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We report the results of a study of measurements of radiated emissions from the NIST spherical-dipole standard radiator in several screened rooms. The measurements were performed in accordance with MIL-STD-462 (1967). Large differences occur in the field intensity measured at different laboratories and even on different days at the same laboratory. There is also a systematic difference at low frequencies between the screened-room results and results obtained in a TEM cell, open-area test site, and anechoic chamber. Results obtained using a monopole radiator are also presented and discussed.

Key words: MIL-STD-462; monopole radiator; radiated emissions; screened room; spherical dipole; standard radiator.

1. INTRODUCTION

The National Institute of Standards and Technology (NIST) has recently developed a spherical-dipole standard radiator for use in electromagnetic interference and compatibility (EMI/EMC) applications. The design, construction, and operation of the device are described in Refs. [1,2], which also present results of tests in various NIST facilities -- the open area test site (OATS), anechoic chamber (AC), transverse electromagnetic (TEM) cell, and mode-stirred chamber. The spherical radiator is a well controlled, well characterized source of electromagnetic radiation for the frequency range of about 5 MHz to over 1 GHz. As such, it can be used to test the ability of a laboratory to measure radiated electromagnetic emissions. That, in fact, was one of the principal motivations for the development of the standard radiator. It can also be used to compare different test methods or to test the validity or credibility of new measurement techniques.

In this report we consider radiated-emissions measurements performed on standard radiators in screened rooms. The original goal of this study was to develop procedures for using the NIST spherical dipole standard radiator in the laboratory accreditation process, particularly in the National Voluntary Laboratory Accreditation Program (NVLAP) for accrediting laboratories performing MIL-STD-462 acceptance testing. To this end, we sought and received the cooperation of three EMC test laboratories to perform MIL-STD-462 RE02 tests on the spherical radiator. In addition to the spherical-dipole standard radiators, a monopole radiator (described below) has also been built and was used in the tests. The intent was to establish a baseline of performance for the radiators, against which measurements at other laboratories could be compared in order to assess their ability to perform MIL-STD-462 tests. Tests at NIST had already characterized the performance of the spherical-dipole standard radiators in test facilities simulating quasi free-space environments (OATS, AC, TEM) and in the mode-stirred chamber, but the radiators had not been tested in screened rooms, which are the common environment for the MIL-STD-462 tests. As discussed below, there are still some points which we must address before this work is really complete. Nevertheless, it seems appropriate to report on the results obtained thus far, since they are of considerable interest. A complete report will be published once the remaining checks have been performed.

Measurements in screened rooms have a (well-deserved) tarnished reputation. We will not examine in detail the causes of the problems of screened-room measurements, but a few comments are useful as background. Our remarks will address the case of radiated emissions, but analogous effects occur for radiated susceptibility. There are many sources of potential errors in EMI measurements inside screened rooms. Perhaps the most obvious effect is that a screened room is a conducting cavity, and thus it exhibits cavity resonances and standing waves. Consequently, the field distribution within the room generally is nonuniform, and the field intensity measured depends on the locations of the equipment under test (EUT) and the measuring antenna, as well as on the electrical size of the room. Another potential source of error is that the behavior of the receiving antenna is affected by the proximity of the conducting walls. The interactions between the antenna and its numerous images change the antenna factor, and consequently the antenna response in a given electric field depends on the antenna's location, the size of the room, and the type of antenna. A similar effect can occur for the EUT. If we think of the EUT as a transmitting antenna, its input impedance will be changed by the interaction with its images, thereby changing the ratio of terminal voltage to input current. Thus the radiated power can depend on the size of the room, the EUT position in the room, and details of the EUT itself. (The loading effect on the standard radiator will be addressed below.) Finally, most screened-room measurements are done at low enough frequencies that the EUT and the receiving antenna are in each other's near field.

The potential problems with screened-room measurements have been widely appreciated for some time [3-6]. Nevertheless, screened rooms are widely used in EMI/EMC. Their appeal is partly economic, partly inertial, and partly due to the fact that competing techniques are not without problems of their own. Open-area test sites admit background noise; anechoic chambers are echoic at low frequencies; TEM cells have high-frequency cutoffs and size constraints; etc. Screened-rooms are particularly prevalent in MIL-STD-462 testing [7], where their use is nearly universal. An extensive revision of MIL-STD-461/462 has recently been released, which contains changes intended to improve screened room test methods [8]. The revised standard is labeled MIL-STD-462D. The tests described in this report were performed according to the old standard, since the contents of the new one were not known at the time of the tests. We will discuss this below.

Over the course of a year, radiated-emissions tests were performed at the three participating EMC labs. All three screened rooms had absorber loading to some degree, and all were large enough to meet MIL-STD-462 specifications. We do not detail the actual sizes and specific configurations of the individual rooms. That information would be needed for diagnosing the cause of inter-laboratory differences, for example, but for this study we are just interested in the fact that they did conform to the (old) MIL-STD requirements. (There was not enough absorber in any of the screened rooms to meet the requirements of MIL-STD-462D [8].) Each set of measurements was performed twice at each laboratory, with the setup disassembled between the two measurements, in order to evaluate the repeatability of the tests. We were thus able to address three major issues: day-to-day variations at a given laboratory, differences between results obtained at different laboratories, and differences between the screened-room results and results obtained at NIST in simulated free-space environments. The results caused us to reconsider the appropriateness of using the standard radiators in the accreditation process for MIL-STD-462 measurements (under the old standard). The differences in all three areas -- day-to-day variations, inter-laboratory variations, and screened-room to free-space differences -- were sufficiently large that the basic validity of the old RE02 test procedures in a screened room must be questioned. This point is addressed in the final section below. In the next section we outline the procedures followed in the tests on the standard radiators. In Section 3 we present the results of the RE02 tests on the spherical-dipole standard radiator, followed by the monopole results in Section 4. Section 5 contains a summary and conclusions.

2. MEASUREMENTS

2.1 Radiators

The spherical-dipole radiator is described in detail in Refs. [1,2]. For present purposes, it is sufficient to recall a few of its principal features. The radiating element is a spherical gold-plated dipole of 10 cm diameter, the basic configuration of which is indicated in fig. 1. The driving voltage is applied at the gap between the center posts, and the current flows up the top post to the inside top of the sphere and down the bottom post to the inside bottom of the sphere. From the poles the current flows on the inner surface of the spherical shell out to the equatorial gap, where it feeds the outer surface of the sphere. Thus, provided that the current propagates from the rf feed uniformly to all points on the equator, we have a center-fed spherical dipole, uniformly excited around its equator. The voltage at the gap of the center post is monitored continuously by a diode detector circuit, and this reading is relayed back to the control unit via optical fiber. This feature enables the operator to verify that the impressed voltage is the same from one test to another, and it also confirms that the unit is operating properly throughout a set of measurements.

The waveform to be radiated is fed to the sphere via optical fiber. Inside the sphere the optical signal is converted to an electrical signal, amplified, and fed to the gap in the center post. In the tests described in this report, a single frequency cw signal was always used. In principle, virtually any waveform could be used to drive the spherical dipole, though the radiated waveform would include the shaping effect of the sphere's frequency-dependent radiation characteristics. The pulse characteristics of the spherical dipole radiator have not yet been examined.

Although the voltage across the gap of the center post is known, we cannot directly calculate the radiated field, since the relationship between the voltage at the post gap and the voltage at the equatorial gap in the spherical shell cannot be easily calculated. Therefore the transfer function between the post gap voltage and the radiated field is determined empirically, by measurements on the NIST OATS and in the AC. Besides the OATS and AC tests at NIST, the spherical dipoles were also tested in a TEM cell (at low frequency) and in a mode-stirred chamber (at high frequency). Based on those tests, a transfer function which relates the indicated post gap voltage to the radiated field intensity was obtained. Using this measured transfer function, we can then compute the field intensity for a given indication of the gap voltage and a given position. Figure 2 plots the field as a function of frequency for a position in the equatorial plane, 1 m from the radiator. The three different sets of data correspond to transfer functions as measured in the TEM cell, OATS, and AC [1]. The results from the OATS and AC agree very well in their region of overlap (200 to 1000 MHz). The TEM cell results fall below those of the OATS by about 2 to 4 dB (except at one anomalous point). This difference is probably due to the loading effect of the TEM cell walls on the sphere, since the radiator was about 30 cm from the walls in the TEM cell measurements. We intend to test the loading effect systematically in the future. Measurements at and above 100 MHz in the mode-stirred chamber [2] did not show evidence of a loading effect on the spherical dipole for a dipole to wall separation of 1 m, at least within the accuracy of the measurements, and the TEM cell results suggest that the effect is of order a few decibels for a distance of 30 cm. In the screened-room measurements, the sphere was never closer to a wall than 1 m. Another point which requires and will receive further investigation is the question of repeatability of the results in the NIST facilities. The excellent agreement between OATS and AC results is an indication that the repeatability is very good. Repeated measurements performed at a few frequencies have agreed to within less than 1 dB, which is about the limit of the test facility, but we have not yet done a systematic study of the repeatability of our spherical-dipole results.

Besides the spherical-dipole standard radiators, we also used a monopole radiator in the tests. The monopole radiator is a small, battery-operated device designed to radiate harmonically related signals derived from two crystal oscillators. The crystal oscillator signals of 8 and 10 MHz are mixed to produce a large number of harmonic products spaced 2 MHz apart, beginning at 2 MHz and continuing to above 500 MHz. The mixing and amplification are performed using two NAND gates of a 7400 integrated circuit. The first gate mixes the output from the oscillators to produce a distorted square wave signal, and the second gate acts as a buffer to drive the signal to the antenna. The power supply for the radiator is regulated to 5 V. The circuit is protected from low battery voltage by use of a comparison circuit. This will prevent the radiator from operating when the battery voltage drops below about 5.7 V. The battery used is a lead-acid gel-cell type with a capacity of 1.2 A-h. The radiator draws less than 55 mA, which permits about 22 hours of operating time on a single charge. (The circuit and first prototype unit for the monopole radiator were developed by Steven Fick at NIST, Gaithersburg, MD.)

Although the monopole radiators are not as well characterized, monitored, or controlled as the spherical dipoles, they do have some advantages which we felt made them worth testing. They are cheaper, simpler to use and maintain, and probably more rugged than the spherical dipoles. In addition, they can be placed on the ground plane/bench, which is the most common configuration for RE02 tests, whereas the spherical dipoles are more suitable for testing in the mobile equipment configuration, supported by foam near the middle of the room. The spectrum radiated by the monopoles is also different from that of the dipoles. In principle, the dipoles can be fed with virtually any signal and will radiate that signal convoluted with the radiation properties of the sphere. In all the tests so far, the dipole has been fed with a single frequency at a time. It can radiate fields which exceed MIL-STD maximum allowable limits from about 5 MHz to a little over 1 GHz. The monopole, on the other hand, continuously radiates all frequencies in its spectrum. Because all frequencies are radiated continuously, an entire band can be tested in a single sweep, so that testing with the monopole is significantly quicker than with the dipole. Also, the relatively dense spectrum of the monopole may enable one to test for problems associated with sweep speed, as will be seen below. Thus, despite the drawbacks of the monopole, we felt it was worth including in the tests. If it performed well, we would then devote additional effort to its characterization.

2.2 Procedures

The three participating laboratories will not be identified in discussion of the results, and only aggregate data will be shown. At the time of the tests, one of the laboratories was NVLAP certified for MIL-STD-462 acceptance testing, and the other two were working toward certification. Tests were performed over two days at each lab. The same spherical-dipole unit and monopole unit were used in all the tests. The intent was that the NIST monopole and dipole radiators would be treated as if they were pieces of electronic equipment submitted to the laboratory for RE02 acceptance testing. The monopole was to be tested on the bench top/ground plane, and the dipole was to be treated as a piece of mobile equipment placed on a foam support out in the room. In all the tests the radiator was oriented so that its axis was vertical. For low frequencies (below 20 or 30 MHz, depending on the laboratory), the receiving antenna was a small monopole, and only the vertical component of the radiated field was measured. From 20 or 30 MHz to 200 MHz, a biconical antenna was used, and vertical and horizontal components were measured separately. Above 200 MHz, all three laboratories used conical log-spiral antennas, sensitive to one circular polarization.

At 20, 30, and 200 MHz, one or more laboratories change the receiving antenna used. At these frequencies, measurements were taken on radiated signals at frequencies at the top of the lower band and at the bottom of the top band (e.g., 19.95 MHz and 20.05 MHz) at the laboratory changing antennas at that frequency. If a lab did not change antennas at that frequency, then just one measurement was taken (e.g., 20.00 MHz). For the computations in which measurements from different laboratories were paired or compared, the

20.00 MHz measurement would be paired or compared with both 19.95 and 20.05 MHz results.

As noted above, the monopole is driven by a comb generator, so that it radiates its entire spectrum continuously, with spikes roughly every 2 MHz from 2 MHz to several hundred megahertz. Thus, for the monopole tests, the radiator was turned on, and the lab swept the receiver through an entire frequency band. For the spherical-dipole tests, on the other hand, the radiator was fed with a single frequency at a time, with the frequencies chosen to correspond to those at which the radiator had been tested in NIST facilities. The engineer or technician performing the test was told the frequency and swept through a small range of frequencies around the one being radiated. The test frequencies for the dipole ranged from 5 MHz to 1000 MHz. The gap voltage of the dipole was maintained at the same value (1.00 V) for all the tests. Each measurement at each frequency was done twice at each lab, typically on successive days, but in some cases in the morning and afternoon of the same day. Between the two measurements the setup was always taken down, connections broken, etc., to insure that the two measurements were as independent as was practical. In at least one case, the positioning of antennas was intentionally altered somewhat, to simulate the variations in placement which could occur in different tests. Thus we generally have two independent measurements for each frequency (and each polarization, where prescribed by the MIL-STD) at each of the three participating laboratories. Insofar as was possible, NIST personnel attempted not to influence the actual conduct of the tests. Some interaction did occur, of course, but we do not believe that there were any substantive effects on our general results.

3. DIPOLE RESULTS

The collected results of the measurements on the spherical-dipole radiator at all three laboratories, for a vertically polarized receiving antenna, are shown in fig. 3. Low-frequency (<30 MHz) results from one of the laboratories were not available because of an error in assembling an antenna. The error was discovered during the tests, but too late to repeat the measurements. Also shown in fig. 3 are the results obtained in the NIST facilities which simulate (to differing degrees) a free-space environment.

The NIST results are connected by solid lines. The single most striking feature of fig. 3 is the large spread in the measurement results. The differences between maximum and minimum values for the radiated field strengths at different labs are as large as 25 to 30 dB at some frequencies, and they are of order 10 dB even at the "good" frequencies. Figure 3 also indicates that there are often large differences between the shielded room results and the results from TEM cell, OATS, and AC. Differences between the two measurements at the same frequency at the same laboratory cannot be seen in fig. 3, but these also can be sizable.

For purposes of addressing separately the three different types of variations (day-to-day, inter-laboratory, screened room to free space) it is useful to present the data in different formats. To address the question of repeatability of results at a given laboratory, we simply compute the difference, in decibels, between the two independent measurements at each frequency at that laboratory. This difference, denoted Δ, is plotted in fig. 4 for all three laboratories. The dashed lines at ±5 dB are included to aid the eye and facilitate discussion. As can be seen, most measurements repeated to within 5 dB, but a significant number (23%) did not, and some day-to-day variations exceeded 10 dB.

For inter-laboratory variations, there are several ways in which the data might be presented. Our choice is guided by the question, "If the same measurement were made on the same device at two different laboratories, how much would the two results differ?" To answer this, we have computed at each frequency the magnitude of the difference (in decibels) between each possible pair of measurements at different labs. Thus, at a typical frequency, where there are two measurements at each of the three labs, there would be 12 different pairs of measurements at different labs. We use D to denote the difference between two measurements at different labs. Figure 5 shows the average and sample standard deviation, *s*,

$$s^2 \equiv \frac{1}{(N-1)} \sum_i (x_i - \overline{x})^2, \qquad (1)$$

of these differences for each measurement frequency. The statistics were done on the field strength, and the results were then converted to decibels. Results below 30 MHz are based on measurements at only two laboratories. Even above 30 MHz, the sample size is not large enough for real statistical significance. Nevertheless, the results are not particularly encouraging. The *average* differences in the measurement of the same quantity at two different laboratories are over 5 dB at most frequencies and over 15 dB in some cases.

To consider differences between screened-room results and those obtained at quasi free-space facilities, we average over the screened-room results obtained at the three EMC labs and compare to the TEM cell, OATS, and AC results at NIST. The results are shown in fig. 6, where again the error bars correspond to the sample standard deviation. At high frequencies the screened-room results are in fair agreement with the quasi free-space results, although the spread in the screened-room results is rather large. Below about 80 MHz the screened-room results tend to be systematically, significantly low. The one exception occurs at 40 MHz, which corresponds to a resonance frequency of two of the screened rooms and where the results in those two rooms are anomalously high, cf. fig. 3. The other eye-catching feature of fig. 6 is the large standard deviation just below the band edge at 200 MHz. The spread in the measurements at this point is so great that the results are essentially consistent with any result from 0 V/m ($-\infty$ dB) to the top of the bar shown on the graph.

For frequencies between 20 or 30 MHz and 200 MHz, emission measurements were also made with the receiving antenna horizontally polarized. Results for the measured amplitude are shown in fig. 7. Unlike the results for vertical polarization, there are no results shown from NIST quasi free-space facilities. That is because the electric field from a vertical spherical dipole in free space has no component in the ϕ direction and no horizontal component at all in the equatorial plane [9]. This was checked in a few instances in the NIST facilities, and no significant field was detected. Thus the horizontally polarized fields of fig. 7 are an artifact of performing the measurements in a screened room.

The day-to-day and inter-laboratory variations in the results for horizontal polarization can be treated in the same manner as they were for vertical polarization. The results are shown in figs. 8 and 9. The day-to-day variations are somewhat worse than the vertical case, as are the lab-to-lab differences. The *average* inter-laboratory differences are all around 10 dB, except at the 40 MHz resonance, where they are considerably worse. Since the horizontally polarized fields are basically room effects, it is not surprising that there is considerable variation from room to room. We should note at this point that if the source were a horizontal dipole, then it would be the vertical fields which arose from room effects. In general, it is the cross-polarized configuration which is due to room effects.

4. MONOPOLE RESULTS

The results obtained for the monopole radiator do not lend themselves to as neat and tidy an analysis as do the dipole results. The principal difficulty is that the monopole has not yet been characterized in NIST facilities. Therefore, we do not know the field strength radiated in free space, nor the location of all the peaks, nor whether the spectrum is stable from day to day. The stability question is a critical problem in view of the large variations between results on different days or from different laboratories observed in the measurements of the spherical dipole. Such variations make it essential that the source is known to be stable, so that we can confidently ascribe the variations to causes other than variability of the source. We have not yet confirmed the stability of the monopole radiator, . Matters are further complicated by the spectrum density of the comb generator, which often makes it difficult to determine whether a peak seen in a given measurement is the same peak seen at a different laboratory or on a different day. The waters are further muddied by the fact that peaks seem to come and go from day to day at each laboratory. Finally, the data collection and compilation procedures were different at the three different laboratories, and consequently we do not have the same information from each. For example, from one laboratory we have record of only the 12 strongest peaks in each band, whereas from another we have all peaks above the noise. Also, an error in the setup, which was discovered the next day, invalidated some data from one of the laboratories.

Nevertheless, we present the data , for use if the monopole proves to be stable when we test it. Figure 10 shows the (vertical) field strengths measured at the peaks at all the laboratories. The spread in the data is impressive, particularly at low frequencies where differences of 30 dB for a single peak are not uncommon. The day-to-day variations at a given laboratory are plotted in fig. 11. For this graph, peaks on different days were taken to be the same peak if their frequencies were the same within 0.5 MHz. If two peaks on one day were within 0.5 MHz of a peak on the other day, only the peak closest in frequency was used. Besides the variation in the strength of the peaks from day to day, there are many peaks which are seen one day and not the other. To quantify this effect, we defined and computed the "here today, gone tomorrow" (HTGT) index,

$$HTGT \equiv \frac{M_1 + M_2}{2 N_f} , \qquad (2)$$

where M_1 (M_2) is the number of frequencies missed on day 1 (2), and N_f is the total number of frequencies radiated. We cannot determine N_f exactly from the measurements since we do not know how many frequencies there were which were radiated but were not seen *either* day. However, that should be a correction which is of order $HTGT^2$, which can be neglected if HTGT is small. The values measured for HTGT at the two laboratories where it could be determined were 9% and 14% for the vertical-polarization measurements. Until the monopole radiator has been shown to be stable, this effect can always be blamed on the radiator. If the radiator is indeed stable, then it could arise as a result of sweeping too rapidly. Because of the presumed stability of the crystal oscillators, it is very unlikely that the frequencies of the peaks are varying; their strengths, however, could be.

The results of horizontal polarization measurements on the monopole are given in figs. 12 and 13. They are qualitatively similar to the results presented above and require no additional comment. The values of HTGT in the horizontal tests were 6% and 17% at the two laboratories where it could be determined. (An outlying point at 54.2 MHz, -31.8 dB, has been omitted from fig. 13.)

5. SUMMARY AND CONCLUSIONS

5.1 Discussion

We base our conclusions primarily on the results of the tests on the spherical dipole since we are most confident of its characteristics and its stable performance. We first address the three main types of variations discussed in the introduction. The emissions tests on the spherical dipole standard radiator, performed according to the old MIL-STD-462, lead us to the following conclusions. (1) Day-to-day variations of about 5 dB or more occur in measurements of radiated fields of the same magnitude, frequency, and polarization. Consistent repeatability of 5 dB or better may be achievable, but probably requires considerable effort and care. (2) The average difference between measurements of radiated, vertically polarized, electric fields of the same magnitude at different laboratories was over 10 dB at several frequencies. It is about 20 dB at a resonance frequency of one of the screened rooms. For horizontal polarization (with a vertically polarized source) the average difference is consistently around 10 dB, except at the resonance frequency, where it is near 20 dB. (3) At frequencies below about 60 MHz, the screened-room results are significantly lower than the quasi free-space results, except at the resonance frequency of the screened room. For frequencies of 80 MHz and above, the average screened-room results are usually consistent with the quasi free-space results, albeit with large standard deviations.

What is the cause of the large variations in test results? There are three obvious suspects: variability of the standard radiator, lack of competence of the test laboratories, and faulty test methodology (pathologies of RE02 screened-room measurements). It is very unlikely that the spherical-dipole radiator is that unstable. The gap voltage is monitored continually and is kept constant within 0.1 dB from test to test. Spot checks in NIST facilities indicate a repeatability for radiated emissions measurements of better than 1 dB. At high frequencies there is some departure from axial symmetry in the radiated pattern [1,2], but this is only of order 3 to 5 dB, and it occurs only for 600 MHz and above. Furthermore, the orientation of the sphere was usually the same at a given laboratory, due to positioning of the fibers running into the sphere. As for the test laboratories, in principle it is possible that they were careless or incompetent in their measurements, but we feel that this is unlikely. NIST personnel present at the tests were not trained or experienced specifically in RE02 measurement techniques and did not attempt a systematic, critical evaluation of laboratory procedures, but our impression was that laboratory personnel were in general competent and careful. As mentioned above, one of the three laboratories was NVLAP certified; and all three are large, reputable laboratories with considerable experience. Furthermore, no one laboratory stood out as having particularly bad results. Consequently, while a given individual bad result could have been due to an error, we do not believe that the general pattern of variability was due to shortcomings of the laboratories or their staffs. The most likely cause of the variability of results and the deviation from free-space results appears to be the basic measurement method itself. Variations in size, shape, and loading of the screened room as well as in positioning of the source and receiving antenna within the room will lead to variations in the measured field. The existence of such effects has been known for some time and has been documented by past work at NIST [5,6] and elsewhere [3,4]. The present study quantifies the magnitude of the effects in some practical measurements.

In discussing the implication of our results, we must emphasize that they *do not* apply to the new radiated emissions measurements as specified in [8]. The new standard incorporates modifications intended to improve various test procedures. In particular, it requires a large amount of absorber around the test setup, nearly transforming the screened room into a semianechoic chamber. The minimum acceptable performance specified for the absorber is rather modest, as it must be if anyone is to meet it; conventional absorbing materials do not perform very well at low frequencies. It is therefore not yet clear how big an improvement the new standard will produce. It is clear, however, that the results of our present study do not apply to measurements in rooms meeting the new standard. They apply only to the old standard, but are significant nonetheless. For one thing, they provide a reference against which a similar study of the new standard can be compared. Such a comparison will measure how much the new standard has improved the test methods. Another consideration is that it will probably be some time before tests according to the old standard are phased out entirely. As long as the old test setup is being used, it is important that the people performing the tests -- or accepting the test results -- realize how accurate those results are or are not.

Besides the three central issues discussed above, a few peripheral points which arose in this study warrant comment. Two comments involve band edges. At one of the laboratories, the software and/or instrumentation were such that a peak occurring at a band edge could be missed. This problem was noted by the laboratory in question at the time of the tests. Another, more general, band edge problem is the fact that measurements in two adjoining bands do not match up at the limit frequency. In this study we found discrepancies as large as 10 to 20 dB at band edges. It would be desirable for the limit frequency (at least) to be included in *both* bands and for techniques and calibrations to be checked until the results of the two bands agree at the limit frequency.

The other point which arose in the course of the measurements was the question of sweep speed (actually the combination of sweep speed, receiver bandwidth, and sampling rate) in the monopole tests. This point is still tentative since the monopoles have not yet been characterized and since there could be causes other than excessive sweep speed. If the monopoles prove to be stable, however, there is a definite problem with missing closely spaced peaks, as evidenced by the 5 to 20% rate of peaks measured one day but not the next. For compliance testing this may not be critical since the presence of a single peak can lead to failure. For diagnostic purposes, however, it would be desirable to capture the entire spectrum.

2 Conclusions

We recognize that there is some unfinished business to which we must attend. The monopole radiator needs to be characterized at NIST facilities, so that the significance of the RE02 test results on it can be assessed.

Also, the spherical dipole should be rechecked at NIST to confirm the long-term stability of its performance, and the effect of a nearby conducting wall on the radiated power needs to be studied in more detail. We have already performed incomplete tests on all these points, and it is very unlikely that the results of further tests will change any of our conclusions, but these points should be checked nonetheless.

The initial purpose of this study was to develop procedures for using the NIST spherical-dipole standard radiator in the accreditation of laboratories doing MIL-STD-462 acceptance testing. The basic idea was to use the spherical dipole as a standard radiator to test whether the laboratory could get the "correct" answer in its radiated emissions measurements. This goal proved unattainable. For one thing, the standard has changed, and our data are not representative of results which would be obtained with the new standard. Even for the old standard, the wide disparity in the results at different labs and even at the same lab on different days led us to conclude that proficiency testing with the NIST spherical-dipole standard radiator would be pointless. Any proficiency testing would have to allow a tolerance of around 15 dB to take into account "reasonable" variations in test results. Such crude testing would not require the precision, sophistication, and concomitant expense of the spherical-dipole standard radiator.

Although we did not develop a protocol for using the standard radiator in laboratory certification, some important general conclusions do emerge from this work. Our data constitute a clear, quantitative demonstration of the shortcomings of radiated emissions measurements in screened rooms. It would now be of great interest to perform a similar study on radiated emissions measured in conformance with the new MIL-STD. We hope to pursue such a study, using the same three laboratories, if possible. Comparison of the results of the new study to those of the old would show how much improvement the changes made.

Besides the specific relevance to MIL-STD tests, this work has demonstrated the value of the NIST standard radiator. The spherical dipole constitutes a unique tool which can be used to develop, improve, and assess methods for measuring radiated emissions. It could even be incorporated into a test procedure, for example, as a standard source for the calibration of antennas. The spherical dipole can also be used by an individual laboratory as a check standard, to check that their measurement system has not changed from day to day, or to refine their measurement procedures in order to improve the repeatability of their measurements. The comb-generator monopole radiators (or similar units available commercially) are less expensive alternatives to the spherical dipole for check-standard applications. Their output is not as well characterized or as flexible, but they are simpler to use and less expensive.

We are grateful to the three laboratories which participated in this study and to the personnel who performed the tests at those labs. We also thank Dr. Stephen Fick of NIST, Gaithersburg, for development of the monopole radiator. This work was funded by the Naval Air Systems Command.

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[8] Military Standard, "Measurement of Electromagnetic Interference Characteristics," MIL-STD-462D, 11 January 1993.

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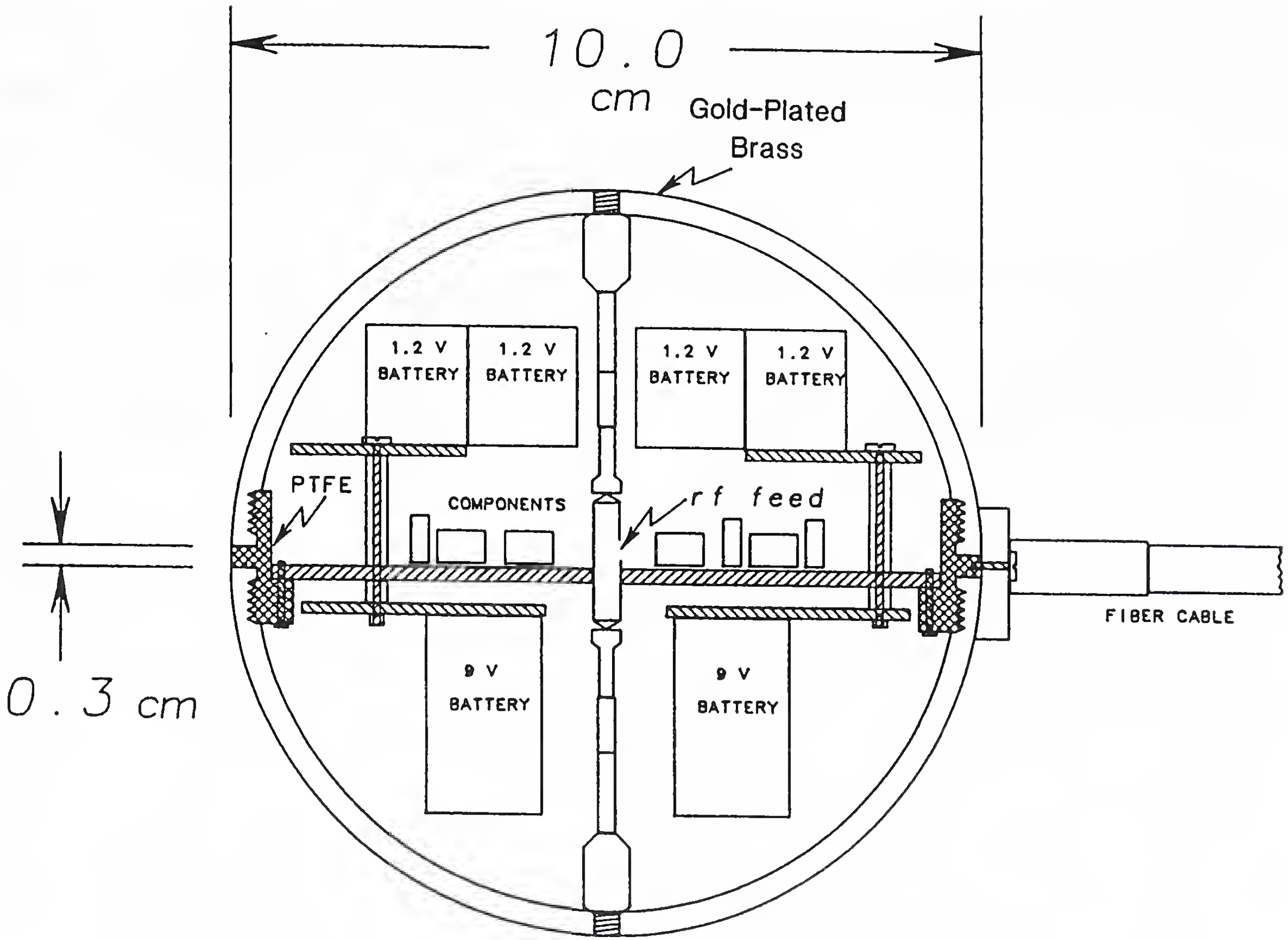

Fig. 1 Mechanical drawing of the spherical dipole radiator.

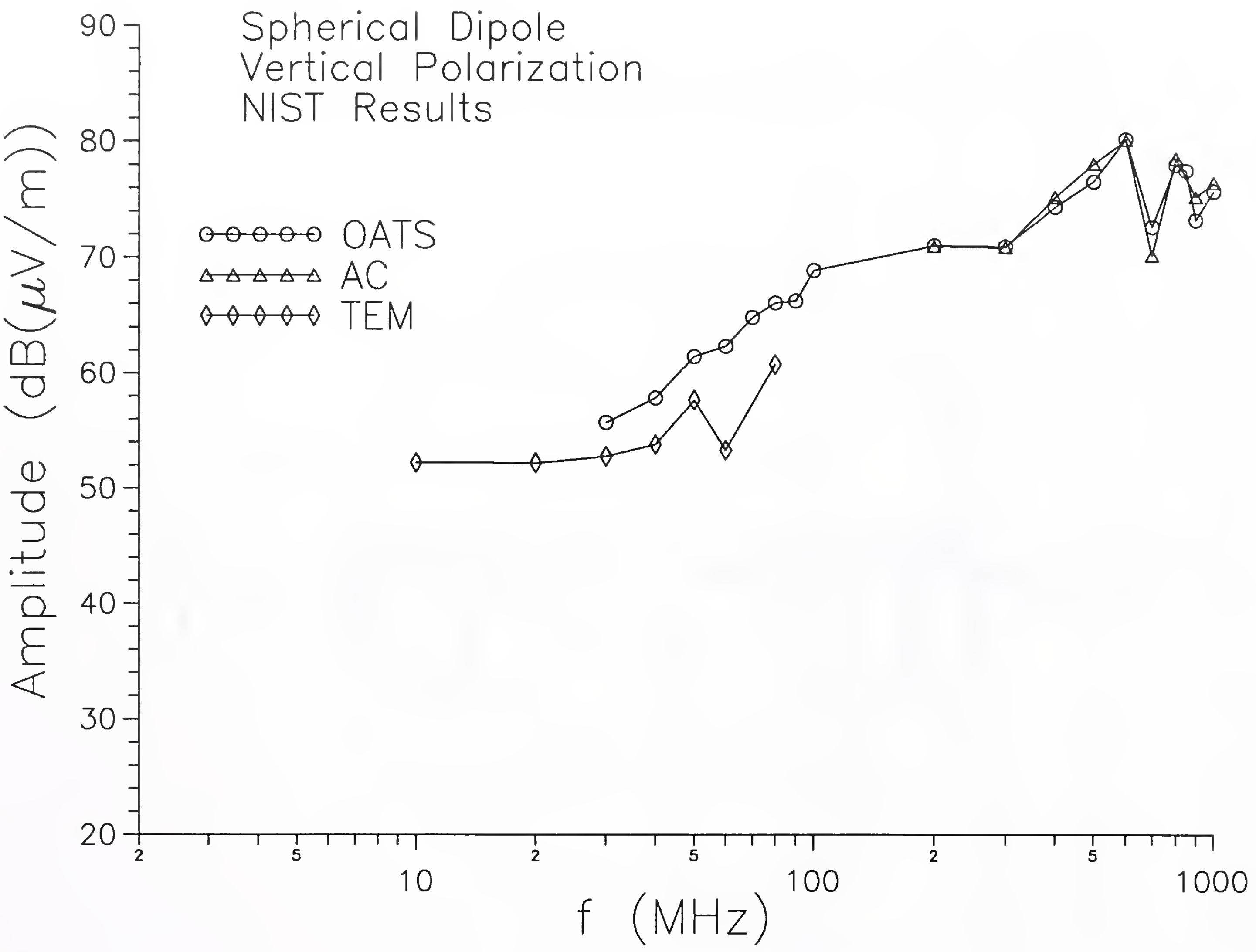

Fig. 2 Calculated field at 1 m distance using transfer function measured at NIST facilities.

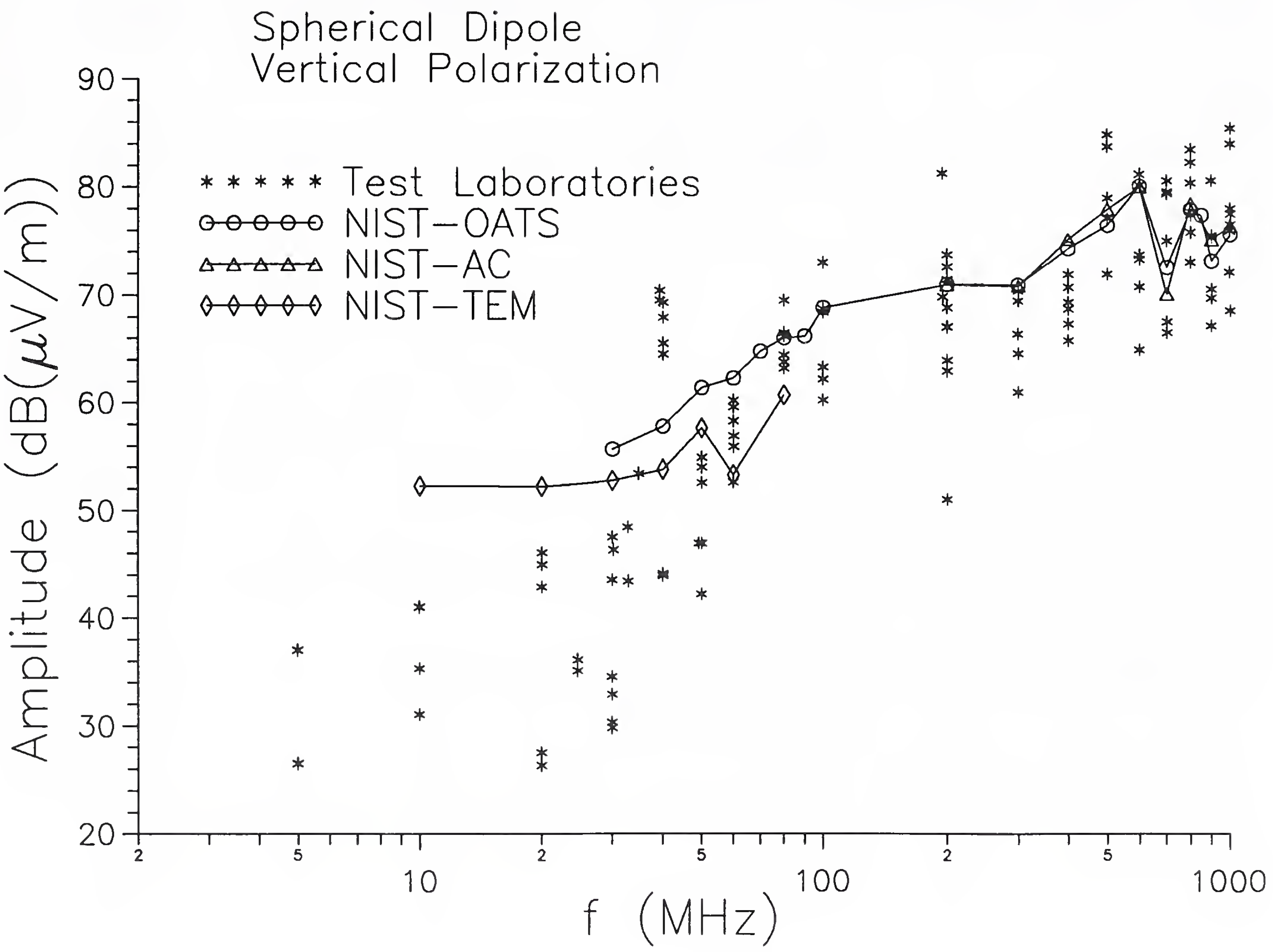

Fig. 3 Measurement results on spherical dipole standard radiator with constant gap voltage.

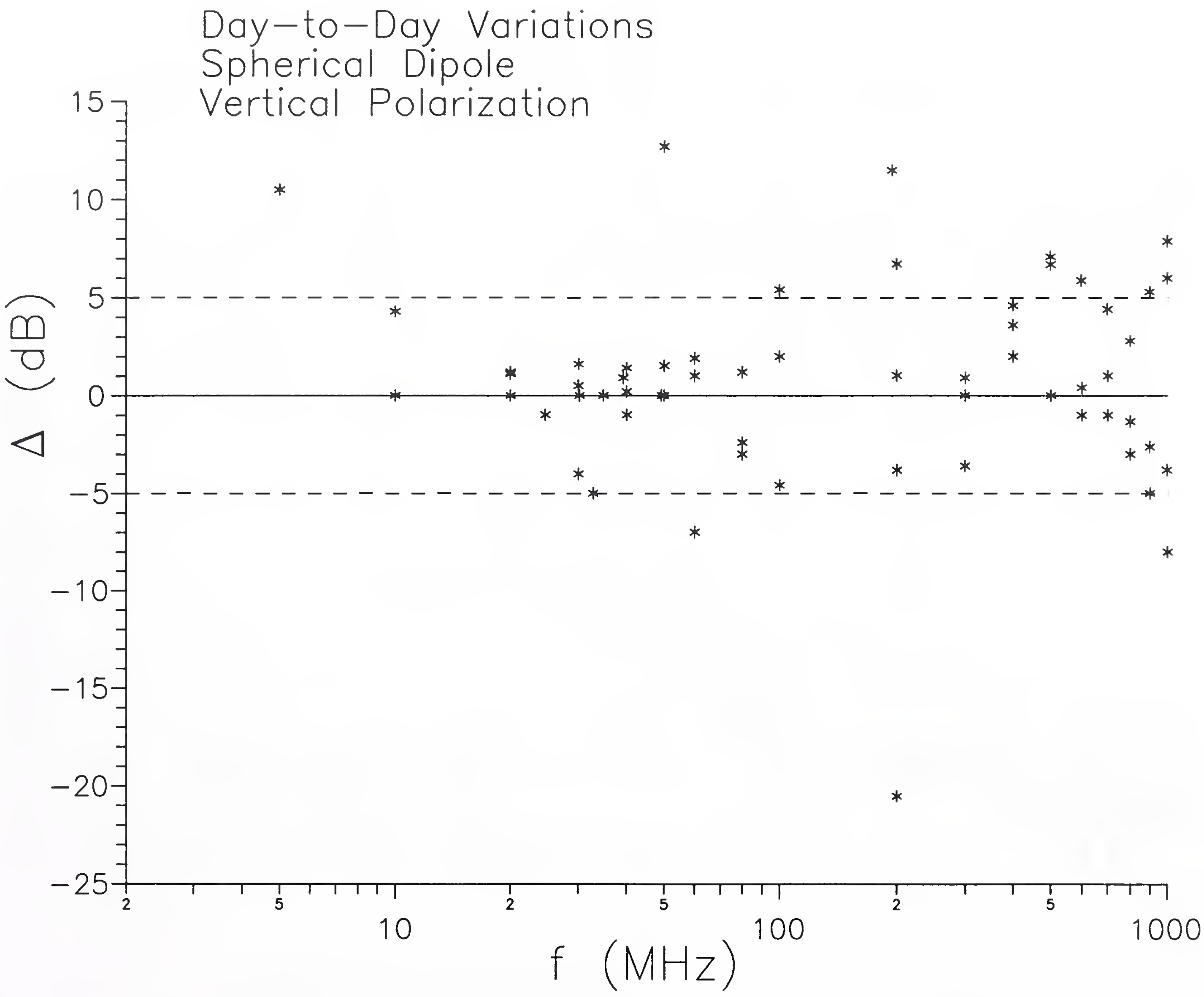

Fig. 4 Day-to-day variations in vertical polarization measurements at the same laboratory.

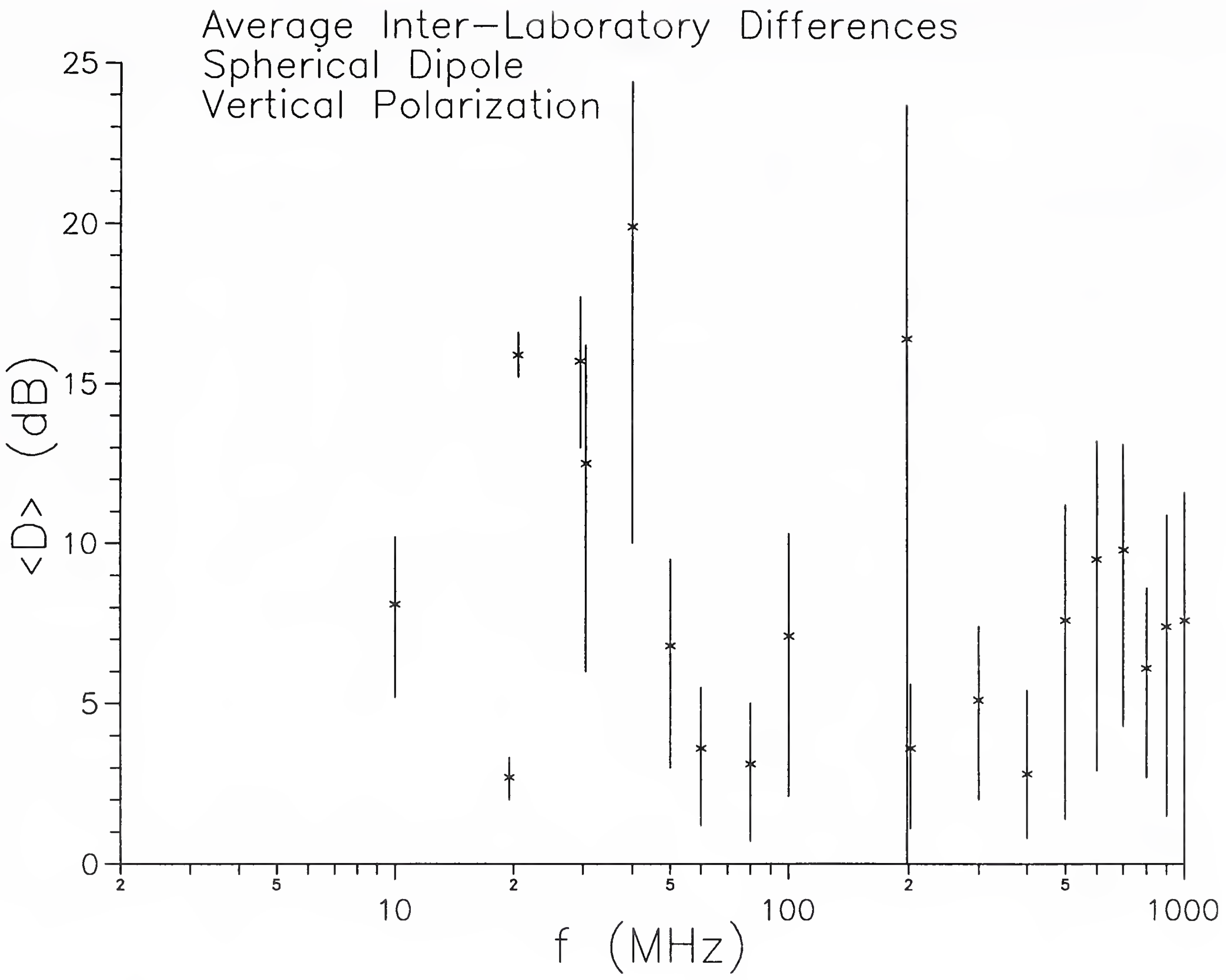

Fig. 5 Inter-laboratory differences in vertical polarization emissions measurements on spherical dipole for constant gap voltage.

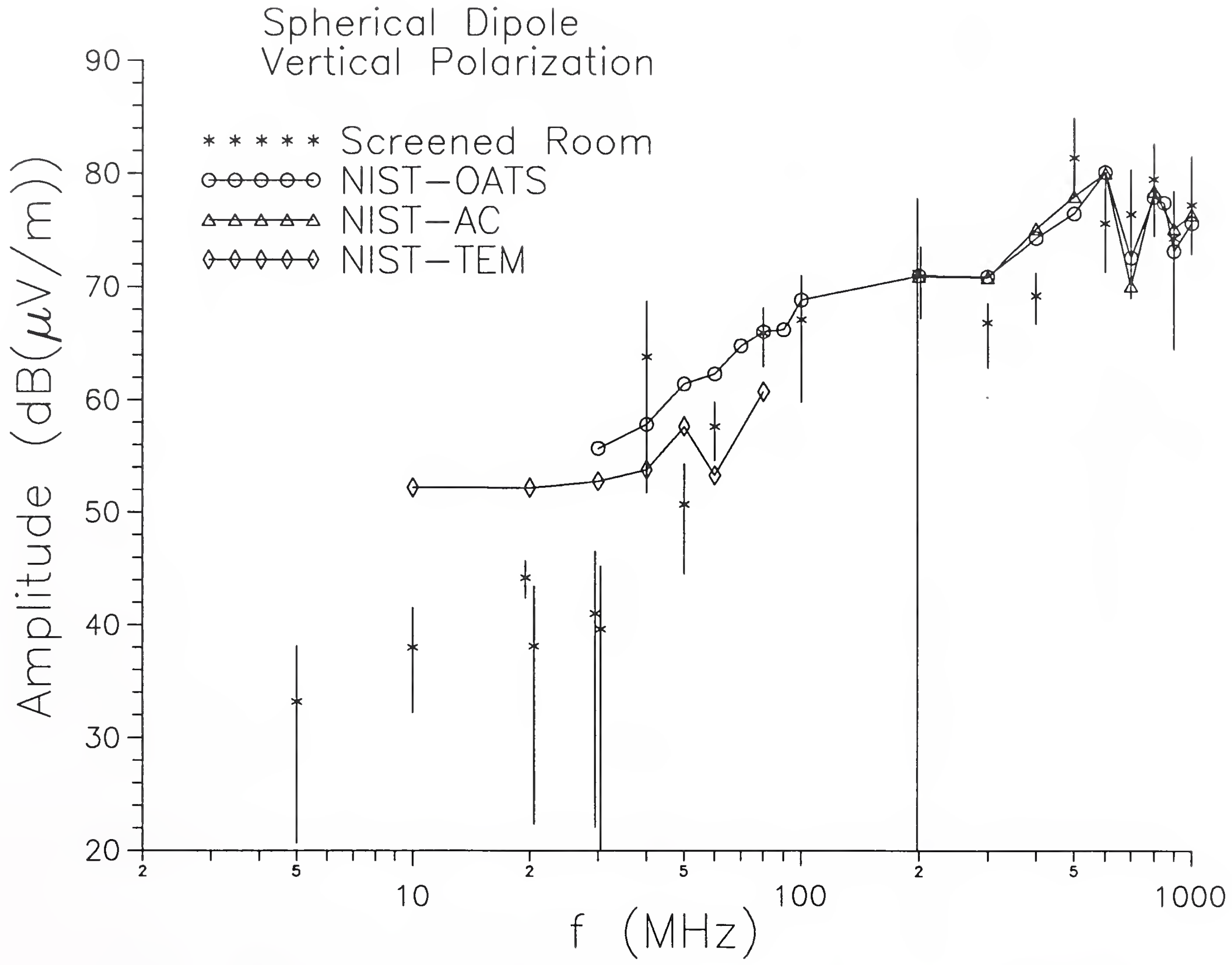

Fig. 6 Combined screened room results compared to quasi-free-space results for vertical polarization measurements on the spherical dipole.

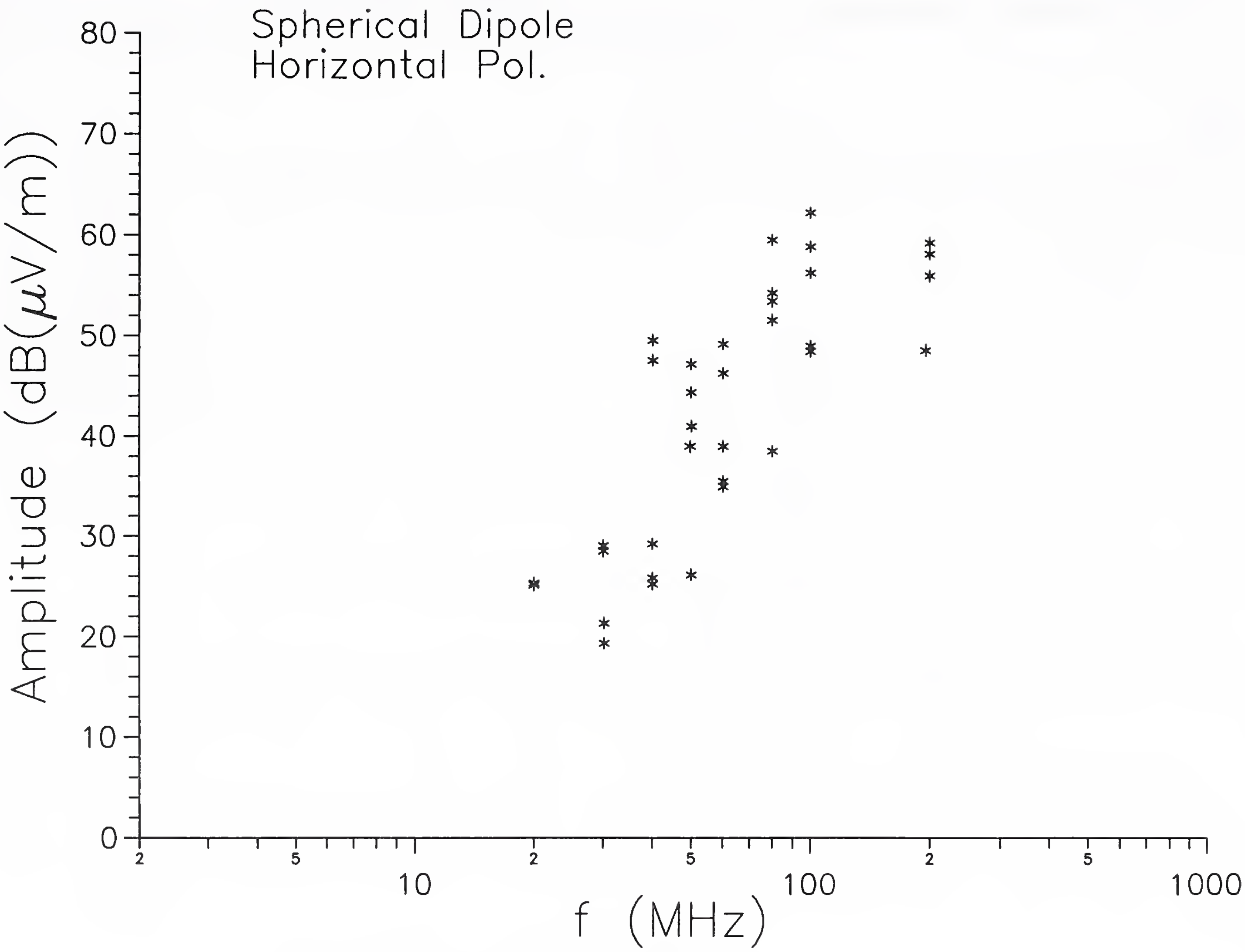

Fig. 7 Horizontal polarization emissions measurements on the spherical dipole.

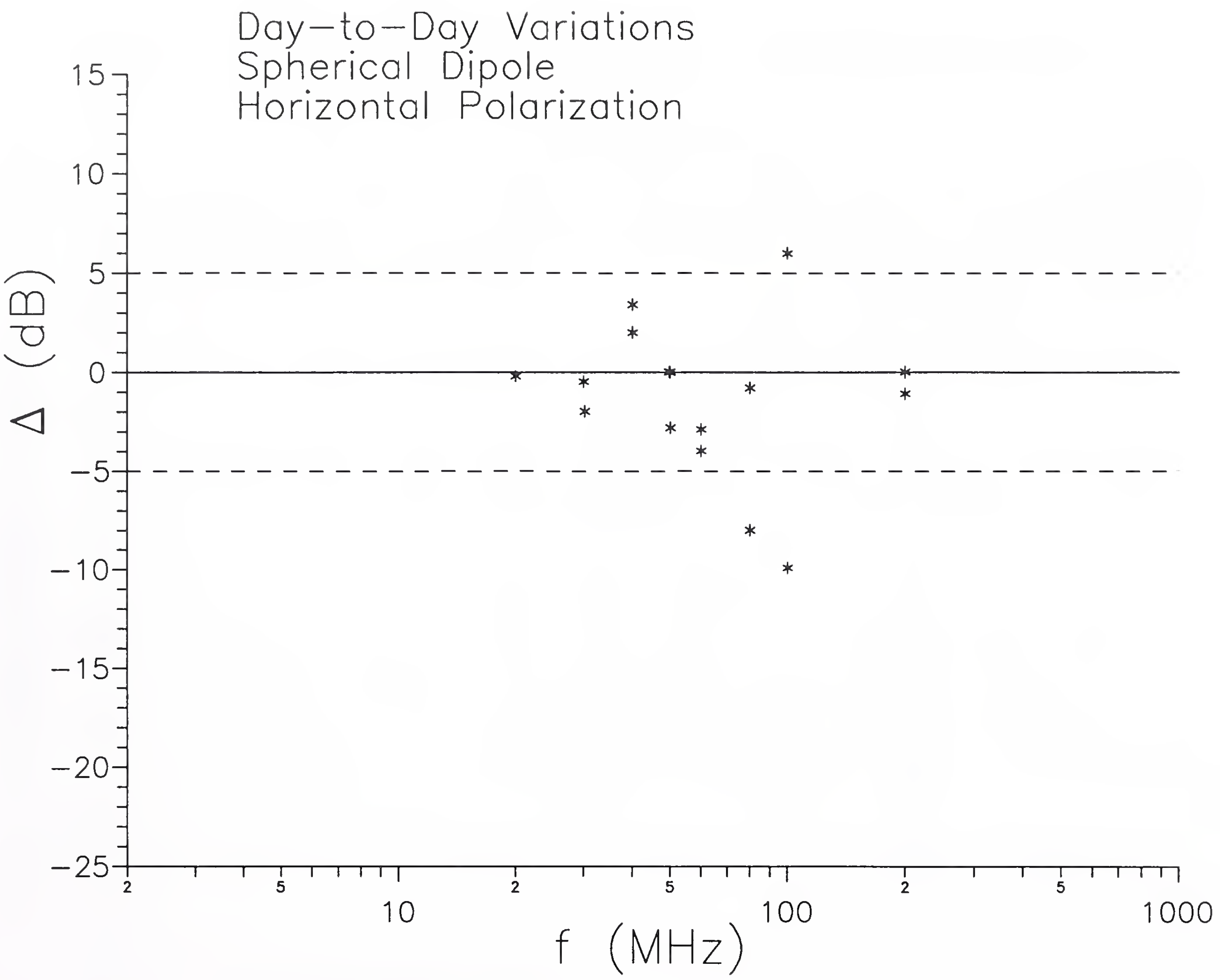

Fig. 8 Day-to-day variations in horizontal polarization measurements at the same laboratory.

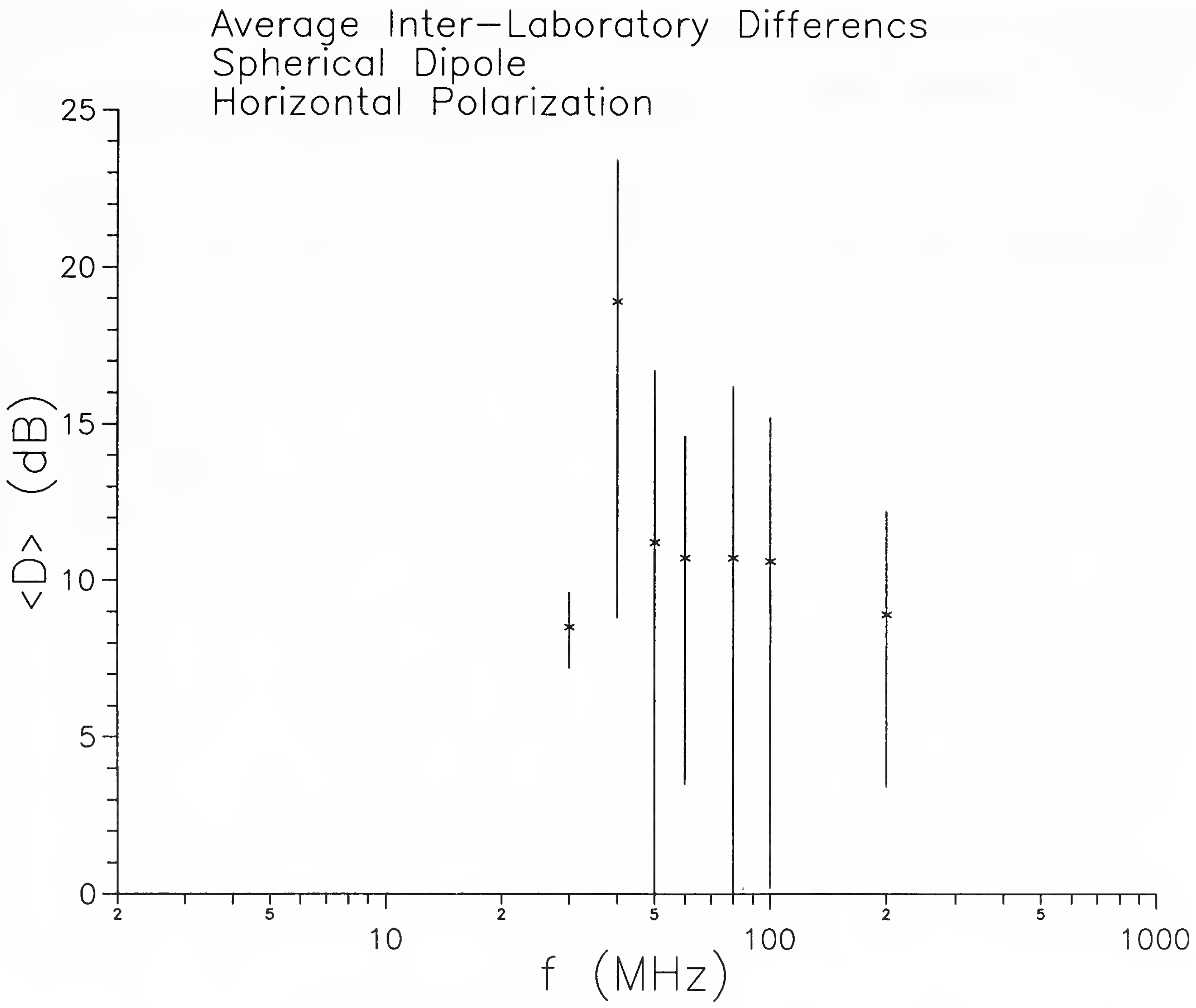

Fig. 9 Inter-laboratory differences in horizontal polarization measurements on spherical dipole for constant gap voltage.

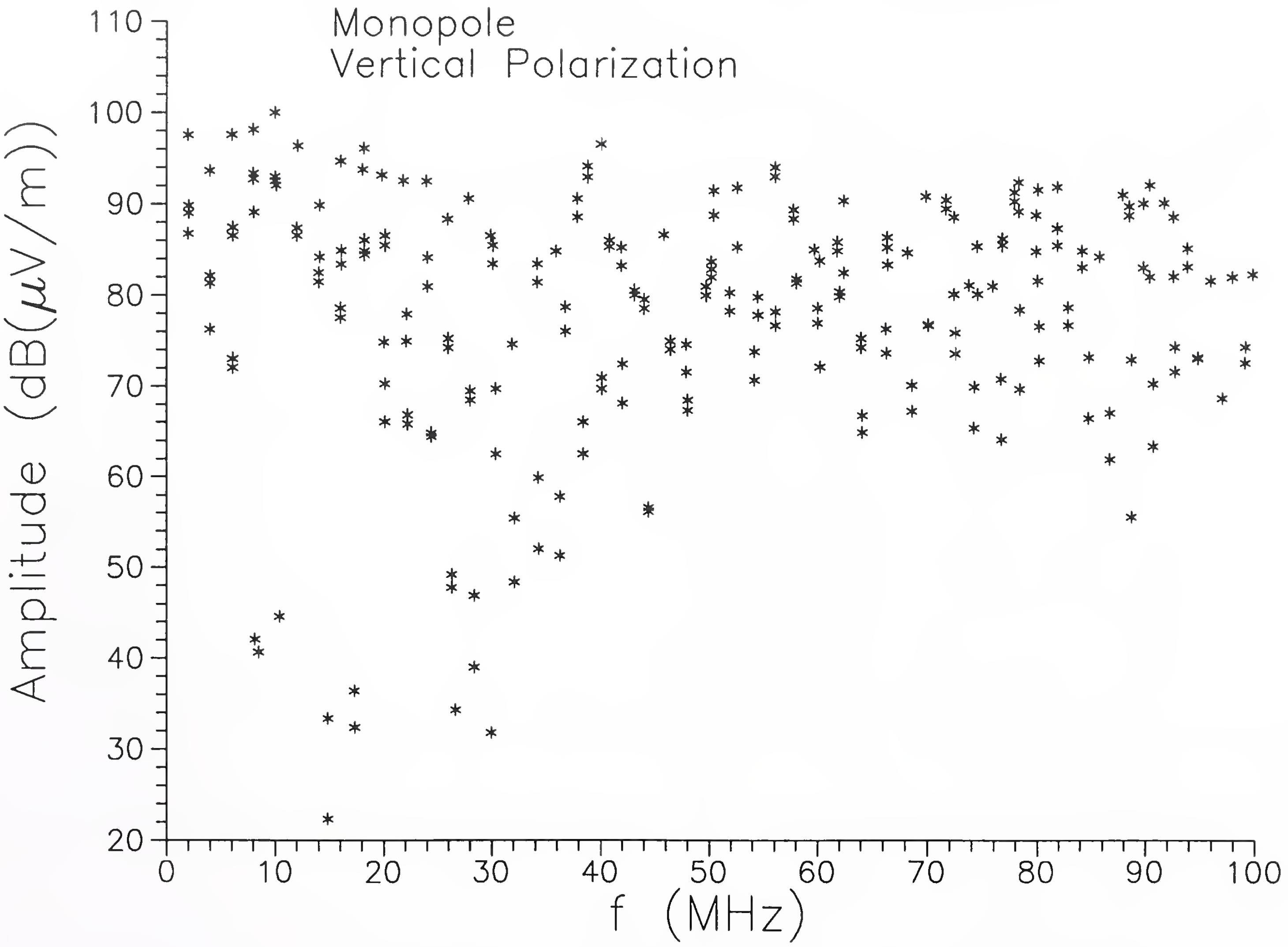

Fig. 10(a) Vertical polarization measurements on monopole radiator, 0 to 100 MHz.

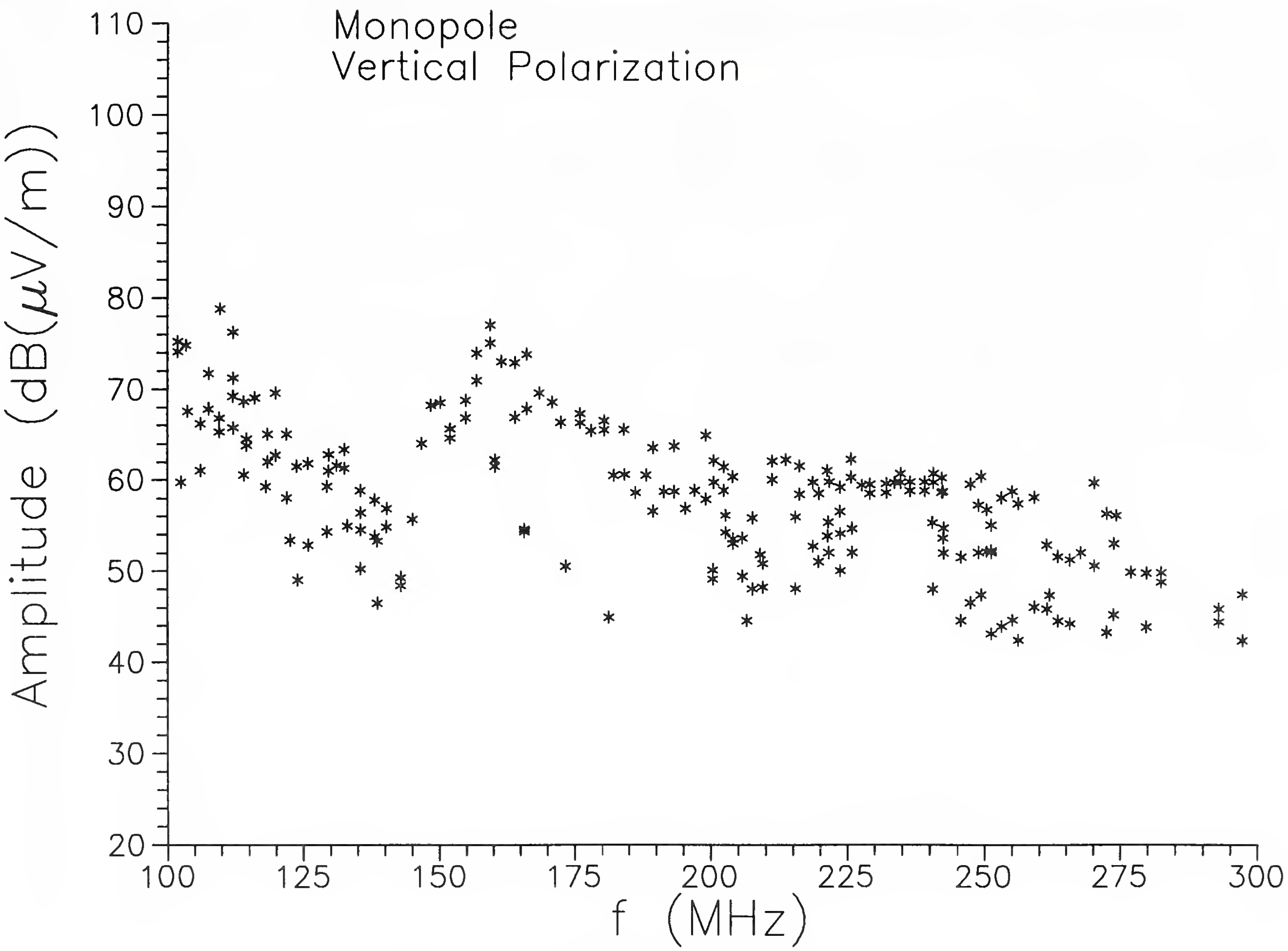

Fig. 10(b) Vertical polarization measurements on monopole radiator, 100 to 300 MHz.

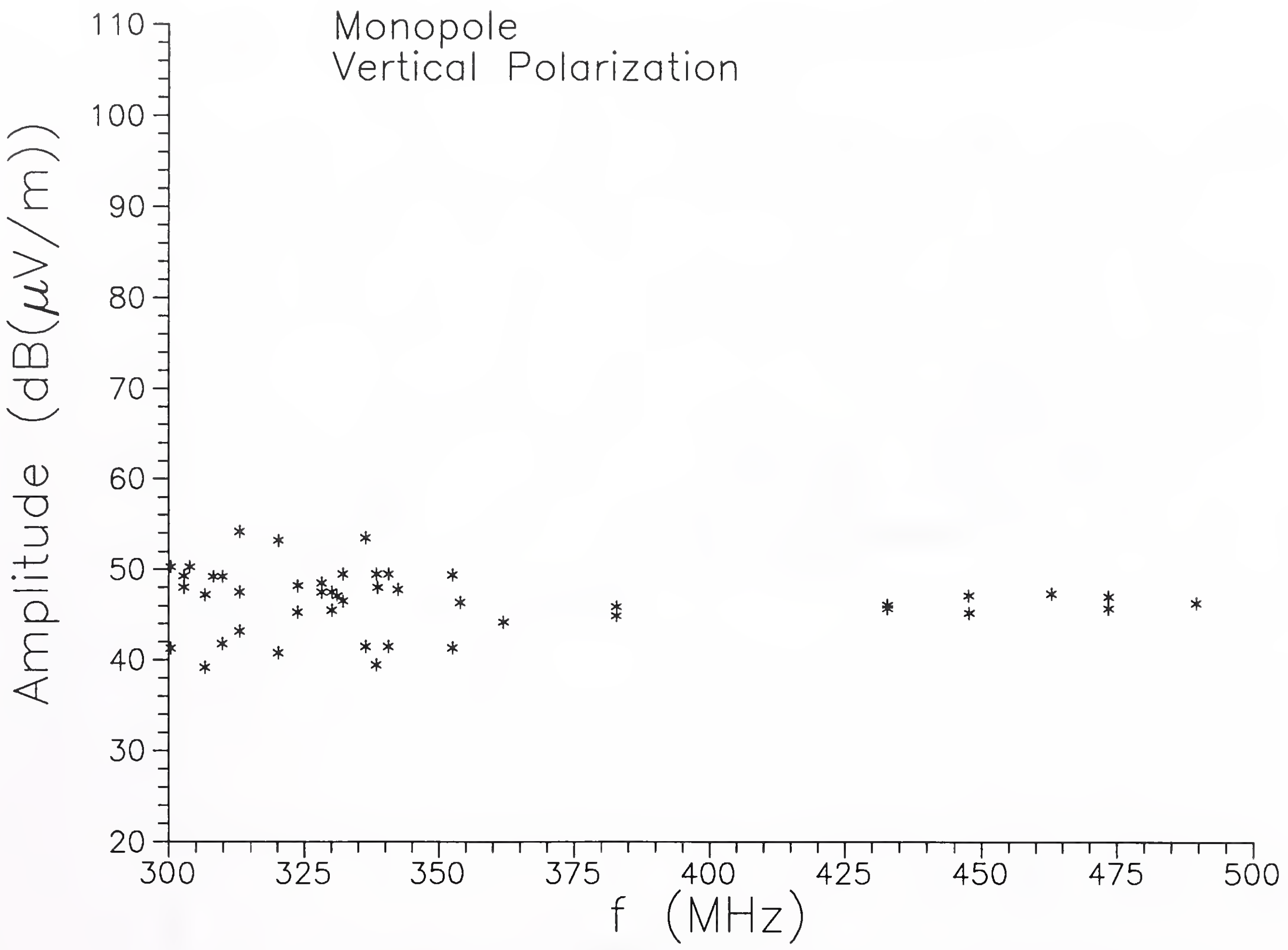

Fig. 10(c) Vertical polarization measurements on monopole radiator, 300 to 500 MHz.

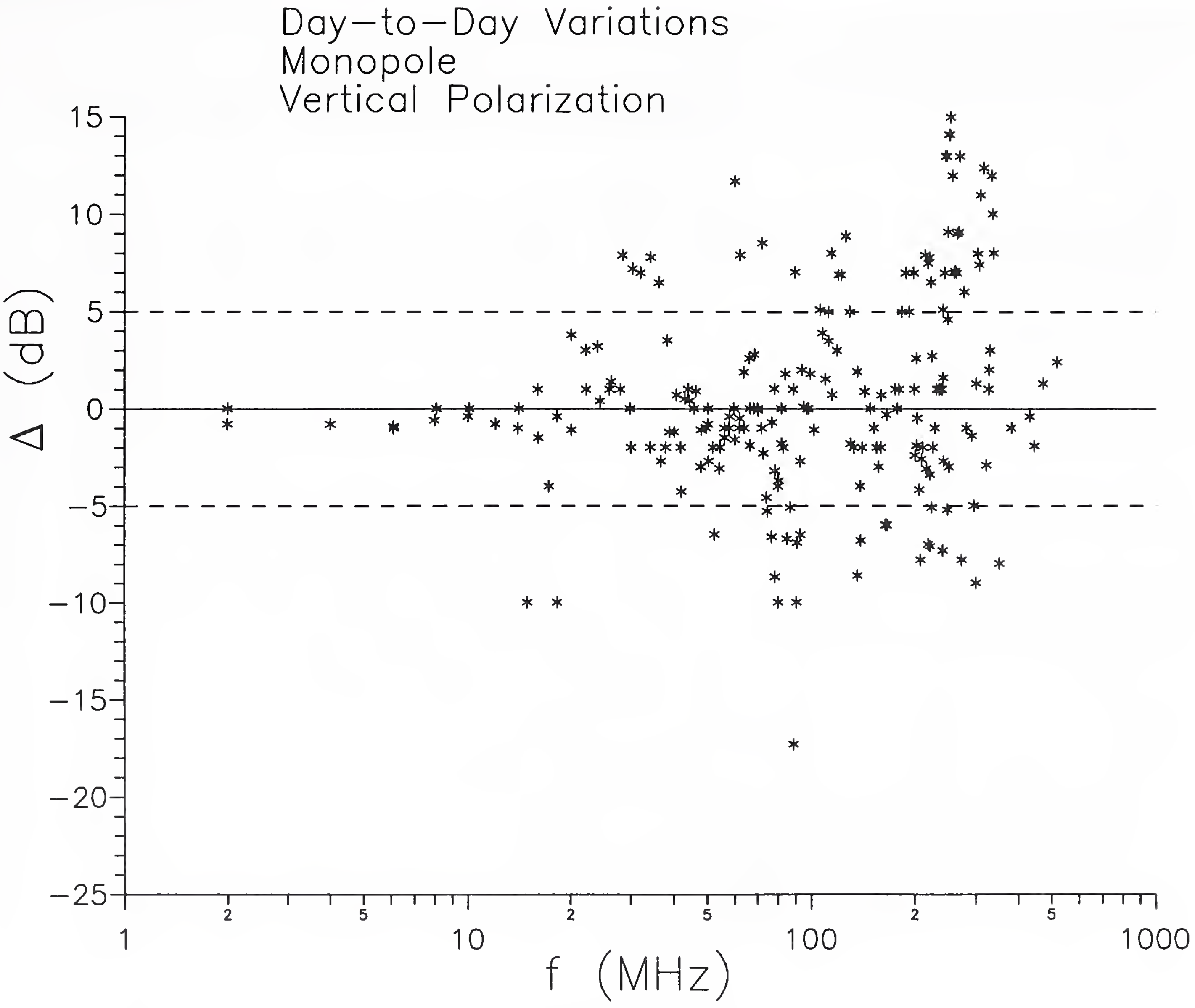

Fig. 11 Day-to-day variations in vertical measurements on monopole.

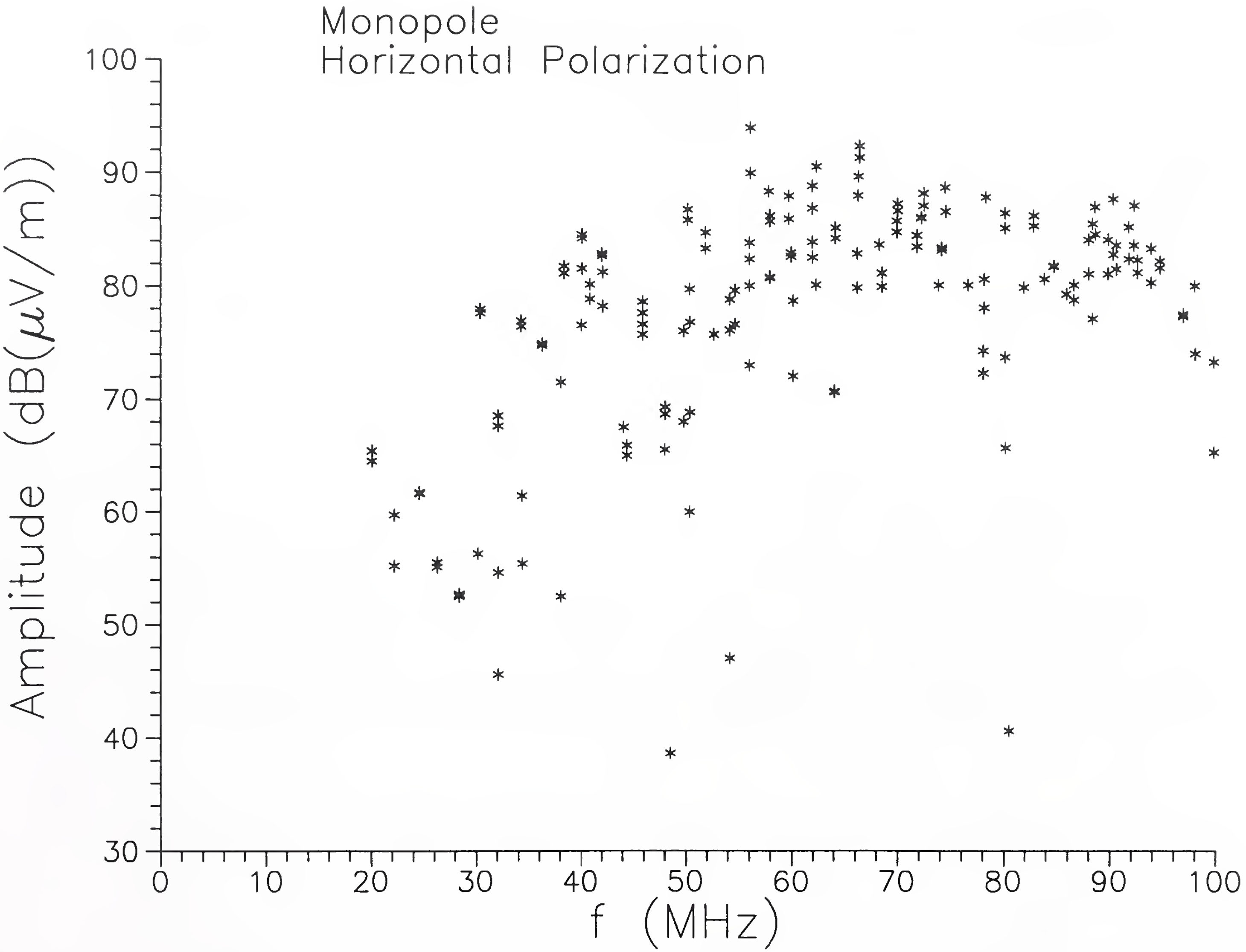

Fig. 12(a) Horizontal polarization measurements on monopole radiator, 0 to 100 MHz.

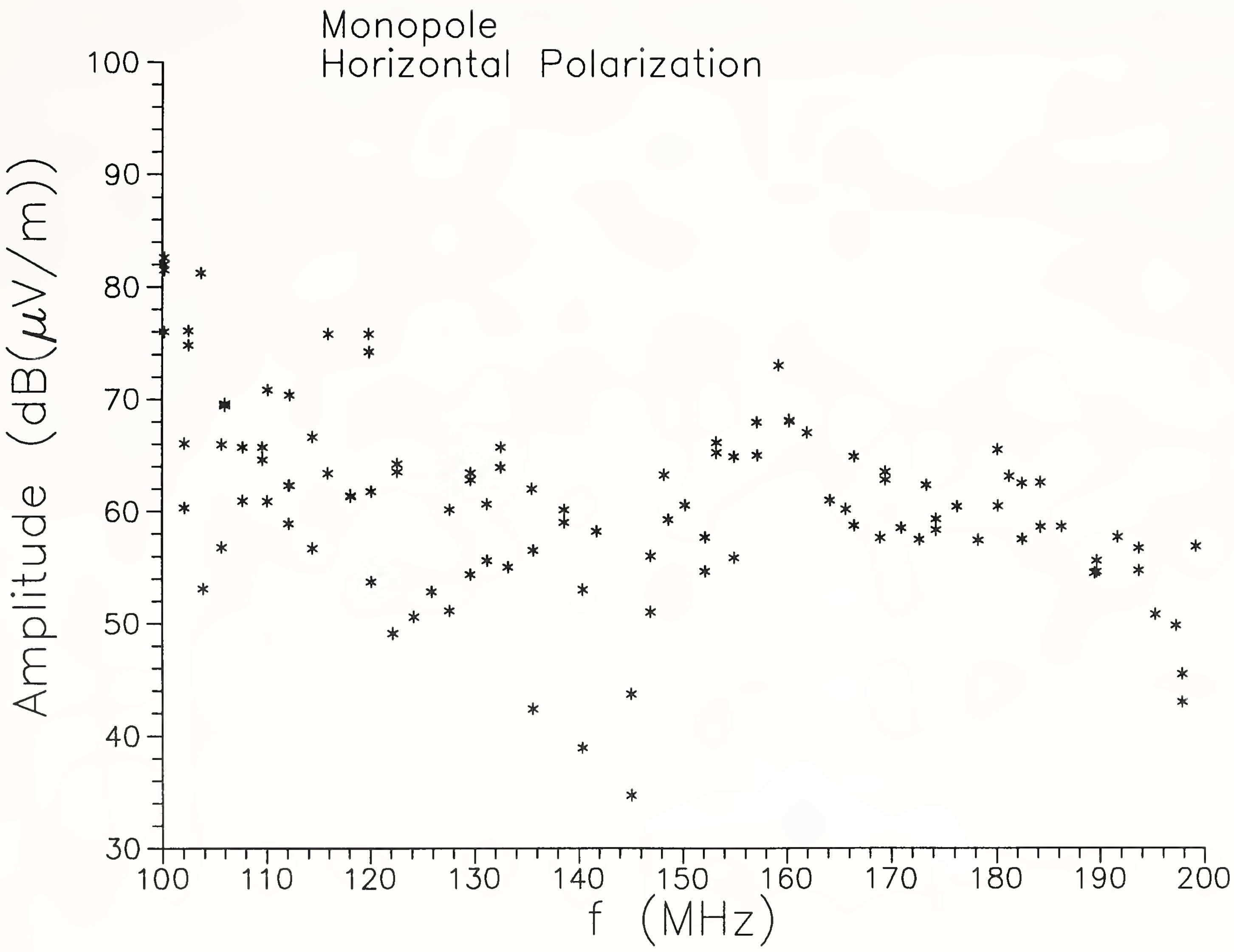

Fig. 12(b) Horizontal polarization measurements on monopole radiator, 100 to 200 MHz.

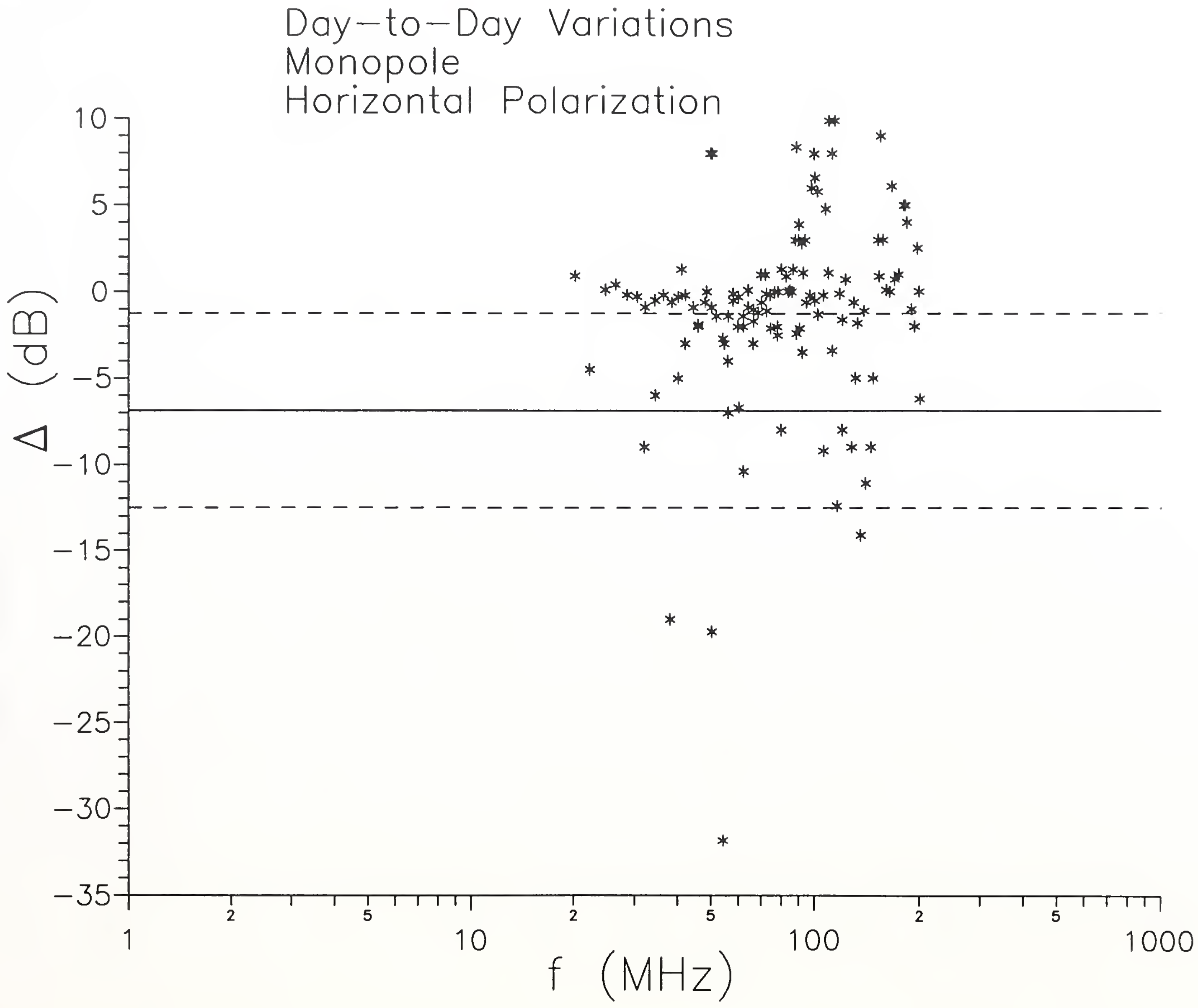

Fig. 13 Day-to-day variations in horizontal measurements on monopole.