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METHODOLOGY FOR STATISTICAL CONTROL OF THE ANECHOIC CHAMBER FIELD GENERATION SYSTEM

Dennis S. Friday

National Bureau of Standards
U.S. Department of Commerce
Boulder, Colorado 80303

January 1986

NBSIR 85-3033

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Electromagnetic Fields Division
Center for Electronics and Electrical Engineering
National Engineering Laboratory
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U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, Secretary

NATIONAL BUREAU OF STANDARDS, Ernest Ambler, Director

CONTENTS

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The microwave anechoic chamber is a National Bureau of Standards laboratory facility in which standard electromagnetic fields are generated. The chamber enables special measurements and electromagnetic compatibility tests to be conducted on antennas and other devices. This paper is concerned with methodology for assuring that the standard field patterns generated in the chamber are repeatable. Procedures are proposed for developing a data base from measurements obtained by placing the system, which generates the fields, in certain relevant reference configurations. Methodology is presented for developing statistical control charts to monitor both the location and the scale parameters of these data over time.

Key words: anechoic chamber; control charts; electromagnetic fields; measurement assurance; standard fields; statistical control.

1. Introduction

The microwave anechoic chamber is a National Bureau of Standards (NBS) laboratory facility in which standard electromagnetic fields are generated. Extremely low reflection levels in the center of the chamber enable specialized measurements and EMI or EMC tests to be conducted on antennas or other electronic devices. This paper is concerned with methodology for assuring that the standard electromagnetic field patterns generated in the chamber are consistent over time. Procedures will be developed to monitor the system which generates the fields. Check-standard type historical data are obtained by placing the system in certain reference configurations and measuring relevant parameters. We will refer to such procedures as "self tests." These measurements will form the data base from which statistical control is established.

Several control chart procedures are presented for maintaining statistical control of the test system. This methodology will provide statistical limits within which future anechoic chamber self test data should fall. A systematic departure from these limits indicates that the system is out of control and must be dealt with accordingly.

2. Related microwave methodology

The theory for the measurements upon which this paper is based is presented in a paper by Kanda [1]. A brief summary will be sufficient for our purposes. Let P_I denote the power incident on the transmitting antenna and P_R be the power reflected. Then:

$$P_I = \left|\frac{S_{34}}{S_{13}}\right|^2 \frac{P_1}{(1 - |\Gamma_1|^2)} |\varepsilon_1|^2 \tag{1a}$$

$$P_R = |S_{24}|^{-2} \frac{P_2}{(1 - |\Gamma_2|^2)} |\varepsilon_2|^2 \tag{1b}$$

where P_1 and P_2 are respective powers at ports 1 and 2 of a directional coupler, and Γ_1 and Γ_2 are the corresponding reflection coefficients (into the power meters). The S_{ij}'s are scattering parameters for ports i and j (port 4 is the input to the transmitting antenna and port 3 the output of the transmitter). See [1,2] for details. The quantities ε_1 and ε_2 are known to be near unity in magnitude (in general <1 percent error). The net power delivered to the transmitting antenna is given by $P_{net} = P_I - P_R$ and is a crucial measurement for determining on-axis field intensity. Unfortunately, practical constraints permit only one determination of P_{net} in a self test. P_{net}, however, is dependent on values of the scattering parameters and it is possible to make repeated measurements of these in each test.

We introduce the following notation. Let

$$M = \left|\frac{S_{13}}{S_{34}}\right| \tag{2a}$$

and

$$S = |S_{24}|. \tag{2b}$$

M is the scattering ratio in the <u>m</u>atched load equation

$$\frac{P_1}{P_4} = M^2 \left(\frac{1 - |\Gamma_1|^2}{1 - |\Gamma_4|^2}\right) \varepsilon_3 \tag{3}$$

(P_4 is the power at port 4, see [2]) and S is the scattering coefficient which (given M) is obtained from the <u>s</u>horted termination equation.

$$\frac{P_2}{P_1} = S^2M^2 \left(\frac{1 - |\Gamma_1|^2}{1 - |\Gamma_2|^2} \right) \varepsilon_4 \qquad (4)$$

where ε_3 and ε_4 are very close to unity.

Control chart procedures will be developed for P_{net}, M, and S. The power P_{net} is monitored because of its basic relationship to field strength. Parameters M and S are monitored not only because of their influence on P_{net} and the possibility of repeated measurements for each self test, but for engineering reasons. The nature of any unexpected changes in M and in S can be used for diagnostic information and provide clues to the reasons for system malfunction.

3. General considerations

No control chart procedure can be considered appropriate for a given application until sufficient data have been obtained to validate the assumptions on which the chart is based. The methods proposed herein are based on a careful study of the system and its theory but not on test data. Only one preliminary measurement was possible at the time of this writing. It is therefore possible that as the data base for this system is developed, some of these procedures will have to be modified or extended. As more is learned about the system, procedures will be "tuned" appropriately. The methods we present, however, provide a good basis from which to begin.

Frequency and frequency band considerations will be not be addressed directly at this stage of development. A single important central frequency should be chosen initially and used for these tests. The procedures will apply to any single frequency. If possible, three or five equally spaced frequencies covering the band of interest should be monitored. Clearly, the practical consideration of system downtime for these tests will be a limiting factor. The system must serve its primary function of test and calibration.

The parameters M and S are defined to be the unsquared magnitudes since they are likely to be less skewed than M^2, S^2, etc. This is conjecture, however, until sufficient data are available. It may be necessary to choose some other function of M or S for improved control.

Given these considerations and reservations we now propose some control chart procedures. To illustrate the methodology we will initially discuss only the M parameter.

4. Control charts for the M and S parameters

If the system is functioning properly, the statistical laws governing the fluctuations in the M parameter will not change over time. In particular the first two moments E(M) and V(M), the theoretical mean and variance, respectively, will be constant over time. We will develop control charts to monitor both of these quantities based on measures of location and dispersion.

4.1 Location control charts (M)

Assume that k repetitions of the measurement sequence for determination of M are done in each self test of the system. If possible, a good compromise is k=10. This would result in a confidence interval about 15 to 20 percent larger than the limiting interval (as $k \to \infty$). About six or seven repetitions should be considered minimum since the size of the confidence region increases rapidly below this value. It is best to choose a reasonable k then stay with it for all the tests. It will be assumed that k is constant here. If it changes, however, the procedure can be generalized.

Let n denote the number of self tests conducted up to the current time; i.e., M(i,j); i=1,...,k; j=1,...,n is the ith measurement of M in the jth self test of the system.

$$\underbrace{\left.\begin{array}{ccc} M(1,1) & \cdots & M(1,n) \\ \vdots & & \\ M(k,1) & \cdots & M(k,n) \end{array}\right\}}_{\text{n different tests}} \text{ repeated measurements of M in each test}$$

Given the data compute:

$$\bar{M}_j = \frac{1}{k} \sum_{i=1}^{k} M(i,j) \qquad \text{(self test averages)} \qquad (5a)$$

$$\bar{\bar{M}} = \frac{1}{n} \sum_{j=1}^{n} \bar{M}_j \qquad \text{(pooled average)} \qquad (5b)$$

$$D_j^2 = \frac{1}{k-1} \sum_{i=1}^{k} (M(i,j) - \bar{M}_j)^2 \quad \text{(self test variance)*} \tag{6a}$$

$$D^2 = \frac{1}{n} \sum_{j=1}^{n} D_j^2 \quad \text{(pooled variance).} \tag{6b}$$

Then the control chart for the location of the M parameter is constructed by plotting

$$\bar{M}_j \text{ vs } j=1,\ldots,n \; .$$

The upper and lower control limits respectively are

$$\bar{\bar{M}} + t_p(n(k-1))Dn^{-1/2}$$

$$\bar{\bar{M}} - t_p(n(k-1))Dn^{-1/2}$$

where t_p is a percentage point of a t distribution with n(k-1) degrees of freedom, and subscript p is the control level chosen for the chart. The value (1-p) is commonly known as the type 1 error level associated with the chart. Tables in references [2] and [3] give the t values for p = 0.95 and p = 0.99 for selected degrees of freedom. It is possible to have two sets of limits, an inner "warning limit" and an outer "action limit."

An illustration of how the t statistic is obtained is illustrated in figure 1.

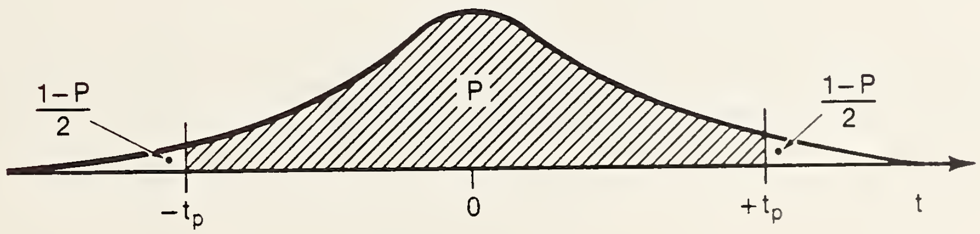


Figure 1: Illustration of how P and t_p are related.

*Since we use S for one of the parameters monitored we use the symbol D for standard deviation. This is common in statistical literature since it is a measure of dispersion.

The p is the probability that the $\bar{M}_j$'s will fall within the limits if the process is in control and the limits are centered so that half of the error probability is allocated to each tail. The underlying theory is described in most elementary statistical texts and will not be repeated here.

A graphical illustration of an M-location chart is given in figure 2.

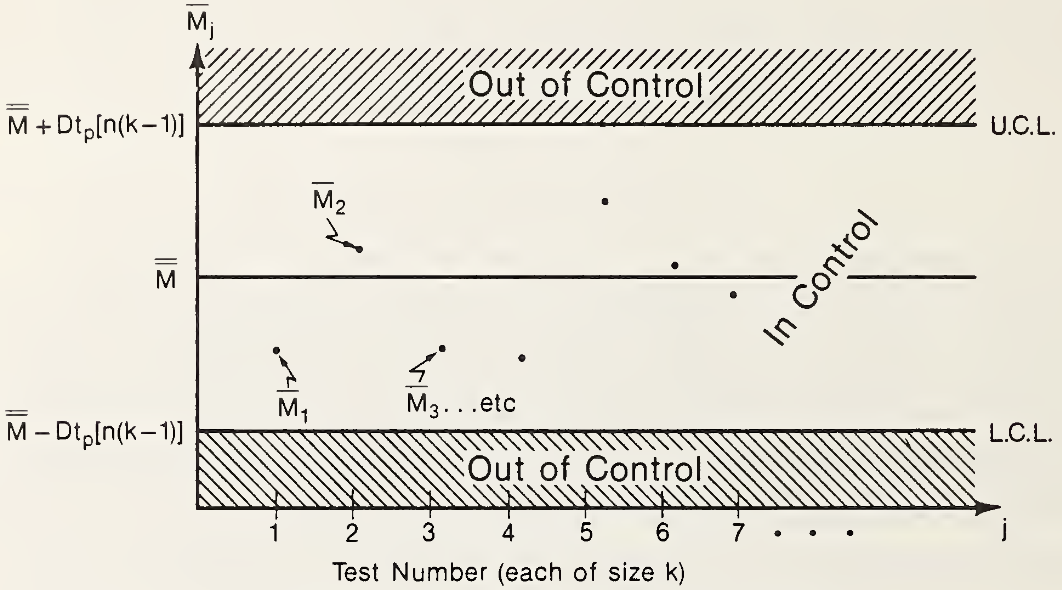


Figure 2: Illustration of an M-Location Chart

All three lines shift (since $\bar{\bar{M}}$ shifts) for each new set of observations (but less as more tests are done). If sample sizes must be different for each test then the formula

$$D^2 = \frac{\sum_{j=1}^{n} (k_j-1)\, D_j^2}{\sum_{j=1}^{n} k_j - n} \tag{7}$$

replaces the previous D^2 where k_j is the size of the sample for the jth test (the number of measurements of M). The degrees of freedom are then $(\sum_{j=1}^{n} k_j - n)$ for finding the t_p value.

4.2 Dispersion control charts (M)

These charts monitor the short term precision of the measurements of M. The points plotted on the control chart are the D_j's (see eq (6)) (assuming k is the same for each test). If k is different, use the D defined in eq (7).

Since we are only concerned about increases in variation we need only have an upper control limit. This is found by using the F tables which can be found in references [3] and [4] or in any standard statistics text. These two references provide a complementary set of degrees of freedom. Let the limit be

$$D \sqrt{F_p(k-1,\ n(k-1))}$$

where D is defined previously, p is the error probability, and (k-1) and (n(k-1)) are the degrees of freedom used in the F Tables.

The M-dispersion chart is illustrated in figure 3.

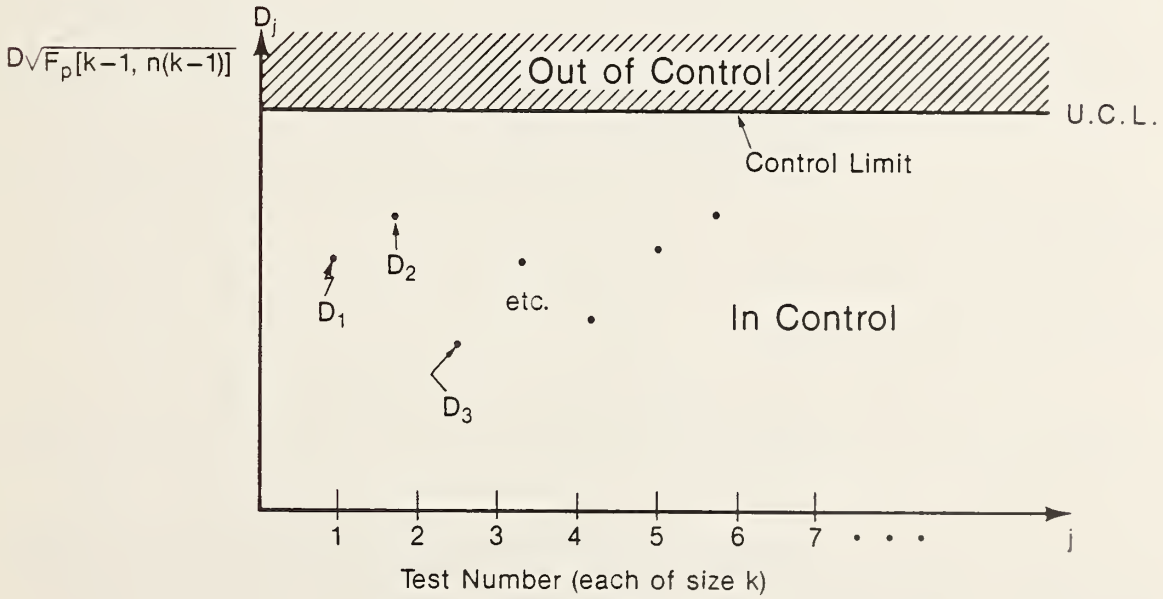


Figure 3: Illustration of M-Dispersion Chart

Again, the control limits shift with each new observation--less so as n increases. It would be good to have the M-location and M-dispersion chart displayed one above the other. This will enable the joint interpretation of the resulting graphs.

4.3 S Location and dispersion charts

These are identical to the corresponding M charts. Just change data and titles and all other theory follows through for S charts. Equivalent statistics for S charts are:

$$\bar{S}_j = \frac{1}{k} \sum_{i=1}^{k} S(i,j) \tag{8a}$$

$$\bar{\bar{S}} = \frac{1}{n} \sum_{j=1}^{n} \bar{S}_j \tag{8b}$$

$$D_j^2 = \frac{1}{k-1} \sum_{i=1}^{k} (S(i,j) - \bar{S}_j)^2 \tag{9a}$$

$$D^2 = \frac{1}{n} \sum_{j=1}^{n} D_j^2 \tag{9b}$$

Plot the three lines

$$\bar{\bar{S}}$$

$$\bar{\bar{S}} \pm Dt_p(n(k-1))\, n^{-1/2}$$

and the points $\bar{S}_j$.

5. Discussion of P_{net} charts

P_{net} charts are different from the other two (M and S) charts in several ways:

i. P_{net} charts can only be based on one measurement per test. It is not reasonable to completely disassemble then reassemble the entire test system several times. This would be required to ensure that the repeated P_{net} measurements are independent statistically and to perturb all factors that would affect its measured values.

A consequence of this is that we cannot depend on central limit theory to statistically determine the error bounds as we did for M and S. Information on the distributional behavior of P_{net} is necessary. We must therefore obtain data from controlled experiments and analyze the data. It will then be possible to develop proper P_{net} control procedures.

ii. P_{net} is functionally dependent on the random variables M and S, the objects of the previous control charts. P_1 and P_2, for example, are also involved in determining P_{net}. Statistical dependence is obvious. M and S may be dependent but we will ignore this for now. Little is understood about the nature of this relationship until data can be obtained.

The end result of this dependence is that the control charts are not independent and therefore the joint error probabilities cannot be treated as such. This should not be an impediment, however. It is possible to develop more complex control charts to monitor M, S, and P_{net} rigorously and simultaneously. This can be done when more information on their statistical properties is obtained.

Initially, an assumption will be made that P_{net} measurements are Gaussian and a preliminary chart will be developed. As data become available, assumptions can be checked and the procedures refined. Proceed as follows.

5.1 A "rough" control chart for P_{net}-location

Define P_1^*, P_2^*,...P_n^* to be the successive values of P_{net} determined by

$$P_i^* = \frac{P_{1,i}}{(1 - |\Gamma_1|^2)} \left(\frac{1}{\bar{M}_i} \right)^2 - \frac{P_{2,i}}{(1 - |\Gamma_2|^2)} \left(\frac{1}{\bar{S}_i} \right)^2 \quad ; i=1,\ldots,n \qquad (10)$$

where $P_{j,i}$ (= P_j) is the measured power at port j for the ith test.

Then the chart should be constructed as follows:

$$\text{Let} \quad \bar{P}^* = \frac{1}{n} \sum_{i=1}^{n} P_i^* \qquad (11)$$

$$D^{*2} = \frac{1}{n-1} \sum_{i=1}^{n} (P_i^* - \bar{P}^*)^2 \qquad (12)$$

Plot the individual P_i^*'s vs i.

The upper bound for control is $\bar{P}^* + t(n-1)\ D^*$.

The lower bound for control is $\bar{P}^* - t(n-1)\ D^*$.

Obtain t(n-1) from the t tables as done in M and S location charts.

This is a special case of the earlier charts for location when k=1. It is not possible to develop dispersion charts for P_{net} corresponding to those for M and S dispersion.

CAUTION: It is important to interpret this P_{net}-location chart with discretion since the bounds in this case are directly dependent on the distributional assumption. Use it as a rough tool only until assumptions can be verified or modified appropriately.

Figure 4 illustrates the format of the P_{net}-location chart.

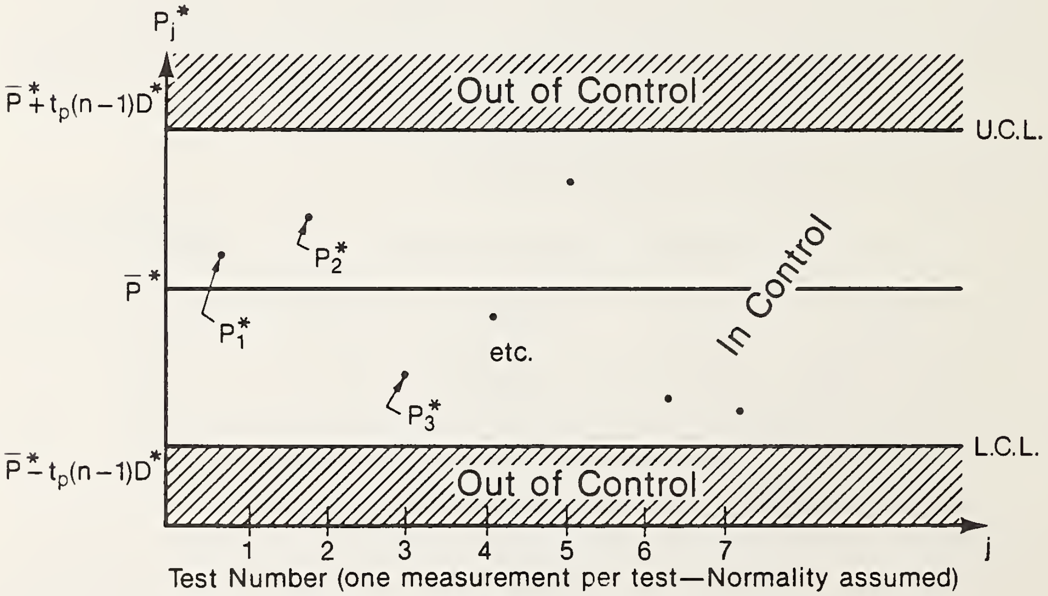


Figure 4: Illustration of P_{net}-Location Chart

Given the lack of distributional knowledge it is reasonable to choose two sets of limits with t = 2 and 3. Under the Gaussian assumption and n large, these would correspond approximately to p = 0.95 and to p = 0.99. This suggests a less artificial reliance on the p's, etc.; just a reasonable set of bounds. Figure 5 illustrates this chart.

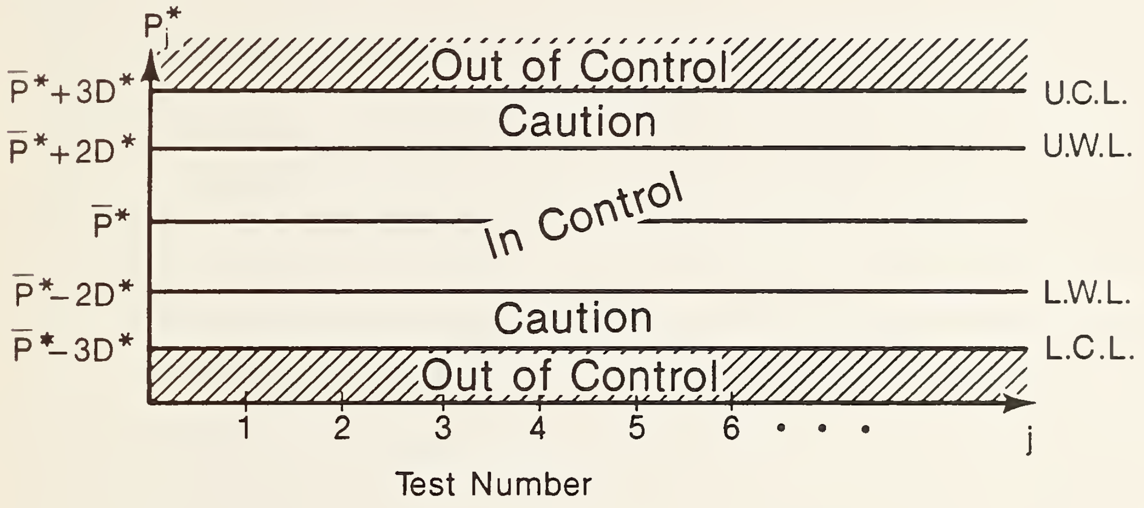


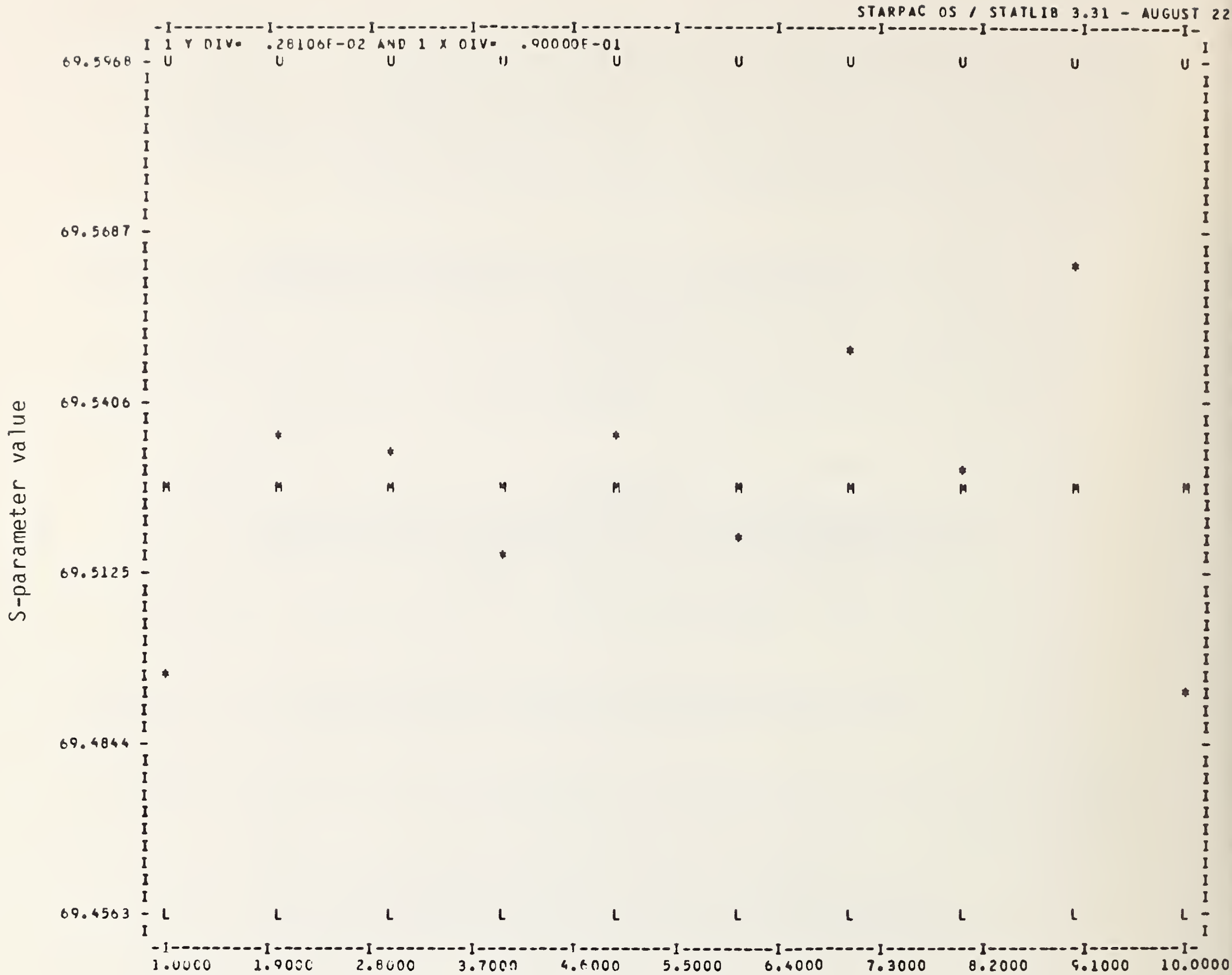
Figure 5: P_{net}-Location Chart with Warning Limits

Given more information, it is possible to improve on this and also possibly to develop dispersion charts or a more specialized chart.

6. Conclusions and Comments

This is only a proposal for a good beginning. Control charts cannot be finalized without data. Control chart methodology also contains more than is discussed here. More specialized methods sensitive to particular types of failures may be developed as more is understood about these measurements.

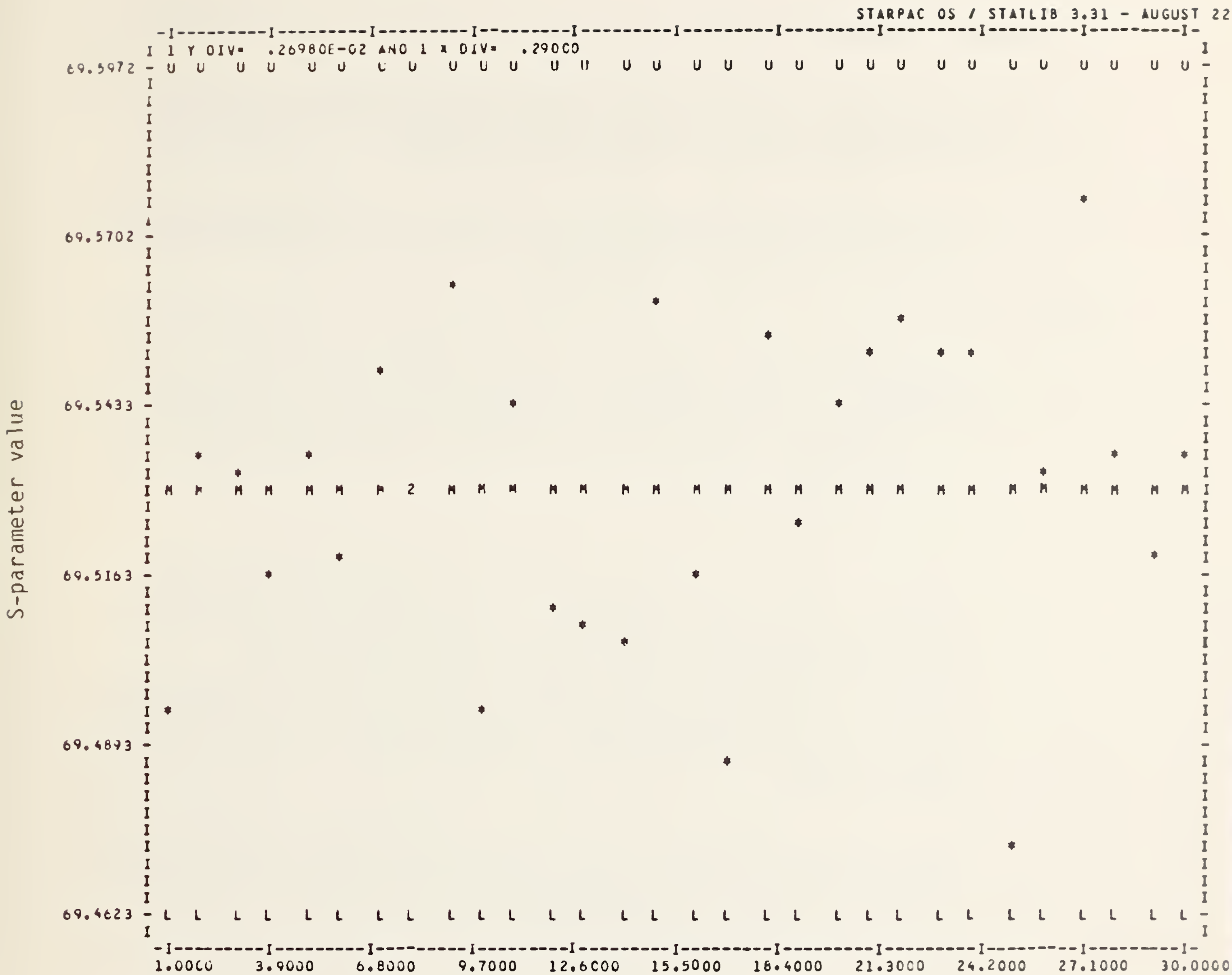
We clearly need data to continue. Attached are two control charts (figures 6,7) for location of the S parameter based on simulations. The first is for 10 self calibrations, each based on 10 measurements. The second is a continuation of 20 more self calibrations. The changing nature of the upper and lower limits and grand mean is apparent. The parameters used for the simulation were obtained from some preliminary measurements of the anechoic chamber field generation system.



Successive self tests of system

Symbols: U; upper limit
M; pooled mean for n=10 (eq (8b))
L; lower limit
*; average S value for each test (eq (8a))

Figure 6. Simulated S-location chart, n=10



Successive self tests of system

Symbols: U; upper limit
M; pooled mean for n=30 (eq (8b))
L; lower limit
*; average S value for each test (eq (8a))

Figure 7. Simulated S-location chart, n=30

To obtain good data the test procedure is important:

> Choose one frequency band--a relevant one in terms of equipment, test methods, calibration requirements, etc.
>
> Test at one center frequency in this band or, if possible, a center and the two band edge frequencies.
>
> Technicians should obtain the data using careful and typical test procedures. The importance of following all steps using realistic lab procedures, dismantling and reassembling equipment, cannot be overemphasized. These self tests should be interspersed with other work and calibrations.
>
> Choose k between 7 and 10 and for each setup of the test system replicate the M and S measurements. They must be spaced in time and interspersed with enough real hardware manipulation (engineering judgement must determine this) to ensure independence of the successive measurements. Lab practices are crucial to good realistic data.
>
> Perform about 10 tests, i.e., 10 P_{net} measurements. These include 10 groups of (say 7) M measurements and 10 groups of (say 7) S measurements; 140 data points in all.
>
> More tests should be performed if possible. Twenty five would provide adequate data, for example, but might be costly in terms of time required and loss of the system for measurements.

These procedures will give a reasonable assessment of anechoic chamber system performance in one frequency band. If this proves to be typical of other frequency bands, methods could be developed for those bands with less initial data.

7. References

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NBS-114A (REV. 2-8C)

U.S. DEPT. OF COMM. BIBLIOGRAPHIC DATA SHEET (See instructions)	1. PUBLICATION OR REPORT NO. NBSIR 85-3033	2. Performing Organ. Report No.	3. Publication Date January 1986

4. TITLE AND SUBTITLE

METHODOLOGY FOR STATISTICAL CONTROL OF THE ANECHOIC CHAMBER FIELD GENERATION SYSTEM

5. AUTHOR(S)

Dennis S. Friday

6. PERFORMING ORGANIZATION (If joint or other than NBS, see instructions)

NATIONAL BUREAU OF STANDARDS
DEPARTMENT OF COMMERCE
WASHINGTON, D.C. 20234

7. Contract/Grant No.

8. Type of Report & Period Covered

9. SPONSORING ORGANIZATION NAME AND COMPLETE ADDRESS (Street, City, State, ZIP)

10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

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12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

anechoic chamber; control charts; electromagnetic fields; measurement assurance; standard fields; statistical control

13. AVAILABILITY

[X] Unlimited

☐ For Official Distribution. Do Not Release to NTIS

☐ Order From Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402.

[X] Order From National Technical Information Service (NTIS), Springfield, VA. 22161

14. NO. OF PRINTED PAGES

20

15. Price

☆ U.S. GOVERNMENT PRINTING OFFICE: 1986—677-898/45123 REGION NO. 8