature conditions from essentially isothermal to a gradient of approximately 18°C. The test configuration is illustrated in Figure 3. Three voltages were measured: the external target signal, V_E; the internal blackbody signal, V_I; and the space or offset signal, V_0. Twelve temperatures were measured: T_S, T_i, T_9 = temperature of the five position mirror in the calibrator, T_{10} = temperature of the calibrator mirror, and T_{ET} = temperature of the external target. Two additional terms were required in the evaluation of the effective temperature T_E when the calibrator is used. To determine the effective blackbody temperature of the VAS internal blackbody when placed external to the VAS and the calibrator the effect of the calibrator 5-position mirror (5PM) and the calibrator telescope optics (CM) had to be taken into account. The calibration data set from the thermal vacuum test is listed in Table 1.

To evaluate the calibration, we write for the measured effective temperature

$$\tilde{T}_E = T_S + \sum_{i=1}^{10} c_i (T_S - T_i),$$

and compare it to the temperature determined from using the measured voltages

VAS PHASE III TEST CONFIGURATION

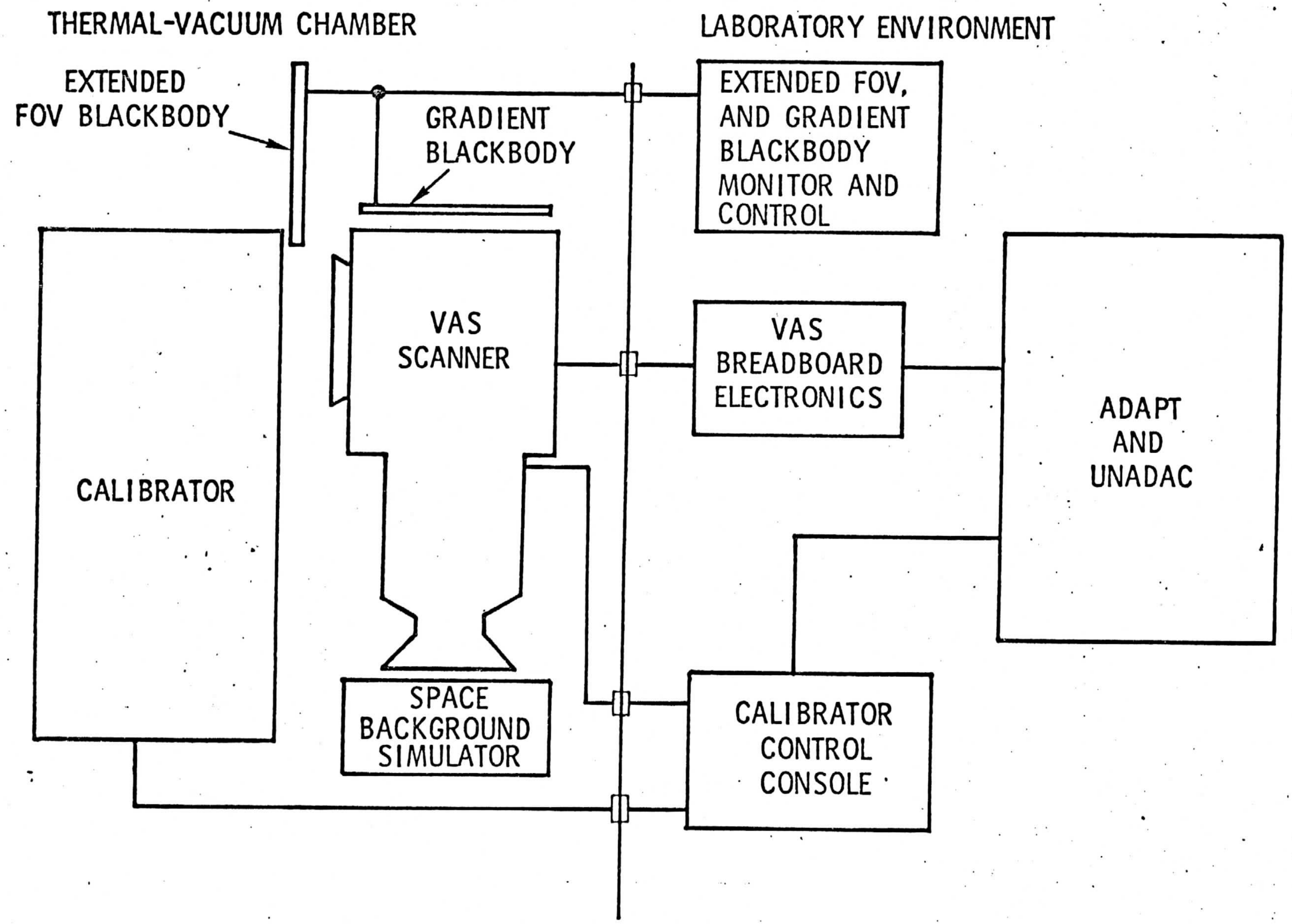


Figure 3

SANTA BARBARA RESEARCH CENTER - VHS TEMP CAL DATA

SET #	BLACKBODY (TS)	SEC MIR (TSM)	PRI MIR (TPM)	SCAN MIR (TSSM)	BAF FWD (TBF)	SHT CAV (TSC)	PRI AP STP (TPAS)	SEC SHLD (TSMS)	BAF AFT (TBA)	5 POS MIR (T5PM)	CAL MIR (TCM)	EXT TRGT (TET)
	TEMPERATURES (DEG C)											
1	26.7835	25.1255	24.3970	25.2894	25.0417	27.3117	23.8787	25.0731	26.6757	25.1000	24.8000	26.3000
2	27.3238	25.1693	24.4284	25.3154	25.0923	27.5223	23.9580	25.0812	26.8486	24.9000	24.8000	26.6000
3	27.5738	25.1379	24.4106	25.2839	25.0729	27.5417	23.9650	25.0253	26.8146	25.0500	24.8000	26.3000
4	27.8168	25.1644	24.4464	25.3405	25.0745	27.6172	24.0782	25.0208	26.6905	25.0000	24.8000	26.3000
5	27.7176	24.9815	24.2066	25.1753	24.8018	27.3954	24.0034	24.7727	26.6643	25.1500	24.8000	26.5000
6	25.9667	19.9604	19.2978	23.2546	16.7845	24.0126	23.8564	15.2784	22.4130	25.0000	24.8000	26.3000
7	25.2480	18.4100	19.1129	22.5074	16.6584	23.7219	23.7127	14.8295	22.1777	24.8000	24.8000	26.5000
8	24.7320	17.3343	18.8967	21.8466	16.3024	23.4703	23.5654	14.2861	21.9202	24.6000	24.8000	25.6000
9	16.3744	14.9887	14.3434	15.2230	15.0330	17.3434	14.4421	14.9858	16.7066	24.0000	14.8000	15.5600
10	16.3744	14.9887	14.3434	15.2230	15.0330	17.3434	14.4421	14.9858	16.7066	24.3000	14.8000	16.5000
11	17.1148	15.0153	14.5605	15.2497	15.2729	17.8804	14.4626	15.0638	17.8483	24.0000	14.8000	16.7000
12	17.1148	15.0153	14.5605	15.2497	15.2729	17.8804	14.4626	15.0638	17.8483	24.3500	14.8000	16.6000
13	17.6757	15.0494	14.7014	15.2641	15.4000	18.0032	14.5094	15.1411	17.2665	23.8000	14.8000	16.8000
14	17.6757	15.0494	14.7014	15.2641	15.4000	18.0032	14.5094	15.1411	17.2665	24.1000	14.8000	16.6000
15	16.6959	12.2134	13.4391	12.0527	13.1466	15.9373	14.4948	10.4294	15.2947	23.4000	14.8000	16.1000
16	16.6959	12.2134	13.4391	12.0527	13.1466	15.9373	14.4948	10.4294	15.2947	23.7000	14.8000	16.2000
17	19.1339	11.2592	13.4014	11.2124	13.0320	16.4426	14.4447	9.7463	15.5703	23.1000	14.8000	16.3000
18	19.1339	11.2592	13.4014	11.2124	13.0320	16.4426	14.4447	9.7463	15.5703	23.3500	14.8000	16.3000
19	26.0690	9.8244	13.2380	9.7496	12.7925	16.7346	14.4111	8.7719	15.6932	22.7000	14.8000	16.2000
20	26.0690	9.8244	13.2380	9.7496	12.7925	16.7346	14.4111	8.7719	15.6932	23.0000	14.8000	16.2000

VOLTAGES (VDC)

SET #	EXT TGT SIG	INT CAL SIG	OFFSET
1	3.493	3.577	0.2042
2	3.509	3.620	0.2041
3	3.490	3.630	0.1988
4	3.480	3.636	0.2086
5	3.496	3.638	0.2055
6	3.499	3.630	0.2015
7	3.511	3.600	0.2042
8	3.513	3.577	0.2038
9	3.130	3.173	0.1997
10	2.858	2.895	0.2491
11	3.130	3.217	0.2080
12	2.865	2.943	0.2560
13	3.135	3.251	0.2059
14	2.865	2.967	0.2510
15	3.110	3.245	0.1983
16	2.838	2.966	0.2579
17	3.122	3.430	0.2015
18	2.855	3.138	0.2542
19	3.118	3.989	0.2016
20	2.839	3.631	0.2530

TE (DEG K) = TS + C1*(TS-TSM) + C2*(TS-TPM) + C3*(TS-TSSM) + C4*(TS-TBF) + C5*(TS-TSC) + C6*(TS-TPAS) + C7*(TS-TSMS)
+ C8*(TS-TBA) + C9*(TS-T5PM) + C10*(TS-TCM) + 273.1

Table 1

to scale the external target radiance

$$T_E = B^{-1}[(V_I - V_0)\ B(T_{ET})/(V_E - V_0)],$$

where B^{-1} indicates the inverse Planck function. The coefficients determined from the physical properites of the VAS telescope (reflectances, emissivities,..) and ray tracing (to determine obscurations ...) are listed in Table 2. With these initial coefficients the absolute error $\overline{\tilde{T}_E - T_E} = 1.35°K$ and the rms deviation $\sigma = 1.22°K$ for the test data. The rms deviation is well outside the accuracy requirements. Without any effort to account for thermal gradients in the VAS telescope $\overline{T_S - T_E} = -2.50°K$ and $\sigma = 2.01°K$. The calculation of $\tilde{T}_E$ is only halving the absolute error and the rms deviation.

It was suggested that possibly some of the coefficients should be reevaluated from better ray trace calculations. This was done at Santa Barbara Research Center (SBRC) and the following adjustments were made: secondary mirror $c_1 = .0564 \rightarrow .0547$; shutter cavity $c_5 = -.0647 \rightarrow -.027$; primary mirror aperture stop $c_6 = .0556 \rightarrow .0471$; and baffle tube aft $c_8 = .087 \rightarrow .06$. The adjusted coefficients yield $\overline{\tilde{T}_E - T_E} = 1.30°K$ and $\sigma = 1.22°K$, which is no improvement.

It was then pointed out that lateral misalignments of the telescope could make the exit pupil stop appear smaller than was previously calculated. With this rationale SBRC adjusted two coefficients, 5 position mirror $c_9 = .03 \rightarrow .01$, and calibrator optics $c_{10} = .09 \rightarrow .11$; and SBRC varied two coefficients to achieve a minimum rms deviation, baffle tube forward $c_4 = .167 \rightarrow .100$, and secondary mirror shield $c_7 = .3056 \rightarrow .1100$. These rather drastic changes resulted in a marked improvement to $\overline{\tilde{T}_E - T_E} = -.097°K$ and $\sigma = .220°K$.

The very large changes in the coefficients are surprising. Estimated errors in the ray trace determination of the initial coefficients were much smaller than some of these changes. Although adjustments of these coefficients

Coefficients Determined from Ray Trace Calculations

i	Symbol	C_i
1	SM	.0564
2	PM	.0434
3	θM	.0417
4	BF	.167
5	SC	-.0647
6	PAS	.0556
7	SMS	.3056
8	BA	.087
9	5PM	.03
10	CM	.09

Table 2

yield acceptable fits to the calibration data, no proven physical justification exists for changes of this magnitude. The question arises whether the calibration data set is well conditioned enough to determine any or all the coefficients from a regression analysis and whether coefficients thus determined agree with the SBRC evaluation. It is the task of this work to answer that question.

4. Regression Analysis of Calibration Data

Working with the twenty data sets we write the relative error $[\tilde{T}_E - T_E - (\overline{\tilde{T}_E - T_E})] = \tilde{T}_i$ where $i = 1,..,20$; the jth telescope component gradient temperature deviation from its mean $[T_S - T_j - (\overline{T_S - T_j})]_i = \Delta_{ij}$ where $j = 1,..,10$; and the increment to the jth initial coefficient d_j. Thus

$$\tilde{T}_i = \sum_j \Delta_{ij} \, d_j \; .$$

In the regression solution we minimize the sum of the squared residuals by varying d_j; therefore

$$\frac{\partial}{\partial d_K} \left\{ \sum_i (\tilde{T}_i - \sum_j \Delta_{ij} \, d_j)^2 \right\} = 0,$$

which leads to the familiar regression solution

$$d_K = \sum_{ij} (\Delta^T \Delta)^{-1}_{Kj} \, \Delta^T_{ji} \, \tilde{T}_i,$$

or

$$\vec{d} = (\Delta^T \Delta)^{-1} \, \Delta^T \, \vec{\tilde{T}} \; .$$

Varying all ten coefficients yields the solution indicated in Table 2. The increments to the initial coefficients are often ten times as large as the coefficient itself and often yield a final coefficient that is unphysical (i.e. a negative scan mirror coefficient implies reflectivities that are greater than 1 or negative, or obscurations that are larger than the field of view). The offset is -3.96 ± 5.04°K and $\sigma = .150$°K.

Proceeding with a stepwise regression analysis we vary the coefficient whose partial correlation coefficient to the relative errors is the highest and fix the remaining nine. Most correlated was $c_{5PM} = c_9$, and upon redetermination it stayed as unphysical as before. In addition the partial correlation coefficients are varying wildly with the redetermination of c_9, thus making additional iterations of this stepwise regression analysis somewhat futile.

An alternate procedure is to vary each coefficient individually leaving the remaining nine fixed to their initial value. The largest rms improvement from an increment that still leaves the coefficient physical comes from the secondary mirror shield; for $c_7 = .306 \rightarrow .071 \pm .015$, we find $\tilde{T}_E - T_E = 1.35 \rightarrow .073 \pm .116°K$ and $\sigma = 1.22 \rightarrow .33°K$. Only an unphysical change in the baffle forward yields a greater rms improvement. Fixing c_7 at .071 and repeating the procedure doesn't yield any improvements in the rms that come from physical changes in the remaining coefficients.

The failure of both stepwise regression procedures arises from the high degree of correlation between the temperature gradients of one component of the telescope with those of another component of the telescope. Most correlations are .9 or higher. Only for temperatures in the baffle forward (4), primary aperture stop (6), and 5 position mirror (9) is the correlation not this high (correlation $\leq .67$ for these three). Varying only these three reduced the rms deviation to .184°K but left c_4 unphysical, c_6 three times bigger, and c_9 roughly zero. Temperatures in the baffle forward (4) and the secondary mirror shield (7), both varied to achieve a minimum rms deviation by SBRC, have a correlation of .985. Varying (4), (7), (9), and (10), as SBRC did, show increments going in the same directions as SBRC but with largely differing magnitudes. Table 3 summarizes these results.

Apparently the data set does not contain sufficient information to determine all the coefficients with a least squares regression analysis. This can be seen more clearly in Figure 4 where the individual temperature

Summary

i	c_i	d_i				
1	.0564	.43±.70				
2	.0434	3.84±6.01				
3	.0417	-2.08±3.02				
4	.167	-5.34±7.41			-.30±.02	-.19±.07 (-.067)
5	-.0647	1.03±1.71				
6	.0556	2.36±1.62			.12±.02	
7	.3056	2.38±3.57		-.24±.02		-.10±.05 (-.1956)
8	.087	- .72±2.11				
9	.03	- .15±.07	-.15±.05		-.03±.01	-.04±.01 (-.02)
10	.09	-1.89±1.26				.07±.02 (+.02)
$\tilde{T}_E - T_E$	1.35	-3.96±5.04	-1.49±.27	.07±.12	-.08±.10	-.04±.09
σ	1.22	.15	1.06	.33	.18	.16
		A	B	C	D	E

A vary all ten coefficients

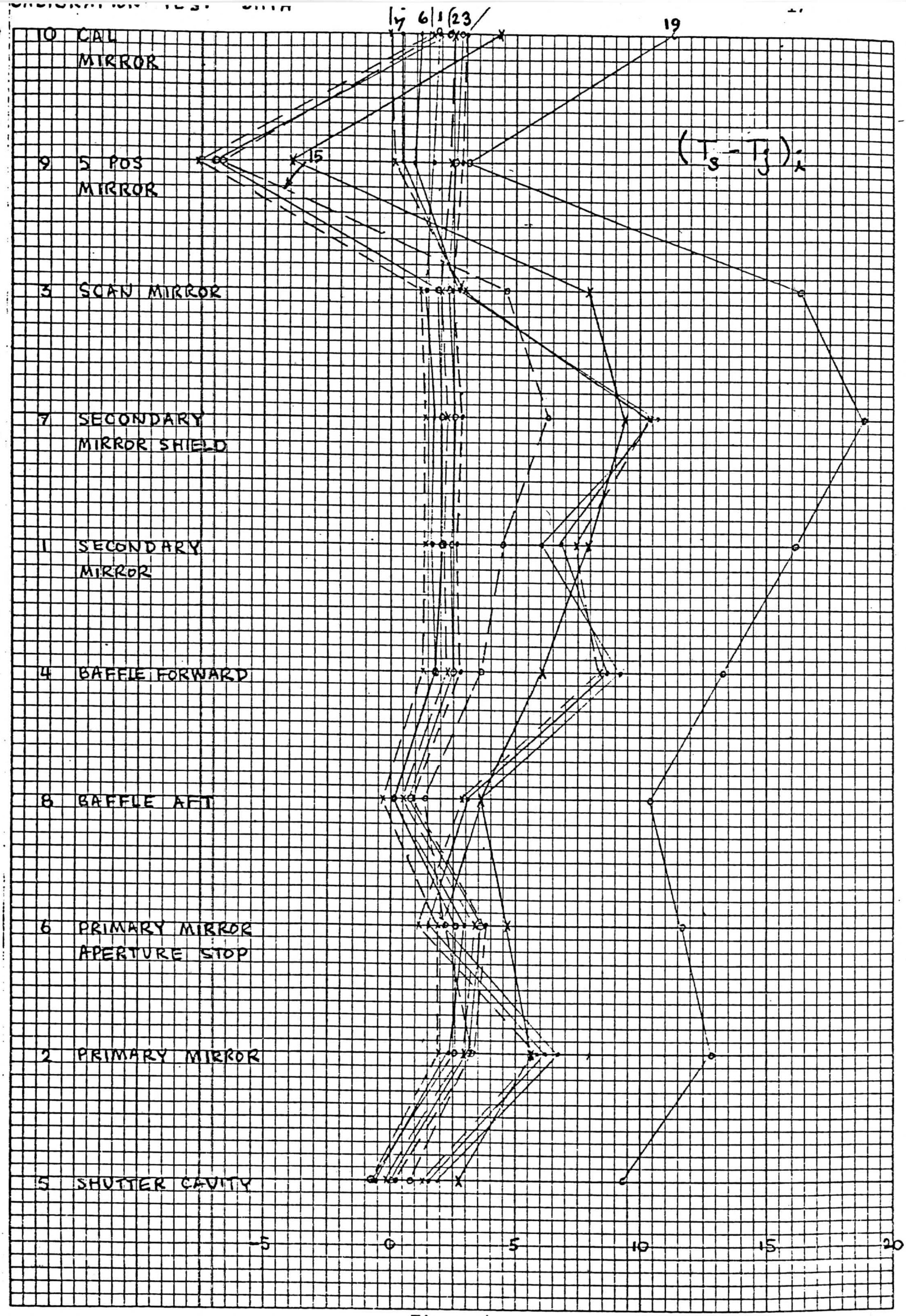
B vary only the coefficient whose partial correlation coefficient to residuals is the highest

C by varying each coefficient individually find largest σ improvement from an increment that still leaves the coefficient physical

D vary only the coefficients of telescope components whose temperature changes are correlated less than .67

E vary coefficients SBRC varied (SBRC results in parenthesis)

Table 3



17
6
1
23
19
15
10 CAL MIRROR
9 5 POS MIRROR
3 SCAN MIRROR
7 SECONDARY MIRROR SHIELD
1 SECONDARY MIRROR
4 BAFFLE FORWARD
8 BAFFLE AFT
6 PRIMARY MIRROR APERTURE STOP
2 PRIMARY MIRROR
5 SHUTTER CAVITY
$(T_s - T_j)_i$
-5
0
5
10
15
20

Figure 4

gradients with respect to the internal blackbody temperature, $(T_S - T_j)$, are plotted for the twenty data sets. At best there are four or five sets of different temperature variations, implying that only four or five equations can be determined relating the ten coefficients. This becomes more transparent in the next section.

5. Analysis of Covariance

To determine explicitly the relationships between the ten coefficients determinable from the calibration data set, we rewrite the regression solution for $\vec{d}$ in terms of the eigenvalues, Λ, and eigenvectors, ∂, of the covariance matrix, $n^{-1}\Delta^T\Delta$, where n is the number of data samples (for the calibration data set n = 20);

$$\vec{d} = n^{-1}\partial\Lambda^{-1}\partial^T\Delta^T\vec{T} .$$

When the square root of the eigenvalue of the covariance matrix is less than the accuracy of the temperature measurements (.1 to .2°K), its contribution to $\vec{d}$ is not reliable. For this data set, six eigenvalues of the covariance matrix are within the noise level of the measurements. Hence we can at best construct four equations and ten unknowns to determine $\vec{d}$;

$$\partial^T\vec{d} = n^{-1}\Lambda^{-1}\partial^T\Delta^T\vec{T} , \quad \sqrt{\Lambda} \gtrsim .1 .$$

Of the four reliable equations one has $\partial^T\vec{d} \sim \partial^T_9 d_9$ so that the 5 position mirror coefficient can be approximated; $c_9 \sim -.01$, again very close to zero. Furthermore most of the telescope correction $\Sigma_i c_i(T_S - T_i)$ arises from the baffle forward (4) and the secondary mirror shield (7), so that changes in these terms dominate wherever ∂^T_4 and ∂^T_7 are non negligible. In this way we find $d_4 + d_7 \sim -.3$; the sum of the coefficients wants to be reduced by .3. The high correlation of the two parameters impedes individual determination of either coefficient. Further conclusions from the four equations are not transparent.

Finally one can repeat the above procedure with the following difference: allow changes only in the coefficients that SBRC allowed to vary (4, 7, 9, and 10) and work with the eigenvalues and eigenvectors of the 4 x 4 covariance matrix of only those four parameters. All eigenvalues of this covariance matrix are acceptable, and solution of the equations yields $c_4 = -.04$, $c_7 = +.21$, $c_9 = -.01$, and $c_{10} = +.15$. The result for c_4 is unphysical and $d_4 + d_7 = -.3$ is the better conclusion in light of the high correlation of these two parameters. Again we find increments going in the same direction as those of SBRC but of much different magnitude.

Performing the same analysis many times but with normally distributed random noise added on to the individual temperature measurements (.2 rms noise for data sets 5, 6, 7, and 8 and .1 rms noise for all others) allows a determination of an error estimate to the four coefficients. From 100 noise runs we find $c_4 = -.04 \pm .10$, $c_7 = .21 \pm .07$, $c_9 = -.01 \pm .02$, and $c_{10} = .15 \pm .03$. All coefficients overlap into physical regions and c_9 is most accurately determined. Figure 5 shows that none of these coefficient estimates overlap with the initial ray trace determined coefficients or the SBRC varied coefficients.

Clearly the vacuum test data has too high a degree of correlation in the telescope temperature gradients to allow a unique determination of the coefficients. To avoid this problem it is necessary to introduce more variation in the telescope temperature gradients. However if non-unique coefficients based on laboratory test data are to be employed, the laboratory gradient conditions should be as close as possible to those expected in space. Table 4 presents typical VAS telescope component temperatures (provided by NASA) tabulated at five times in the year. Figure 6 shows those space thermal gradients which are clearly different from the laboratory induced thermal gradients. Analysis of covariance of this data shows three of the eight equations reliable with (3), (4), and (7) (scan mirror, baffle forward,

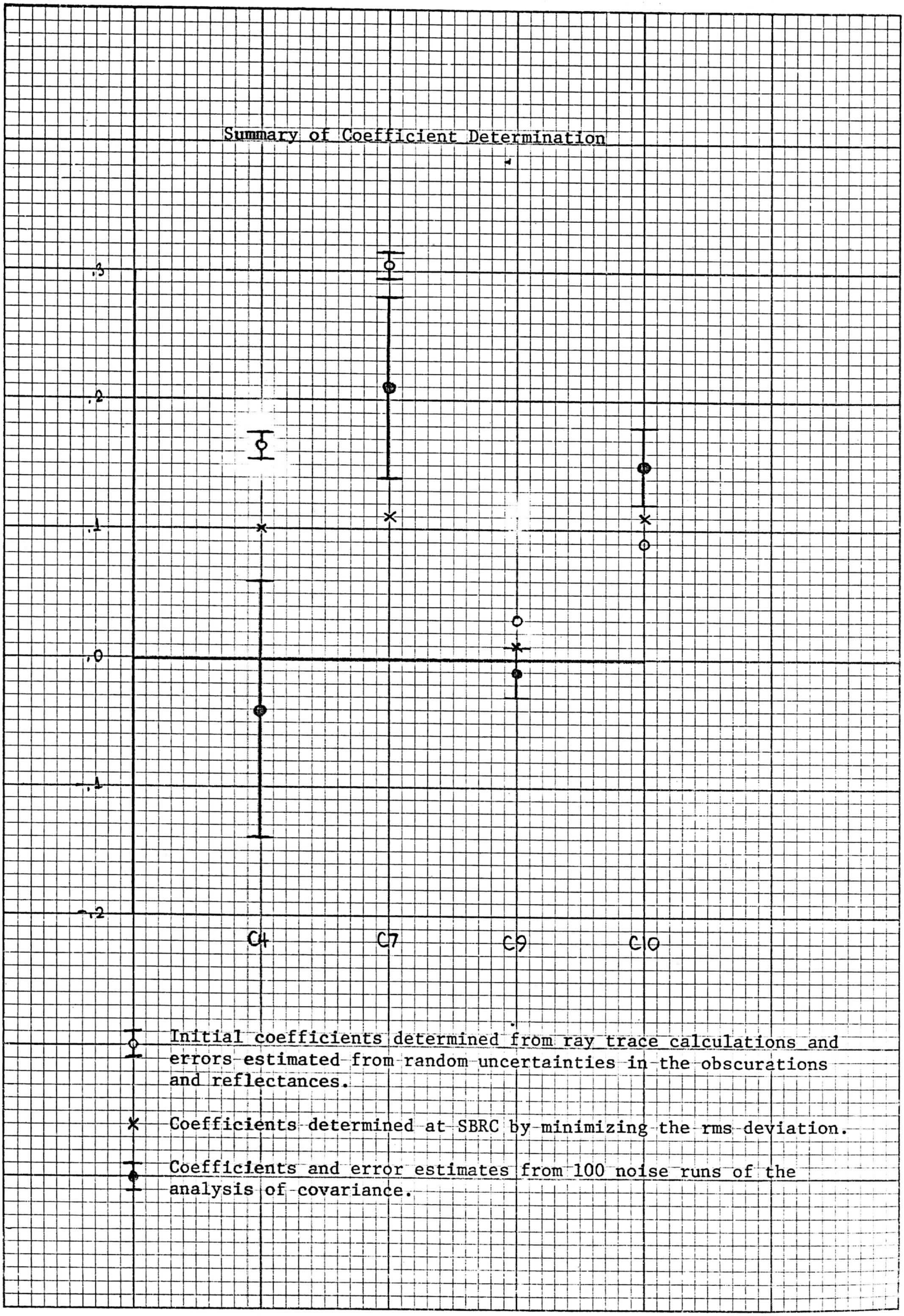

Summary of Coefficient Determination
.3
.2
.1
.0
-.1
-.2
C4
C7
C9
C10
Initial coefficients determined from ray trace calculations and errors estimated from random uncertainties in the obscurations and reflectances.
Coefficients determined at SBRC by minimizing the rms deviation.
Coefficients and error estimates from 100 noise runs of the analysis of covariance.

Figure 5

Typical VAS In-flight Temperatures (°C)

	S	SM	PM	θM	BF	SC	PAS	SMS	BA
winter	16.4	13.7	16.0	14.0	17.35	16.2	14.6	13.8	16.2
-10	17.7	17.0	18.5	17.2	16.95	17.4	15.98	17.45	17.3
equinox	18.2	23.5	21.0	17.5	16.25	17.9	16.45	21.4	17.55
+10	18.7	14.9	20.2	15.5	16.05	18.2	17.42	15.45	17.85
summer	25.2	9.5	28.1	10.4	19.05	23.7	24.33	9.65	22.75

Table 4

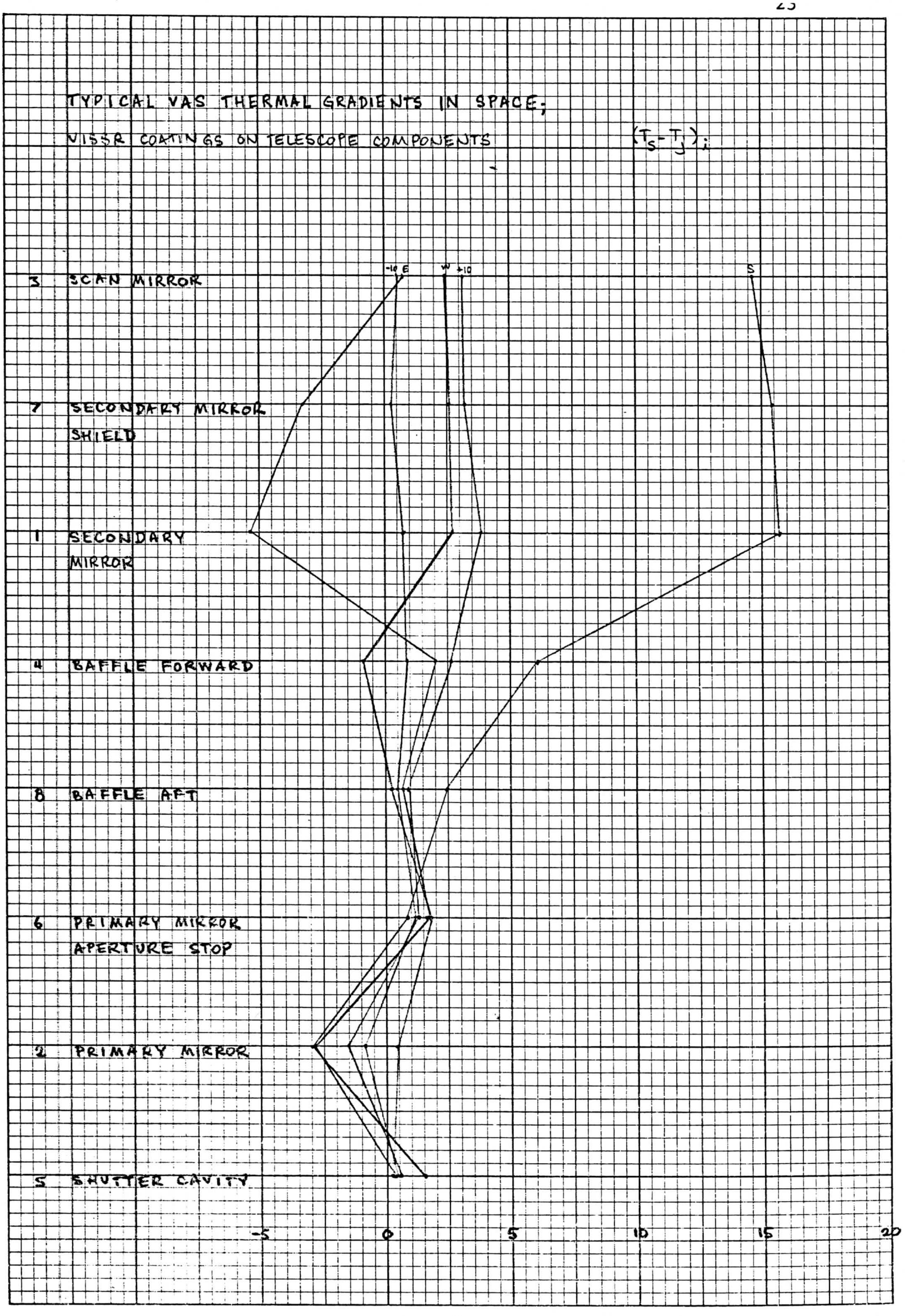

TYPICAL VAS THERMAL GRADIENTS IN SPACE;
VISSR COATINGS ON TELESCOPE COMPONENTS
$(T_S - T_J)_i$
-10 E
W +10
S
3 SCAN MIRROR
7 SECONDARY MIRROR SHIELD
1 SECONDARY MIRROR
4 BAFFLE FORWARD
8 BAFFLE AFT
6 PRIMARY MIRROR APERTURE STOP
2 PRIMARY MIRROR
5 SHUTTER CAVITY
-5
0
5
10
15
20

Figure 6

and secondary mirror shield) most determinable. High correlations (>.98) exist between (1) and (7), (secondary mirror and secondary mirror shield), and between (5) and (8), (shutter cavity and baffle aft). Thermal gradients of 10 to 15°K are not uncommon.

SBRC has most likely already achieved the practical limits for producing independent variation in the telescope temperature gradients and for reproducing expected space thermal gradients in the laboratory. However, if it is possible, efforts should be directed toward producing laboratory variation in the temperature gradients of the baffle forward (4) and the secondary mirror shield (7) that are uncorrelated and that allow reliable determination of these two coefficients. More accurate evaluation of these two coefficients would produce the most significant improvement in the calibration since most of the telescope correction comes from them under expected space conditions.

6. Conclusions

In summary, although the calibration data set does not allow unique determination of all the coefficients, it does indicate the following conclusions.

(a) The present calibration scheme implemented with coefficients determined explicitly from the physical setup of the telescope does not satisfy the accuracy requirements. By changing some of the coefficients the calibration can be made to meet the accuracy requirements. However several of these changes move the coefficients far outside the range defined by their calculated values and their estimated errors.

(b) The high degree of correlation in the telescope temperature gradients during the thermal vacuum tests prevents a unique determination of the coefficients. At best there are four equations from which relationships between the coefficients can be deduced. The coefficient for the 5 position mirror is best determined and tends to be zero (possibly the 5 position mirror temperature is not being correctly monitored). The sum of the coefficients of the baffle forward and the secondary mirror shield tends to be reduced by .3 (perhaps temperature gradients within the component itself can account for this discrepancy).

(c) If calibration coefficients are to be uniquely defined by laboratory test data, it is necessary to introduce more variation in the telescope temperature gradients than was present in the Engineering Model Thermal Vacuum Test. Most significant improvement in the calibration would come from accurate determination of the baffle forward and secondary mirror shield coefficients. Laboratory variation in the telescope temperature gradients of especially these two components should be uncorrelated and should allow unique determination of these coefficients. In addition telescope temperature gradients should be as close as possible to those expected in space (Figure 6), so that possible non-unique coefficient changes based on laboratory test data would be representative.

(d) Finally, even if a unique determination of the coefficients could be made, the speculation that the coefficient changes are due to small lateral misalignments in the telescope relay optics indicates that the stability of the coefficients is in question. In other words if the calibration coefficients were established prior to launch, could they be perturbed so much by handling and launch vibrations that they would not meet radiometric accuracy requirements?