A Re-Examination of the AGC Calibration Procedure

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In this article a re-examination of automatic gain control (AGC) calibration errors was made to determine if an improvement in reported spacecraft carrier power could be obtained by modifying the signal level tracking calibration procedure. The calibration errors (as a function of the number of independently obtained calibration points) were evaluated to determine if a new AGC calibration procedure using 15 independent calibration points should be adopted. Results of this study indicate that the improvement in calibration accuracy is insignificant and would not warrant a new calibration procedure requiring considerably more time and effort.

I. Introduction

At present, DSN Standard Test Procedure No. 853-51 4A-07 Rev. B is used to calibrate the receiver automatic gain control (AGC) voltage vs the received carrier power so that the digital instrumentation subsystem (DIS), telemetry and command processor (TCP), and the voice report all yield an accurate estimation of the received spacecraft carrier power. Fifteen power-level/AGC voltage pairs covering a 30-dB range are used in the calibration. The test transmitter output signal level is adjusted for the desired calibration levels using the Y-factor method.

The Y-factor detector assembly is used to adjust signal levels for only five of the 15 calibration points. After a given Y-factor is set, the AGC voltage is measured with the integrating digital voltmeter. Then, the next two calibration signal levels are created by incrementing the test transmitter step attenuator (10 dB per step). This technique produces three calibration points for each of the five Y-factors, representing a significant saving in time and effort. This technique has the disadvantage that the signal level error associated with each Y-factor will bias three of the 15 calibration points in the same direction. Certainly there would be an improvement in the AGC calibration accuracy if 15 uncorrelated calibration points were obtained by using 15 independent Y-factors. The purpose of this study was to determine whether the degree of improvement in calibration accuracy would warrant changing the new signal level calibration procedure (Ref. 1).

II. Method of Evaluation

The method used to determine the AGC calibration errors (as a function of the number of independent Y-factors used) is an extension of an approach by Lesh (Ref. 2). I refer the reader to this article for background material and definitions, instead of duplicating that work here.

To incorporate the effects of Y-factor errors on the calibration accuracy, it is necessary to modify the covariance matrix of the coefficient estimation error G. The covariance matrix is used with the expression

$$E\left\{\frac{(y-\hat{y})^2}{x}\right\} = g_{11} + 2g_{12}x + [2g_{13} + g_{22}]\,x^2 + 2\,[g_{23} + g_{14}]\,x^3 + [2g_{24} + g_{33}]\,x^4 + 2g_{34}x^5 + g_{44}x^6 \tag{1}$$

to calculate the mean square error between the fitted third-degree equation and the "ideal" third-degree model.

The covariance matrix calculation involves a column vector α whose elements are the signal power errors as mapped from the noisy AGC voltage through the third-degree polynomial. It is necessary to add another column vector whose elements are the errors in the test transmitter signal level. Major factors contributing to the errors in the test transmitter signal levels include (Ref. 3):

(1) The resettability and nonlinearity of the AIL precision attenuator in the Y-factor detector assembly.

(2) The operator's ability to "eyeball average" the strip chart recorder trace and to duplicate that average by adjusting the test transmitter output level.

(3) The test transmitter CW power stability during the Y-factor measurement.

(4) Errors in the system parameters which are incorporated in the Y-factor calculations (Ref. 4). These parameters include system operating temperature, test transmitter reference step attenuator (PAD) value, and the Y-factor detector assembly uncorrected filter bandwidth and gain factor. These four parameters are periodically measured to verify/re-establish their values.

The total error in each Y-factor will result in a test transmitter signal level error at each of the 15 calibration points. It is assumed that the calibration signal level error is a zero mean gaussian random variable. These signal power errors are arranged in a column vector:

$$\beta = \begin{bmatrix} \beta_1 \\ \beta_2 \\ \cdot \\ \cdot \\ \cdot \\ \beta_{15} \end{bmatrix} \tag{2}$$

It is assumed that the signal power errors resulting from independent applications of Y-factors will be uncorrelated and we can say

$$E\{\beta_i \beta_j\} = 0 \tag{3}$$

for i, j belonging to different Y-factors. Now that we have defined the vector β and given the vector α we can compute

$$E\{[\alpha+\beta][\alpha+\beta]^T\} \tag{4}$$

Expanding this term we get

$$E\{[\alpha+\beta][\alpha+\beta]^T\} = E\{\alpha\alpha^T\} + E\{\alpha\beta^T\} + E\{\alpha^T\beta\} + E\{\beta\beta^T\} \tag{5}$$

where the elements of the matrix $E\{\alpha\alpha^T\}$ have the values

$$E\{\alpha_i\alpha_j\} = (a_2 + 3a_3x_i)(a_2 + 3a_3x_j)\,\sigma_i^2\sigma_j^2 \tag{6}$$

for $i \neq j$, and for $i = j$,

$$E\{\alpha_i^2\} = (a_1 + 2a_2x_i + 3a_3x_i^2)^2\,\sigma_i^2 + 3\,[(a_2 + 3a_3x_i)^2 + 2a_3(a_1 + 2a_2x_i + 3a_3x_i^2)]\,(\sigma_i^2)^2 + 15a_3^2\,(\sigma_i^2)^2 \tag{7}$$

Let us define the matrix $C = [C_{ij}]$; $i, j = 1, 2, \cdots, 15$, where

$$C_{ij} = E\{\alpha_i\alpha_j\} \tag{8}$$

Expanding the second term in Eq. (4) gives

$$E\{\alpha\beta^T\} = E\begin{bmatrix} \alpha_1\beta_1 & \alpha_1\beta_2 & \cdots & \alpha_1\beta_{15} \\ \alpha_2\beta_1 & \alpha_2\beta_2 & \cdots & \alpha_2\beta_{15} \\ \cdot & \cdot & & \cdot \\ \cdot & \cdot & & \cdot \\ \cdot & \cdot & & \cdot \\ \alpha_{15}\beta_1 & \alpha_{15}\beta_2 & \cdots & \alpha_{15}\beta_{15} \end{bmatrix} \tag{9}$$

We can say that

$$E\{\alpha\beta^T\} = 0 \tag{10}$$

since every element of the matrix $E\{\alpha\beta^T\}$ is equal to the expected value of the product of two independent random variables, one of which is zero mean.

Looking at the third term of Eq. (4) we can see that

$$E\{\alpha^T\beta\} = 0 \tag{11}$$

for the same reason as above.

Expanding the fourth term of Eq. (4) gives

$$E\{\beta\beta^T\} = E\begin{bmatrix} \beta_1^2 & \beta_1\beta_2 & \beta_1\beta_3 & \cdots & \beta_1\beta_{15} \\ \beta_2\beta_1 & \beta_2^2 & \beta_2\beta_3 & \cdots & \beta_2\beta_{15} \\ \beta_3\beta_1 & \beta_3\beta_2 & \beta_3^2 & \cdots & \beta_3\beta_{15} \\ \cdot & \cdot & \cdot & & \cdot \\ \cdot & \cdot & \cdot & & \cdot \\ \cdot & \cdot & \cdot & & \cdot \\ \beta_{15}\beta_1 & \beta_{15}\beta_2 & \beta_{15}\beta_3 & \cdots & \beta_{15}^2 \end{bmatrix} \tag{12}$$

Let us first consider the case where we have 15 independent β's, i.e., a calibration procedure using 15 independent Y-factors. For those elements where $i \neq j$

$$E\{\beta_i\beta_j\} = 0 \tag{13}$$

because those elements are the expected values of the products of uncorrelated zero-mean random variables.

For the elements on the principal diagonal ($i = j$)

$$E\{\beta_i^2\} = \sigma_i^2 \tag{14}$$

where σ_i^2 is the variance of the signal power error produced by the ith Y-factor.

If we define the matrix $D = [D_{ij}]$; $i, j = 1, 2, \cdots, 15$, where

$$D_{ij} = E\{\beta_i\beta_j\} \tag{15}$$

then the final form of the covariance matrix for 15 independent Y-factors is

$$G = (X^TX)^{-1} X^T (C + D) X (X^TX)^{-1} \tag{16}$$

Now consider the case where we have only five independent values for β and each value is triply used such that

$$\beta_i = \beta_{i+5} = \beta_{i+10}$$

and

$$\beta_j = \beta_{j+5} = \beta_{j+10}$$

for $i, j = 1, 2, 3, 4, 5$. This yields no change in the first three terms of Eq. (4). The fourth term, however, is no longer a diagonal matrix. Correlation between signal power errors results in some additional nonzero elements in this matrix.

Consider the elements

$$E\{\beta_i\beta_j\} \qquad i, j = 1, 2, 3, 4, 5$$

of the matrix $E\{\beta\beta^T\}$ whose elements are

For $|i - j| = 0, 5, 10$

$$E\{\beta_i\beta_j\} = E\{\beta_i^2\} = \sigma_r^2 \qquad r = 1, 2, 3, 4, 5$$
$$\text{and } \sigma_r^2 = \sigma_{r+5}^2 = \sigma_{r+10}^2 \tag{17}$$

For $|i - j| \neq 0, 5, 10$

$$E\{\beta_i\beta_j\} = E\{\beta_i\}\,E\{\beta_j\} = 0 \tag{18}$$

If we define the matrix $D^* = [D^*_{ij}]$; $\quad i, j = 1, 2, \cdots 15$

$$D^*_{ij} = E\{\beta_i\beta_j\} \tag{19}$$

then the final form of the covariance matrix for five independent Y-factors is

$$G = (X^TX)^{-1} X^T (C + D^*) X (X^TX)^{-1} \tag{20}$$

III. Calculations

An existing FORTRAN computer program was modified to include the calibration errors introduced by the Y-factor method. To determine the DIS computer calibration errors, calibration data from five stations were compiled. Each data set consisted of 15 signal power/AGC voltage pairs as well as the variance for each value of voltage.

It was desired to evaluate the degree of improvement in calibration accuracy which would result from setting up 15 instead of five independent Y-factors. The quantity which best indicates the calibration accuracy is the integral mean square error defined by:

$$I = \frac{1}{x_u - x_v} \int_{x_v}^{x_u} E\{(y - \hat{y})^2/x\}\, dx \tag{21}$$

This quantity represents an averaged value for the calibration error over the 30-dB calibration range. It was computed for each of the five stations, using Y-factor rms errors of 0.0 dB, 0.3 dB, and 1.0 dB. These five data sets were averaged and then the integral root mean square calibration errors (in dB) were calculated and recorded in Table 1.

IV. Conclusion

The purpose of this study was to determine if a significant improvement in the AGC calibration accuracy could be obtained by increasing the number of independent Y-factors used in the calibration procedure from five to 15. Using 15 independent Y-factors, the theoretical decrease in the standard deviation of the DIS estimation error is on the order of 0.002 dB, given a Y-factor rms error of 0.3 dB. For a Y-factor rms error of 1.0 dB, the decrease in the standard deviation of the DIS estimation error is about 0.008 dB.

This small theoretical improvement in the DIS calibration accuracy is insignificant. Also, the time requirement for the calibration would be considerably greater if 15 independent Y-factors were used.

References

1. *Signal Level Tracking Procedure*, DSIF Standard Test Procedure 853-51 4A-07, Rev. B. Jet Propulsion Laboratory, Pasadena, Calif., July 1, 1973 (an internal document).
2. Lesh, J., "Carrier Power Estimation Accuracy," in *The Deep Space Network Progress Report*, Technical Report 32-1526, Vol. IX, pp. 207–217, Jet Propulsion Laboratory, Pasadena, Calif., June 15, 1972.
3. Stelzried, C. T., *Precision Power Measurements of Spacecraft CW Signal Power With Microwave Noise Standards*, Technical Report 32-1066, pp. 2–15. Jet Propulsion Laboratory, Pasadena, Calif., Feb. 15, 1968.
4. *Y-Factor Computer Program DOI-5343-SP-B, DSIF Support Program.* Jet Propulsion Laboratory, Pasadena, Calif., Sept. 9, 1972 (an internal document).

Table 1. Comparison of integral root mean square calibration errors (in dB) as a function of the number of independent Y-factors set up in the calibration procedure (degree of curve fit = 3; -132 dBm $\geq$ Ps $\geq$ -160 dBm)

Number of independent Y-factors	Y-factor rms error = 0.0dB		Y-factor rms error = 0.3dB		Y-factor rms error = 1.0dB	
15 independent Y-factors	0.0129	Narrow AGC BW	0.145	Narrow AGC BW	0.480	Narrow AGC BW
	0.0270	Medium AGC BW	0.147	Medium AGC BW	0.481	Medium AGC BW
	0.0312	Wide AGC BW	0.147	Wide AGC BW	0.481	Wide AGC BW
5 independent Y-factors (used to generate 15 calibration points)[a]	0.0129	Narrow AGC BW	0.147	Narrow AGC BW	0.487	Narrow AGC BW
	0.0270	Medium AGC BW	0.148	Medium AGC BW	0.488	Medium AGC BW
	0.0312	Wide AGC BW	0.149	Wide AGC BW	0.489	Wide AGC BW

[a]Present method of calibration.