DRAFT

Measurement of R.F. Module Calibration Constants and Tolerances

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#4

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The expected response of the RF Module position channel is given in BPM Design Note #1 (Equation 6):

$$\left(\frac{A}{B}\right)_{dB} = \frac{-20}{\ln 10} \ln \tan\left\{C_1(V-V_0) + \pi/4\right\} \qquad (1)$$

where C_1 and V_0 are calibration constants. The beam position system was designed assuming Equation (1) to be correct. Testing shows that a slight improvement in fit of this curve to module data can be achieved by including a fudge factor F:

$$\left(\frac{A}{B}\right)_{dB} = \frac{-20}{F \ln 10} \ln \tan\left\{F C_1(V-V_0) + \pi/4\right\} \qquad (2)$$

The nominal value of the constant V_0, which represents the value in volts of the position channel output for $(A/B) = 0$ dB, is precisely zero. The nominal value of the gain constant C_1 was chosen with consideration given to the signal levels commonly employed in analog instrumentation circuits: For $(A/B)\,dB = \pm\infty$, the voltage output is ∓ 2.5 volts. This leads to (with $F=1$):

$$C_1 = \pi/10 \qquad .2974 \qquad (3)$$

IDEAL POSITION CHANNEL CALIBRATION

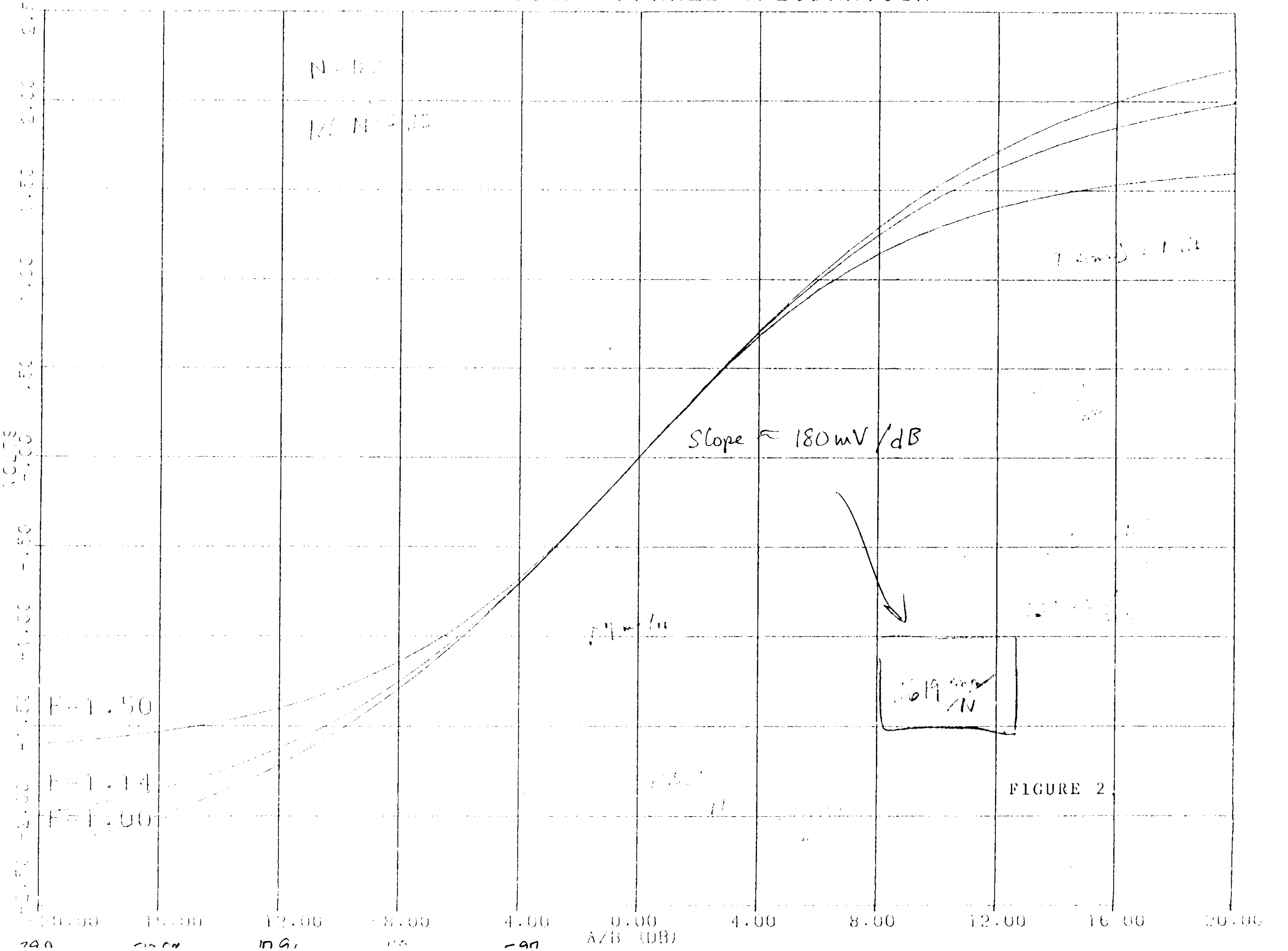


FIGURE 2

The effect of the value of F on the response for $V_0 = 0$ and $C_1 = \pi/10$ is shown in Figure (1). Figure (1) also shows a typical set of RF Module data for comparison to the curve. Note that of the three curves, the best fit occurs for $F = 1.14$. The slope of the curve in Figure (1) is given by (see Appendix 1):

$$\frac{dV}{d(A/B)\,dB} = \frac{\ln 10}{40 C_1} \operatorname{sech}\left[\frac{F \ln 10}{20}\left(\frac{A}{B}\right)_{dB}\right] \qquad (4)$$

Hence at $(A/B) = 0$ dB, the slope is independent of F and is approximately 180 mV/dB.

Due to the presence of a large temperature coefficient in C_1 (about 4000 ppm/°C) and the requirement that C_1 be stable to less than ±.5% over the range 15°C–35°C, thermistor stabilization of the output op amp circuit was required, (See Appendix 2). The thermistor compensates for drift in the double balanced mixer.

The calibration constants are determined from measurements. Figure (2) shows the connection of test equipment and the unit-under-test, the position signal voltage, for various settings of the A, B and COMMON attenuators is measured. Electronically switchable attenuators were used to enhance measurement repeatability. Measurements were taken for a range of input signal power levels; specifically:

$(A+B)$ dBm $= +5, -5, -15, -25$ and -35 dBm

For each power level, 21 points were measured with (A/B) dB ranging from −20 to +20 dB. The measurements were made on five modules at two temperatures. The raw data is shown in tables (1)–(10).

Each of the columns in the tabulated data were reduced by the method of least squares fit. A general least squares fit takes the following form – For N measured points (x_i, y_i) which are expected to fit a function $y = f(x)$, the least squares fit finds values of the unknown coefficients of $f(x)$ such that the function:

$$\sum_{i=1}^{N} \left[y_i - f(x_i) \right]^2 \text{ is a minimum.}$$

The most probable values for C_1 and V_0 are shown in Tables (11) and (12). These results are plotted in Figures (3) and (4). To obtain the most probable values of C_1 and V_0, and their tolerances at each power level, the averages of the fitted values were calculated.

(A+B) (dBm)	C_1 (1/VOLT)	V_0 (VOLT)
+5	.2934 ± .0054 (±1.85%)	.0172 ± .0213
−5	.2967 ± .0014 (±.47%)	.0190 ± .0218
−15	.2967 ± .0013 (±.46%)	.0223 ± .0207
−25	.2983 ± .0016 (±.54%)	.0161 ± .0177
−35	.3020 ± .0028 (±.93%)	.0052 ± .0207

Since the nominal values of V_0 are less than the deviations, the nominal values can be set to zero. Overall values are obtained using $\boxed{F=1.14}$.

$$\boxed{C_1 = .2974} \pm .0036 \quad (\pm 1.20\%)$$

$$V_0 = 0 \pm .026$$

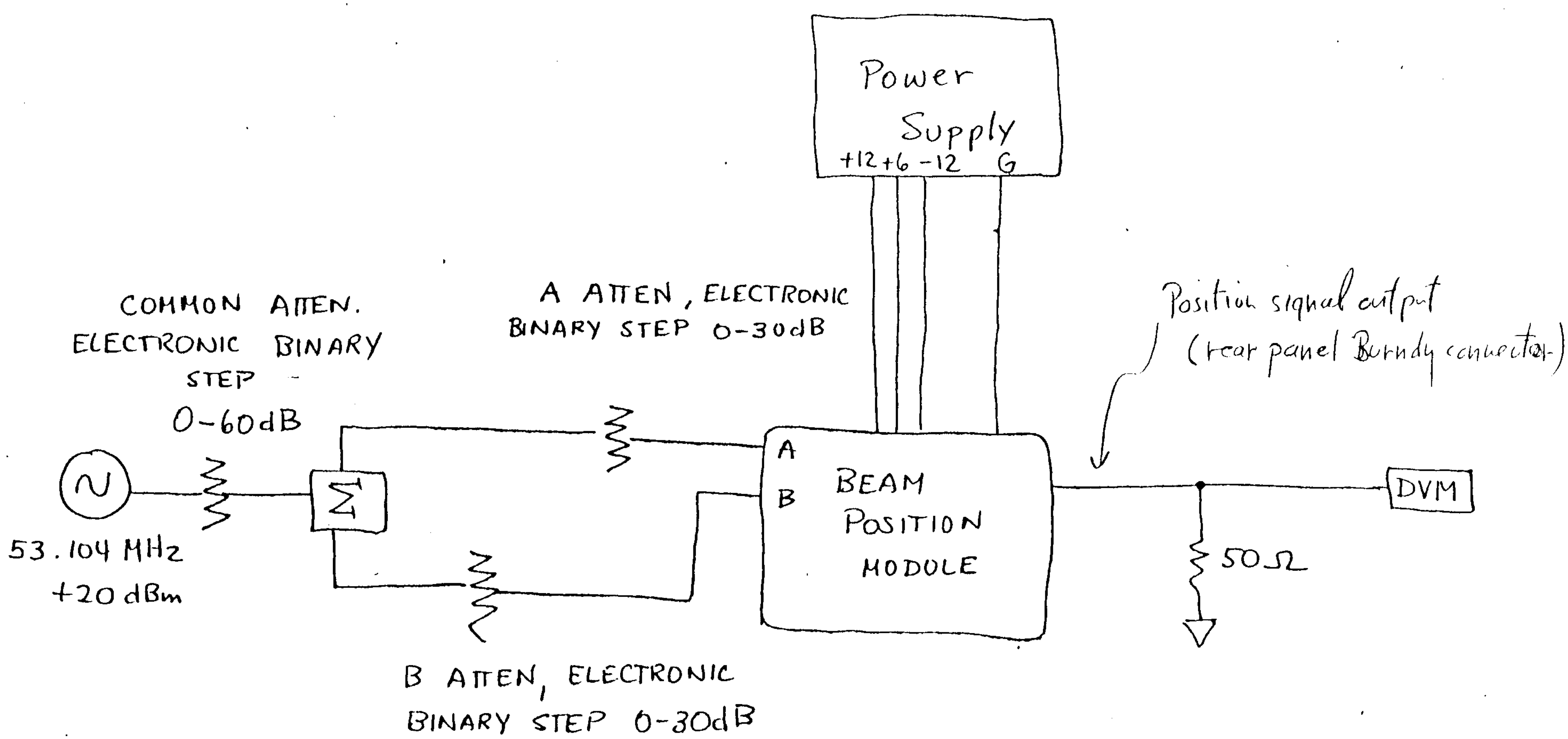
Conclusion

Individual data sets of (A/B) dB versus V (volts) fit the ln-tan function, Equation (1), well; typically this contribution to tolerance on C_1 is $\pm .2\%$. Contribution to the tolerance on C_1 caused by a change in temperature (within $\pm 10°C$ of $25°C$) is typically less than $\pm .5\%$. A reduction in the change of V_0 with temperature did not occur as a result of the temperature compensation as expected. The largest contributors to the tolerance on C_1 are unit-to-unit variation and change in signal level.

The reported deviation on parameter C_1 is $\pm 1.2\%$. This deviation is nearly within the tolerance on parameter C_1 suggested in BPM Design Note #1. The deviation of V_0 is about ± 25 mV. This exceeds the suggested tolerance of ± 10 mV. The variation of offset V_0 is principally a result of random, statistical variations in the parameters which characterize electronic components. Therefore, no straightforward hardware modification is envisioned for reducing this deviation.

* The numerical calculations required in this note were made using computer routines. K. Ueno wrote the computer program which performed the least squares fit operation. E. Faught wrote and executed programs for the tolerance calculation and generation of,

the various CALCOMP graphics.



TEST SET-UP

FIGURE 2

PARAMETER VO VS. (A+B) DBM
SUMMARY OF TABLES 11.12
(F=1.14)

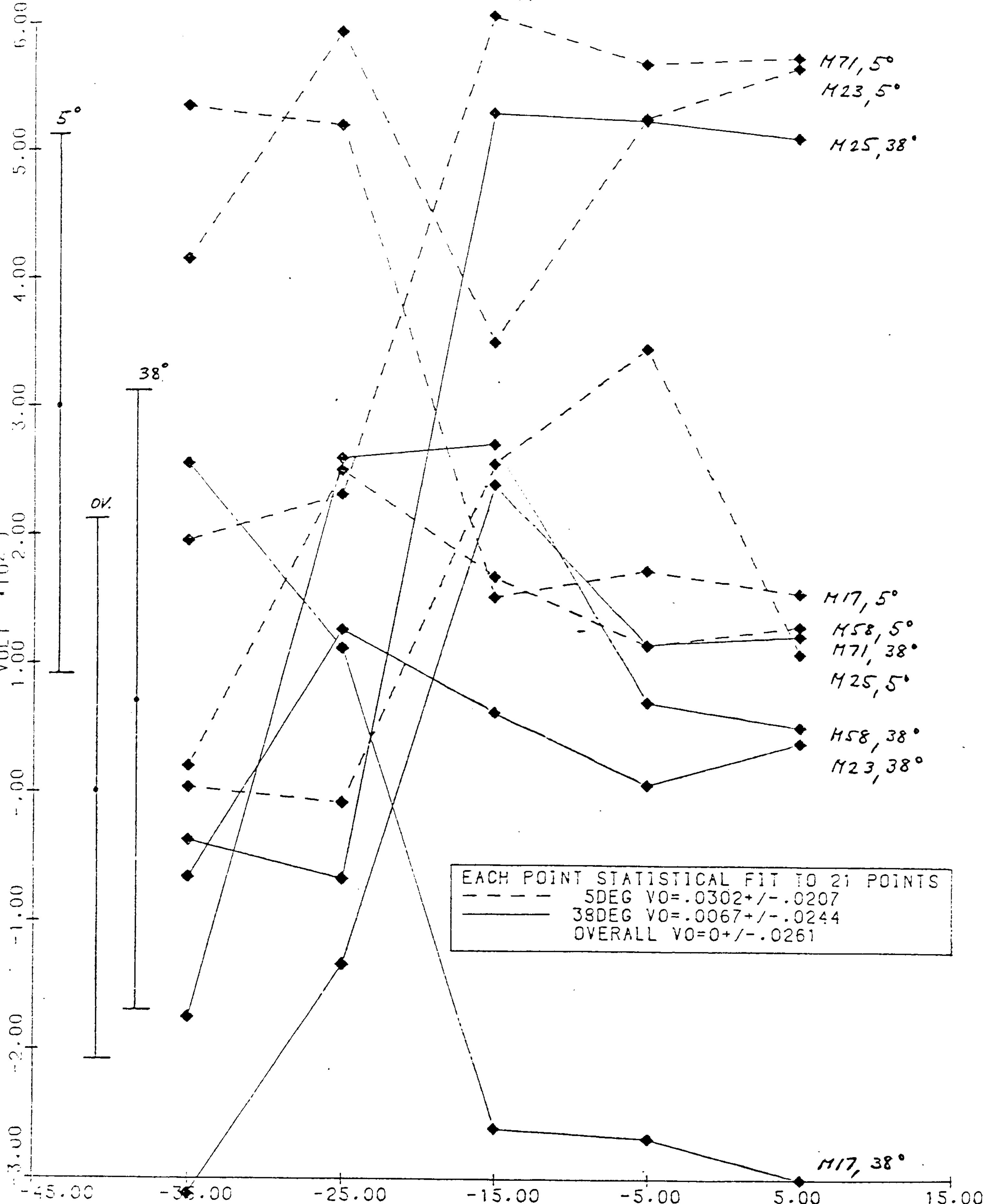


FIGURE 34

PARAMETER C1 VS. (A+B)DBM
SUMMARY OF TABLES 11.12
(F=1.14)

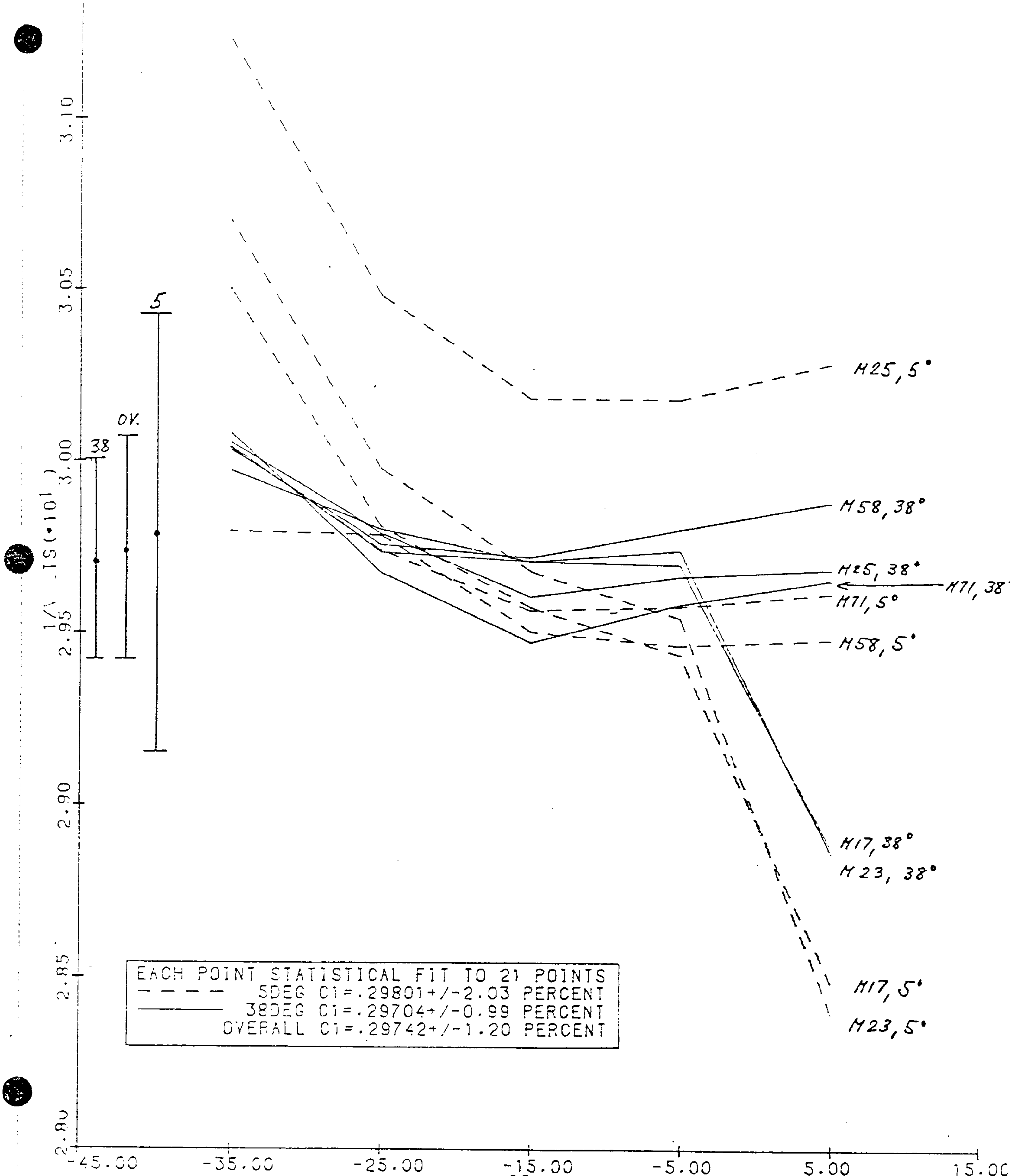


FIGURE 4

Appendix 1

$$V = V_0 + \frac{1}{FC_1}\left\{\tan^{-1}\left(\exp\left(\frac{F\ln 10}{20}R\right)\right) - \pi/4\right\} \qquad R = (A/B)\,dB \quad (1)$$

$$\frac{\partial V}{\partial R} = \frac{1}{FC_1}\left\{\frac{F\frac{\ln 10}{20}}{1+\left[\exp\left(\frac{F\ln 10}{20}R\right)\right]^2}\right\}\exp\left(\frac{F\ln 10}{20}R\right) \qquad (2)$$

$$= \frac{\ln 10}{20C_1}\,\frac{1}{\exp\left(-\frac{F\ln 10}{20}R\right) + \exp\left(\frac{F\ln 10}{20}R\right)} \qquad (3)$$

$$\frac{\partial V}{\partial R} = \frac{\ln 10}{40C_1}\,\mathrm{sech}\left(\frac{F\ln 10}{20}R\right) \qquad (4)$$

for $C_1 = \pi/10$ and $R = 0$

$$\frac{\partial V}{\partial R} = \frac{\ln 10}{40(\pi/10)} = \frac{\ln 10}{4\pi} \cong .1832\ V/dB \qquad (5)$$

for $R \to \pm\infty$

$$\frac{\partial V}{\partial R} \to 0 \qquad (6)$$

$$\frac{\partial V}{\partial F} = \frac{-1}{C_1F^2}\left\{\tan^{-1}\exp\left(\frac{F\ln 10}{20}R\right) - \pi/4\right\} +$$

$$\frac{1}{FC_1}\left\{\frac{\frac{\ln 10}{20}R}{1+\left[\exp\left(\frac{F\ln 10}{20}\right)R\right]^2}\right\}\exp\left(\frac{F\ln 10}{20}R\right) \qquad (7)$$

$$\frac{\partial V}{\partial F} = -\frac{1}{F}\frac{1}{FC_1}\left\{\tan^{-1}\left[\exp\left(\frac{F\ln 10}{20}R\right) - \pi/4\right]\right\} + \frac{R}{F}\frac{\ln 10}{40C_1}\operatorname{sech}\left(\frac{F\ln 10}{20}R\right) \quad (8)$$

$$\frac{\partial V}{\partial F} = -\frac{V}{F} + \frac{R}{F}\frac{\partial V}{\partial R} \quad (9)$$

$$\frac{\partial V}{\partial F} = \frac{1}{F}\left(R\frac{\partial V}{\partial R} - V\right) \quad (10)$$

$$R = 0 \qquad \frac{\partial V}{\partial F} = \frac{1}{F}\left(0\cdot\frac{\ln 10}{4\pi} - 0\right) = 0 \quad (11)$$

No change in V with a change in F for $(A/B)dB = 0$.

Appendix 2

Temperature Compensation Scheme

A sampling of BPM's showed the position channel to be temperature sensitive. The average value of this sensitivity was determined, from measurements of ten units, to be approximately −3790 ppm / °C.

For a given temperature T, temperature sensitivity is defined in this case as:

$$Y(T) = \frac{1}{A(T)} \frac{dA(T)}{dT} \quad \text{(normalized change in gain/°C)} \qquad (1)$$

For temperature compensation, the value of Y(T) for the position channel can be set equal to the desired value of Y(T) for the amplifier/buffer circuit (with change in sign) if one assumes the amplifier circuit to have zero contribution to the overall effect.

$$Y(T)\ \text{(POSITION CHANNEL)} = -Y(T)\ \text{(AMPLIFIER CIRCUIT)} \qquad (2)$$

Figure (A1) is a simplified schematic of the op-amp circuit.

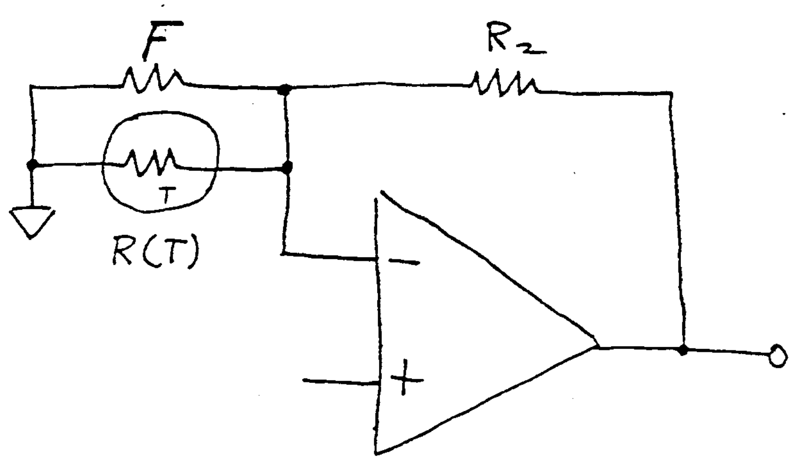


FIGURE A1.

R_2 = fixed feedback resistor
F = fixed parallel resistor
$R(T)$ = resistance of thermistor

At low video frequencies the gain of the circuit in Fig. (A1) is very nearly:

$$A = 1 + \frac{R_2(F+R(T))}{FR(T)} = 1 + \frac{R_2}{R(T)} + \frac{R_2}{F} \tag{3}$$

and:

$$R(T) = R(T_0)\exp\left[\beta\left(\frac{1}{T}-\frac{1}{T_0}\right)\right] \tag{4}$$

To calculate $Y(T)$ in Equation (1) we need dA/dT.

$$\frac{dA}{dT} = \frac{R_2}{R(T_0)}\frac{d}{dT}\exp\left[-\beta\left(\frac{1}{T}-\frac{1}{T_0}\right)\right] \tag{5}$$

$$= \frac{R_2}{R(T_0)}\exp\left[\beta\left(\frac{1}{T_0}-\frac{1}{T}\right)\right]\frac{\beta}{T^2}$$

$$\frac{dA}{dT} = \frac{R_2}{R(T)}\frac{\beta}{T^2} \tag{6}$$

Using Equation (1):

$$Y(T) = \frac{\beta}{T^2}\frac{FR_2}{FR(T) + FR_2 + R_2R(T)} \tag{7}$$

Solving Eq. (7) for resistance F allows F to be selected to give the desired gain change with temperature

$$F(T) = \frac{R_2T^2Y(T)R(T)}{\beta R_2 - T^2Y(T)R(T) - T^2Y(T)R_2} \tag{8}$$

$$F(T_0) = \frac{R_2 T_0^2 Y(T_0) R(T_0)}{\beta R_2 - T_0^2 Y(T_0) R(T_0) - T_0^2 Y(T_0) R_2} \qquad (9)$$

The values used in Equation (9) are:

$R_2 = 3600$ OHM $\qquad T_0 = 298.15$ °K

$R(T_0) = 2000$ OHM $\qquad Y(T_0) = +.00379$

$\beta = 3400$ °K

The calculated value for $F(25\,°C) = 234.3$ OHMS.

At the operating temperature, the point where the compensation is designed to be best, we would like the compensation to vary as little as possible with change in temperature. That is:

$$\frac{dY(T)}{dT} \cong 0 \qquad 15°C < T < 35°C \qquad (10)$$

$$\frac{dY(T)}{dT} = Y^2(T) \frac{(F+R_2)}{FR_2} R(T) - \frac{2Y(T)}{T} \qquad (11)$$

The requirement Equation (10) yields a value of F.

$$F(T_0) = \frac{Y(T_0) R_2 T_0 R(T_0)}{2R_2 - Y(T_0) T_0 R(T_0)} \qquad (12)$$

$F(25\,°C) = 1646.9$ OHMS for $dY/dT = 0$.

Lastly, we would like to choose the nominal gain of the stage as an afterthought. We would like:

$$\frac{dY(T)}{dR_2} \cong 0 \qquad (13)$$

R_2 is the only resistance that can be changed

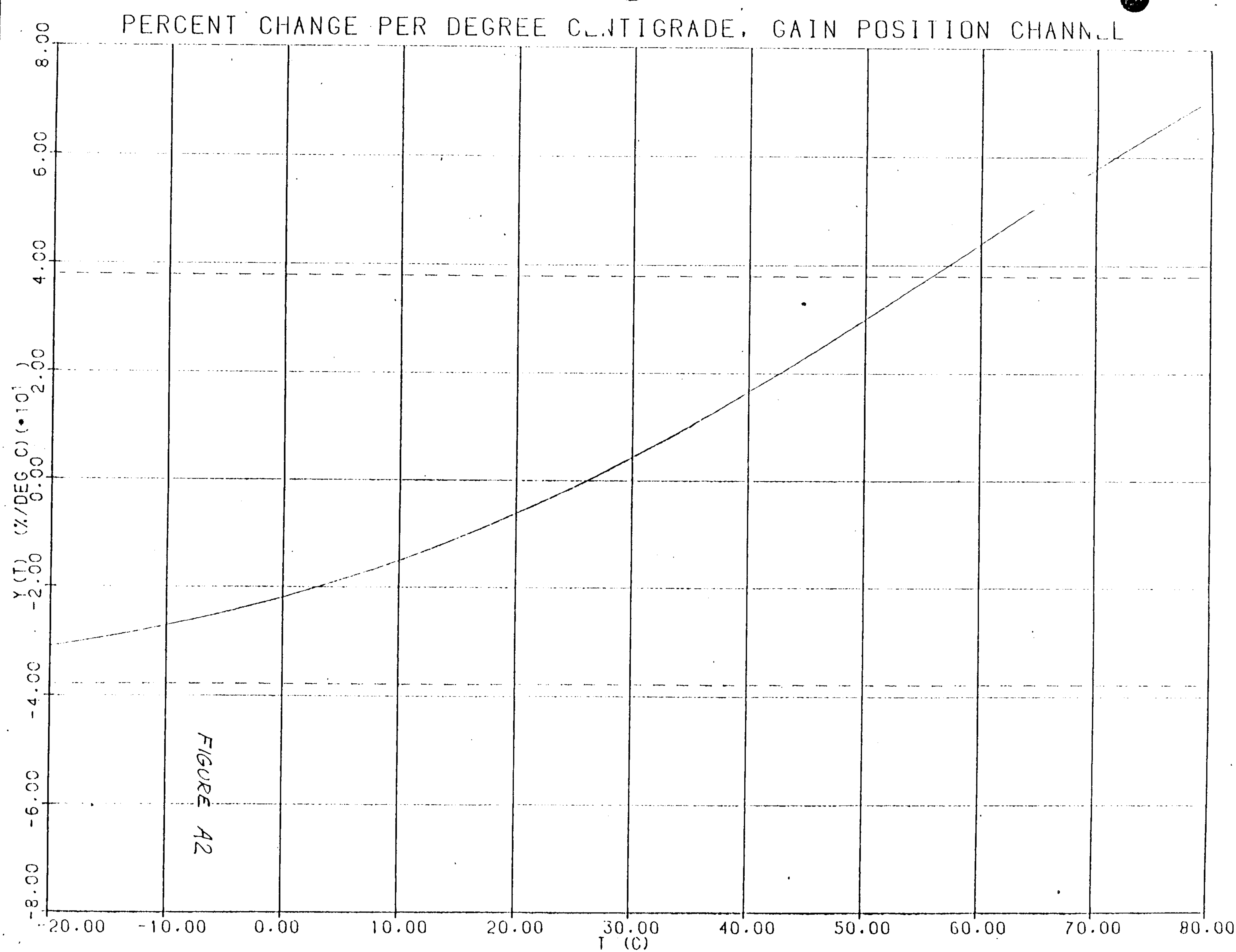

PERCENT CHANGE PER DEGREE CENTIGRADE, GAIN POSITION CHANNEL
Y (T) (%/DEG C)(*10¹)
T (C)
8.00
6.00
4.00
2.00
0.00
-2.00
-4.00
-6.00
-8.00
-20.00
-10.00
0.00
10.00
20.00
30.00
40.00
50.00
60.00
70.00
80.00

FIGURE A2

to establish the gain (about 18 VOLTS/VOLT is desired).

$$\frac{dY(T)}{dR_2} = \frac{Y(T)}{R_2}\left\{1 - \frac{T^2 Y(T)}{\beta F}\left[F + R(T)\right]\right\} \quad (14)$$

FOR $\frac{dY(T)}{dR_2} = 0$ $\quad F = \frac{T^2 Y(T) R(T)}{\beta - T^2 Y(T)}$ (15)

$F = 219.9$ OHMS

Choosing the value of F takes account of the three criteria established. The most important of these is that $Y(T_0) = +.00379$. Therefore, F was chosen to be 220 OHMS.

With the value of F established, Y(T) is plotted versus temperature. Note in Figure (A2) that $Y(T) \cong 0$ for $T = 25°C$. The horizontal lines $Y(T) = -.00379$ and $Y(T) = +.00379$ represent the gain change of the uncompensated position channel (i.e. regardless of temperature, the percent change in gain per degree centigrade is always $-.379$. Note that for temperatures above approximately 55 °C, the addition of temperature compensation exacerbates the position channel temperature dependence.

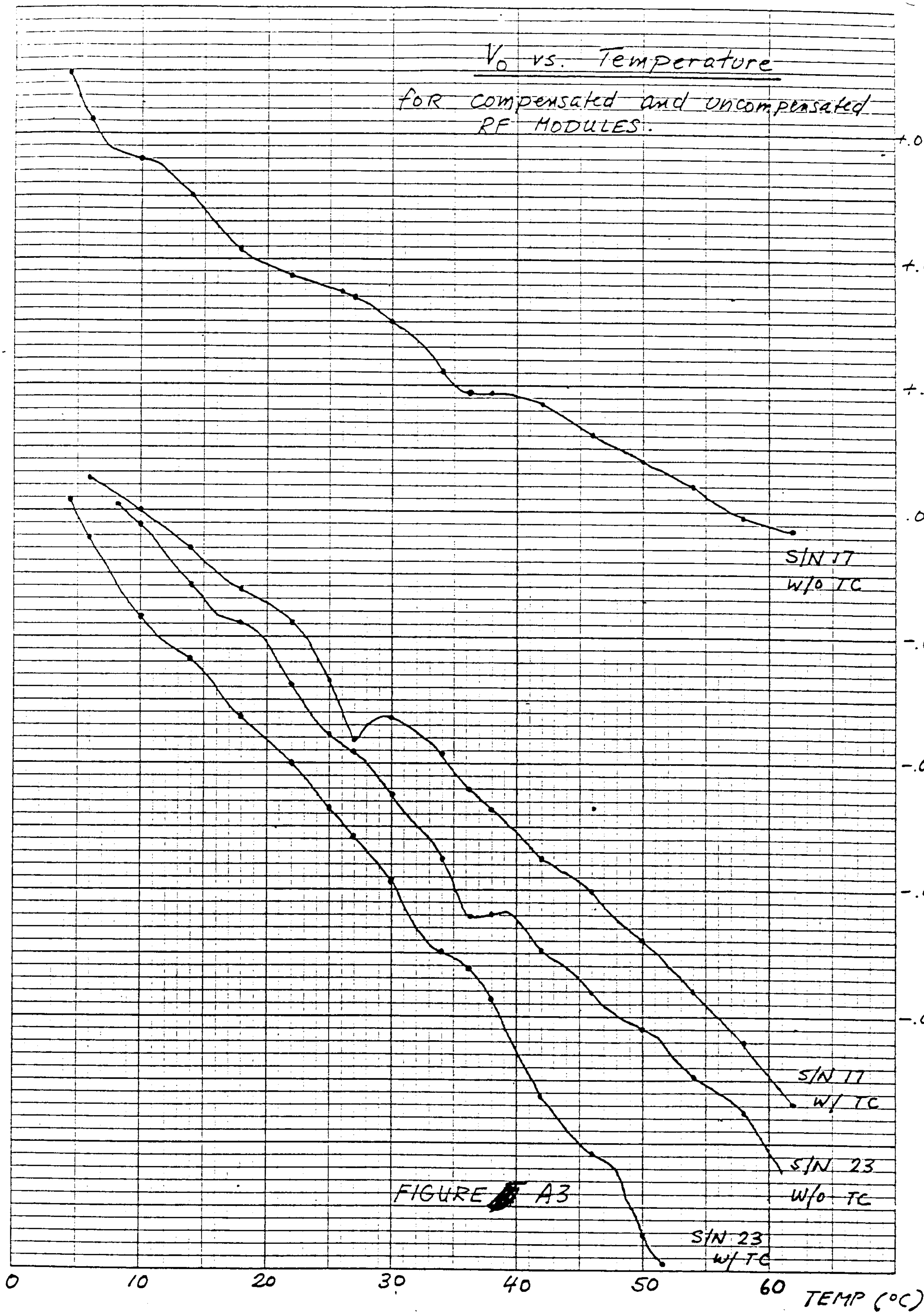

V_o vs. Temperature
for compensated and uncompensated RF MODULES.
S/N 17 W/o TC
S/N 17 W/ TC
S/N 23 W/o TC
S/N 23 W/ TC
0
10
20
30
40
50
60
TEMP (°C)
.00

FIGURE A3