SECTION 3
NTIA MEASUREMENT PROCEDURES

INTRODUCTION

Desiring to perform measurements that would reveal more information about the emission characteristics of microwave ovens, NTIA investigated measurement techniques other than those specified by the FCC and CISPR, selected a test procedure and measurement equipment configuration, and measured the characteristics of the ovens. Also, as a lead-in to the testing of the individual ovens, it was necessary to perform tests identifying the impact of variation of the test parameters. The basic test procedure and measurement equipment configuration is discussed in this section. Results of the parameter variation tests are provided in Section 4. Results of the oven measurements are provided in Section 5 and Appendices B, C, and D.

UNITS FOR TEST

In order to simulate tests that would reflect compliance procedures that a manufacturer might have to perform, NTIA determined to test new ovens.[19/] The microwave ovens used in this measurement program were provided to NTIA by three microwave oven manufacturers. In accepting these ovens, NTIA agreed not to identify the manufacturer of each individual oven. For this reason, ovens are referred to by an arbitrarily assigned number 1 through 12. Though the manufacturers did not guarantee the ovens to be new (in some cases, the ovens had been used for test purposes), none of the ovens had been sold to the public or used extensively. The ovens supplied by the manufacturers were understood to be recently produced, unmodified units which were taken at random from the production inventory. The oven units were representative of the equipment that is available at the present time on the consumer market. Though only 12 models from three manufacturers were measured, they are sold under a variety of brand names and associated model numbers and therefore represent a significant portion of the microwave oven models on the market.

Near the end of the measurements, NTIA chose to purchase two ovens from retail outlets in the Boulder area. It selected one to match the manufacturer and model number of Oven #7, which during initial testing showed a relatively good emission spectrum. This purchase was intended to help determine whether the performance of the oven was characteristic of others of its model. This additional oven was numbered #7DUP (for #7 duplicate). NTIA selected Oven #13 to match the manufacturer of Oven #7 but to have a different model number, choosing to evaluate whether the characteristics of Oven #7 were consistent with other models of the manufacturer. ITS limited tests of these additional ovens to spectral emission characteristics, considering those results sufficient to confirm similarities or differences with Oven #7.

19/ The previous NTIA measurement effort (see note 3) tested older, used ovens available in or near the ITS facility.

All of the ovens operated at 2450 MHz[20/] and were manufactured during 1991 or 1992. They varied in size from 0.023 to 0.042 m^3 (0.8 to 1.5 ft^3). They varied in rated power from 700 to 1000 Watts. Some had turntables or browning elements and some did not.

Operational Checkout

ITS received the manufacturers' ovens at its laboratory in Boulder, CO. ITS personnel unpacked the units and configured them as indicated in each unit's instruction manual, including the installation of turntables. All of the ovens except one, Oven #3, operated from 110 volt commercial power on three-prong plugs. Oven #3 used 220 volt power on an industrial plug, and was incompatible with the sockets available at the ITS lab. Therefore, Oven# 3 was eliminated from the tests.

Each oven was turned on with a 1-liter water load and observed for unusual behavior. All ovens appeared to operate properly. Each oven was also operated intermittently for a total of about one hour, so as to eliminate any behavior which might be peculiar to the first few minutes of operation with all-new, never-powered components.

Oven Fundamental Power Test

Each oven comes with a manufacturer-specified rating for power output. The manufacturer confirms this power output rating using Procedure IEC-705. NTIA tested the units, not to verify this procedure, but rather to ascertain the typical, average power coupling between each oven and a 1-liter water load. The results of the measurements are presented in TABLE 3-1.

The measurement procedure used for each oven was as follows: 1 liter of water was poured into a cylindrical container, and its initial temperature (°C) was measured with a thermocouple thermometer. The water was then placed in the oven under test and heated at full power for 4 minutes or 240 seconds (longer heating caused evaporation). The water was then removed and its temperature immediately measured. The average power was then calculated under the assumption that 1 calorie will raise the temperature of 1 ml of water by 1 °C. A 40°C rise in the temperature of 1000 ml of water implies 40,000 calories of heat energy coupled into the water. This caloric output was then multiplied by a conversion factor of 4.187 joules/calorie to get the energy, in joules, coupled into the water. Dividing that quantity by the heating time in seconds yields the average power coupled into the water in joules/second, or Watts. To summarize, if the temperatures are measured in degrees

20/ This is a nominal operating frequency. All microwave ovens shift in frequency during operation, and most do not emit their highest levels of emissions at 2450 MHz. Peak levels are generally seen between 2450 and 2480 MHz.

centigrade, the time is measured in seconds, and the water load is a constant 1 liter = 1000 ml, then the calculation is:

$$\text{Power into load (Watts)} = ((T_f - T_i) * 4187)/(\text{cooking time}).$$

As can be seen in TABLE 3-1, the measured power levels are typically about 16% or about .8 dB less than the labelled power levels. There could be several reasons for this; for one, the energy being lost in vaporization could not be ascertained. Also, the procedure used at ITS did not try to replicate the IEC-705 procedures, thereby decreasing the probability of identical results. In many cases on the microwave oven units, the manufacturers indicated the IEC-705 power and their own manufacturer's determined values. In each case, the IEC-705 value indicated a higher power level than the manufacturer rating. Nonetheless, the measured values were sufficiently close to the indicated output values to consider the units to be operating at their nominal power output levels.

TABLE 3-1
MEASURED VS. LABELLED POWER OUTPUT OF MICROWAVE OVENS

Oven #	T_i (°C)	T_f (°C)	Time (s)	ΔT (°C)	Energy (Joules)	Measured Power(W)	Labelled Power(W)	Diff. (%)	Diff. (dB)
1	22.2	49.9	180	27.7	115980	644	800	−20	−0.9
2	15.2	59.4	240	44.2	185065	771	900	−14	−0.7
3	(Incompatible power plug--no tests performed)								
4	17.0	46.8	240	29.8	124772	520	700	−26	−1.3
5	12.9	54.1	240	41.2	172504	719	800	−10	−0.5
6	15.8	55.8	240	40.0	167480	698	800	−13	−0.6
7	17.0	55.3	240	38.3	160362	668	750/850	−21	−1.0
8	14.2	60.3	240	46.1	193020	804	1000	−20	−0.9
9	17.1	60.8	240	43.7	182972	762	800	−4.8	−0.2
10	16.3	54.1	240	37.8	158269	659	800	−18	−0.8
11	15.9	56.8	240	40.9	171248	714	800	−11	−0.5
12	17.1	56.7	240	39.6	165805	691	900	−23	−1.1
7DUP	18.7	58.7	240	40.0	167480	698	750/850	−18	−0.8
13	18.6	57.7	240	39.1	163712	682	750/850	−20	−0.9

Measurement Configuration

The arrangement of equipment for the NTIA microwave oven tests is shown in Figure 3-1. The measurements were all performed indoors in a non-anechoic laboratory room, since tests performed in association with NTIA Technical Memorandum 92-154 (note 3) showed no significant differences between data obtained at an outdoor test range with a ground plane and the indoor, non-anechoic lab.

Each oven was mounted on a wooden table, with the base of the oven 1 meter above the floor. A 1.7-2.6 GHz, National Institute of Standards and Technology (NIST)-calibrated, standard gain horn was mounted at a height of 1.1 meter at a distance of 3 meter from the front face of the oven.

A short (approximately 1 meter long), low-loss (approximately 1 dB at 3 GHz) RF line connected the horn to the front end of the measurement system. The front end was a custom-designed and constructed 2-18 GHz preselector which combined the features of noise diode calibration, 0 to 70 dB of interactive RF attenuation, automatic tracking YIG preselection, and 2-18 GHz low noise amplification.

A longer, higher-loss section of RF line connected the front end box to a second low noise amplifier (LNA) at the front end of a Hewlett-Packard 8566B spectrum analyzer. Fixed attenuation was introduced into the line, both ahead of and after the second LNA, so as to maximize the measurement system's instantaneous dynamic range while simultaneously providing just enough gain to overdrive the noise figure of the RF path and the spectrum analyzer (see Calibration, below).

The spectrum analyzer video output was directed to a Tektronix 2430A digital oscilloscope, where time waveforms could be measured and recorded (see Time Domain Measurements, below). All system components were operated via an 80486-based PC controller, which was in turn operated under a custom-designed and written, general-purpose program named DA (data acquisition). Measurements were recorded on magnetic mass storage disks for subsequent analysis.

To monitor frequency drift of microwave ovens, a Hewlett-Packard 53310A modulation domain analyzer was operated. The modulation domain analyzer was operated manually.

Calibration

All system calibrations were performed with noise diodes. The measurement system could be calibrated with a noise diode at the horn antenna output, or at the front of the preselector box. A calibration was performed once a day at the horn output, and at more frequent intervals with the built-in diode in the preselector box. The horn-position calibration was used to automatically correct measurement values prior to recording those values. The preselector box calibrations were performed to check that the sensitivity and gain of the system had not changed, and to verify that the YIG was tracking properly.

The noise diode calibrations utilized the Y-factor method, and are accurate to within ± 1 dB if the overall noise figure exceeds about 2 dB. Typically, the noise figure of the measurement system was 9 dB, and the gain for the entire signal path, excluding the measurement antenna, was about 30 dB. To minimize noise figure while maximizing instantaneous dynamic range, fixed attenuators were introduced into the signal path until the excess noise observed from the LNAs ahead of the spectrum analyzer was observed to overdrive the spectrum analyzer noise figure by about 3 dB.

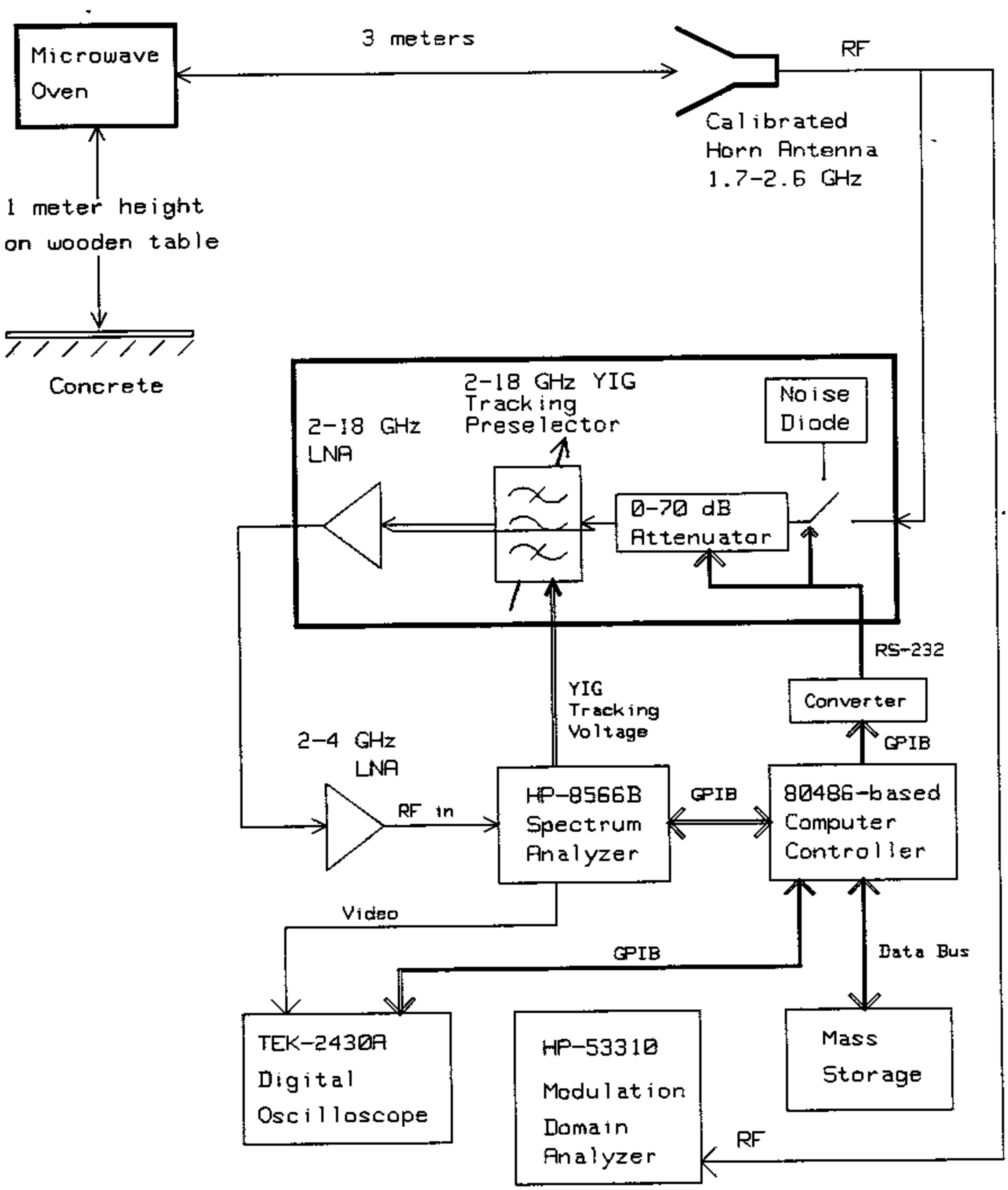

Figure 3-1. Measurement configuration.

TYPES OF MEASUREMENTS

Frequency Domain Measurements

All ovens were measured in the frequency domain to ascertain their spectral emission characteristics. Power received in a bandwidth was measured as a function of frequency for each oven. The fundamental unit of these measurements is power, in dBm, measured in 50 ohms in bandwidths of 30 kHz to 3 MHz.

Although the units of the measurement are absolute in the 50 ohm measurement circuit, they do not take into account the antenna correction factor (ACF) of the broadband horn, and thus indicate only emission levels in free space if no corrections are made to the recorded dBm values. If the ACF is factored into the recorded dBm values, then the field strength in dBμV/m, which is incident at the receiving antenna, can be determined. Also, the ACF can be combined with the recorded dBm values, and the 3 meter path loss can be factored in to yield the effective isotropic radiated power (EIRP) from the ovens under test, in dBpW.[21/]

An example of a spectral emission characteristics measurement is provided in Figure 3-2. Samples of spectral emission characteristics of individual ovens are presented in Section 5 while the rest of the results are provided in Appendix B.

For high duty cycle emitters (CW or nearly CW), the measurement of emitted power as a function of frequency involves sweeping a spectrum analyzer across the frequency range of interest, putting it in a maximum-hold mode, and waiting long enough to fill in a spectral envelope. For pulsed emitters (radars in general, and microwave ovens in particular), the choice of measurement algorithm is non-trivial and has an enormous effect on the

---

21/ Field strength at 3 meters and EIRP were calculated from measured values of dBm in 50 ohms (assuming free space propagation and no near-field effects) via the following two equations:

$$\text{Field Strength in dB}\mu\text{V/m (at 3 meters)} = P_{meas} + (77.2\ \text{dB}) + 20\log(f) - G_{dBi}$$

and

$$\text{EIRP in dBpW} = P_{meas} + (72\ \text{dB}) + 20\log(f) - G_{dBi}$$

where

P_{meas} = Power, dBm, measured in 50 ohms;
f = frequency in megahertz;
G_{dBi} = gain in decibels relative to isotropic of measurement antenna at frequency f.

To convert EIRP to effective radiated power relative to a dipole (ERP), subtract 2.14 dB from the EIRP value.

measurement results. Selection of a technique to measure microwave ovens is exacerbated by the fact that the ovens do not generally operate at a single, stable center frequency. ITS examined two basic algorithms for measuring emission spectra: swept and stepped.

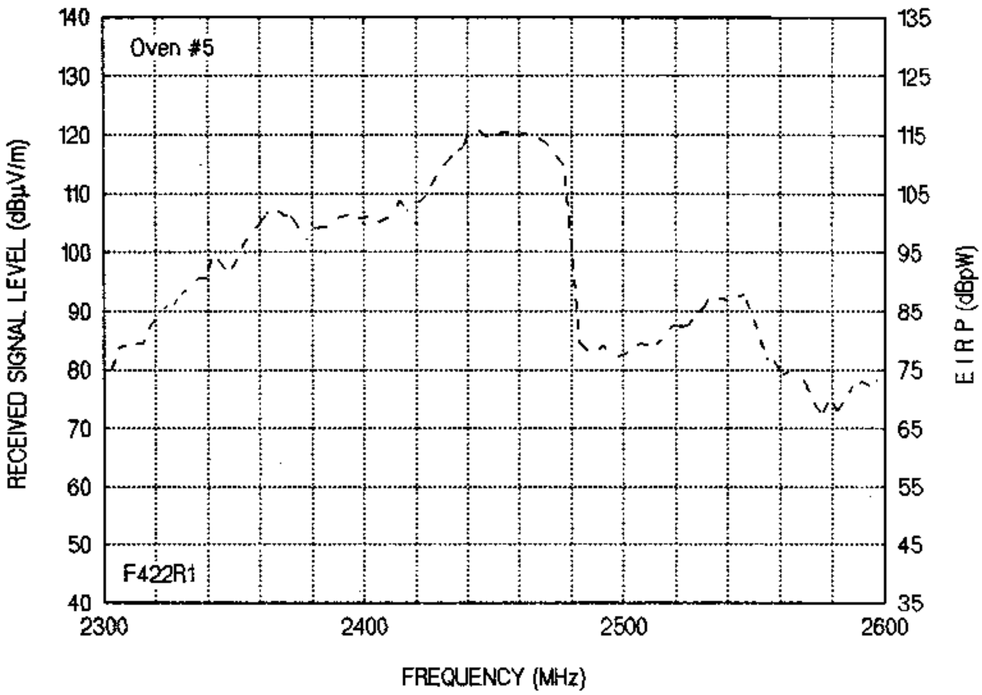

Figure 3-2. Example of emission spectrum.

Swept Spectrum Measurements. In swept measurements, the spectrum analyzer is sweep-tuned continuously across a desired frequency range. With respect to the method of making peak measurements, the simplest approach is to utilize an off-the-shelf spectrum analyzer which is swept across the spectrum of interest with a peak detector and a maximum-hold display. The bandwidth should be as wide as possible to capture the impulsive characteristics of the microwave oven emissions.

One problem with swept measurements, however, is that the time required to perform them can add to the difficulty of the tests. The emissions from the oven at any given frequency can vary by as much as 30-40 dB during a period of about one second, and it was observed during the measurements that the behavior at any given frequency also tends to repeat within about one second. This means that, to record the highest emission that can occur at any given frequency, the measurement must look at each of the spectrum analyzer bins for about one second. If the analyzer has 1001 measurement bins, and each bin must be monitored for a total of one second, then the total time which must be spent sweeping to get a reasonable peak occupancy envelope is about 1001 seconds, or about 17 minutes. This could be accomplished by running a single 17-minute sweep, or by running 60 sweeps at 17 seconds each, etc. It is crucial that on any given sweep, the time spent measuring at each bin within each sweep should not be less than the pulse interval of 1/60 of a second (17 ms), so that at least one pulse can be sampled at each bin on each sweep. Therefore, 17 ms/bin = 17 seconds/sweep would be the minimum adequate sweep time, and 60 such sweeps would be required to complete the measurement. This technique takes so long (17 minutes minimum) that the water load in the oven may boil before the test is completed causing variations in the results. Thus the test must be halted two or three times while the load is changed.

A more serious problem is that system dynamic range is limited to the instantaneous dynamic range of the spectrum analyzer. ITS usually tries to achieve a goal of a 100 dB dynamic range, but instantaneous dynamic range of the spectrum analyzer is likely to be only about 60 to 70 dB. This may not be enough to show both the spurious emission sidebands and the center-frequency amplitude accurately. If additional sensitivity is desired and an LNA is placed ahead of the analyzer, then instantaneous dynamic range is restricted even further. Thus, an experimenter doing this measurement may have to decide between measuring the sidebands while the center frequency is saturating (thus rendering the entire measurement questionable) or else using enough RF attenuation to get a good reading of center-frequency amplitude while losing the extended spectrum in system noise. The only way around that problem with an off-the-shelf measurement approach would be to do the spectrum in segments, and to use tunable bandpass/highpass/lowpass and notch filters to keep the system linear. This further complicates and slows the measurement process, not to mention creating calibration difficulties.

The ITS measurement system solves the tracking problem by utilizing a YIG filter at the front end and tracking the filter with the spectrum analyzer sweep voltage. But the dynamic range problem cannot be eliminated with a sweeping measurement algorithm.

An additional difficulty occurs in the measurement of average levels in a swept mode. The sampling required to derive averages tends to be inherently biased toward either the pulse peaks from the oven or toward the measurement system noise floor, depending upon the sweep rate which is used. The bimodal nature of the average (either it tends to be the same value as the peak emissions, or else it tends to be down at system noise) occurs because the ovens are pulsed emitters.

The oven emits pulses at the rate of 60 Hz, or once every 17 ms. If the analyzer sweeps slowly enough that a pulse is sure to occur at each bin in the sweep (sweep time is at least as long as 17 ms x number of bins/sweep), and if positive peak detection is used, then the single point which the analyzer selects for display in each bin will usually be the peak amplitude of a pulse. If average statistics are derived from such data, then the average will be almost as high as the peak data. If sample detection is used instead of peak detection, then the biasing in favor of peaks is removed, but the maximum emission envelope (which must be gathered simultaneously in swept/m3 algorithm) cannot be obtained.

If, on the other hand, sweeps are run at a high rate (20 ms/sweep, for example, which translates into 20 μs/bin), then the analyzer almost always samples on its own noise floor, and the average data look like the measurement system noise. Neither solution works very well.

Stepped Spectrum Measurements. ITS has developed an alternative that overcomes these problems, stepping instead of sweeping. If a measurement steps from one frequency to the next in increments of the measurement bandwidth, then it is only necessary to measure N steps, where N = (measurement range)/(measurement bandwidth), instead of the 600 or 1000 points that most analyzers display. For example, if we want to measure 300 MHz of spectrum (2300-2600 MHz) in a 3 MHz bandwidth, then only 100 steps are required. At 1 second per step plus 20% data transfer overhead, the measurement period comes out to just 2 minutes instead of the 17 minutes required by the swept measurement. The water does not have to be changed in that interval. Furthermore, it is possible to change the front-end RF attenuation while the measurement progresses across the band, and thus the measurement's available dynamic range can be extended by the additional 70 dB available in the preselector front end. However, this process requires a computer-controlled spectrum analyzer and tracking preselector so that stepping can be performed. The RF front end must track the stepped-tuned frequencies, which is performed by the analog tracking voltage available from the spectrum analyzer, just as with the swept algorithm. But the stepped technique allows the measurement to take full advantage of the dynamic range extension from the RF attenuation, and that in turn allows the maximum exploitation of the sensitivity afforded by the front end LNAs.

For these reasons, it makes more sense from both a theoretical and a practical standpoint to make measurements of microwave ovens in a stepped, rather than swept, mode.

Selected Parameters. For the NTIA measurements, stepped measurements were performed on each oven tested. The measurement parameters are displayed in TABLE 3-2.

Time Domain Measurements

Time domain measurements at single frequencies are an important method for obtaining non-spectral data, including time waveforms and amplitude-probability distributions (APDs). Time scans were taken in two phases. During Phase 1, time waveforms were measured at 2300, 2325, 2350, 2375, 2400, 2425, 2450, 2475, 2500, 2525, 2550, 2575, and 2600 MHz for all ovens. Because time waveform measurements are very time-consuming, it was not possible to acquire an exhaustive set of data on each oven. Therefore, for detailed time domain measurements, NTIA selected a subset of five ovens having the best and worst spectral emission characteristics (Ovens #1, #5, #7, #10, and #11). For each oven in this set (Phase 2), time waveforms were collected for each of the six measurement bandwidths and seven frequencies (2300, 2350, 2400, 2450, 2500, 2550, and 2600 MHz).

TABLE 3-2
PARAMETERS USED FOR STEPPED SPECTRUM MEASUREMENTS

Parameter Description	Value(s) Used for Measurements
Detection	Positive Peak
Time/Step	0.9 seconds
IF Bandwidths	30 kHz, 100 kHz, 300 kHz, 1 MHz, 3 MHz
Frequency Range	2300-2600 MHz (wider in a few cases)
Steps/Spectrum	As required to fill in spectrum without gaps (e.g., 100 steps for 3 MHz bandwidth, 300 steps for 1 MHz bandwidth, etc.)

During Phase 1, the period scan was .1 seconds and no LNA was used. This approach provided sequences of approximately six oven pulses, thereby revealing variation in the recorded pulse shapes, but limited the dynamic range of the measurements. An example of a raw time waveform scan is shown in Figure 3-3. During Phase 2, ITS performed 100 scans at each frequency and bandwidth. Each time scan was composed of 1001 points acquired in 20 ms using the sample detector and added the LNA to the measurement configuration. Thus, at each frequency and bandwidth combination, a total of 100,000 points, at 20 μs/point were accumulated. A total of 2 seconds of time waveform data were acquired with 20 μs resolution at each combination of bandwidth and frequency for each of the five ovens. Though this approach limited the number of pulses recorded in each scan, it increased the resolution of the recorded signals and the associated APDs. Samples of time waveforms for individual ovens are presented in Section 5, while the rest of the results are provided in Appendix C.

From the time domain data of the Phase 2 measurements, APDs were produced. The APDs show the percentage of acquired points (x-axis) which exceed an amplitude (y-axis). APD plots are useful for determining the total percentage of time that oven emissions exceed given amplitudes. As noted previously, the APD plots are based on 100,000 points over a 2-second period, allowing calculation of percentages to one thousandth of a percent or 10^{-5}. This level of resolution is particularly crucial for evaluation of impact to digital systems. At the oven operating frequency, an APD should show a near vertical increase in pulse amplitude near 50%, representing the oven duty cycle. As the measurement system is tuned off of the oven operating frequency, as is the case in Figure 3-4, less of the pulse will be recorded and the break point should move toward a lower percentage. In that example, pulses exceeded 60 dBμV/m about 6% of the time. The graph levels at the higher amplitudes, where the levels are less frequently reached.

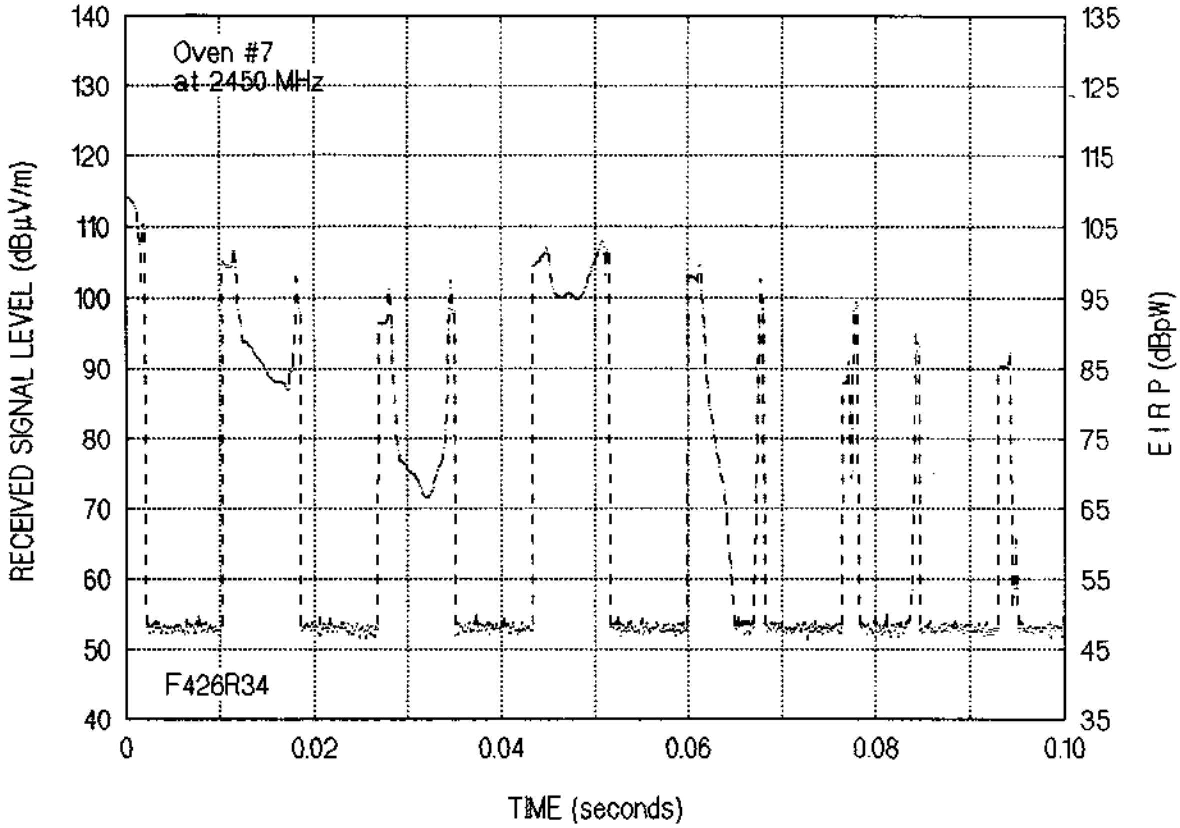

Figure 3-3. Example time waveform.

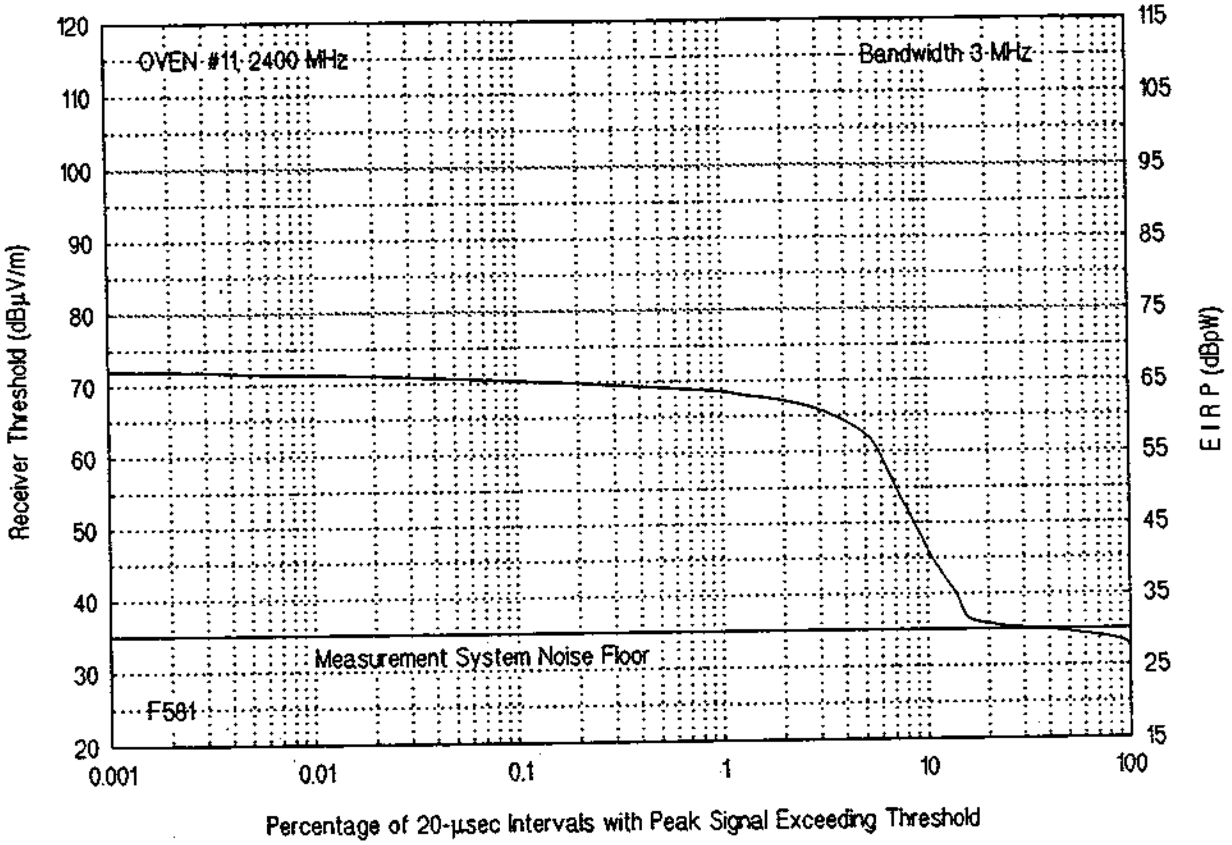

Figure 3-4. Example amplitude probability distribution.