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An initial examination of the occupancy and use of the wireless-radio bands

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An Initial Examination of the Occupancy and Use of the Wireless-Radio Bands

by
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13. ABSTRACT (maximum 200 words)

Data on the occupancy and use of the license-exempt wireless-radio bands collected over a 10 year period is summarized. Numerous examples of measured results are presented in a time-history format. The time- and frequency-varying properties of radio noise and radio interference are visually portrayed where the noise and interference is usually highly impulsive and highly changeable.

Of primary concern is that the interference could not be effectively described in standard statistical terms such as peak power, average power, root-mean-square power, amplitude probability plots, or other such conventional measures. The noise and interference was nonstationary in nature with time and frequency variations comparable to message lengths.

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PREFACE

Defining the occupancy and use of the wireless-radio bands at first glance appears to be a simple task that can be solved by relatively straightforward spectrum measurement techniques. But, significant pitfalls were encountered during initial attempts to make measurements and to describe the results. The primary problem was the difficulty of making measurements that would characterize the intermittent and erratic interference and noise, especially in the license-exempt wireless bands, in terms useful for the assessment of its impact on the reception of desired signals. This document provides a summary of an attempt to define the occupancy and use of the wireless-radio bands. Most readers of this document will find it best to start by reviewing the first 27 pages. These pages provide a summary of the interference and noise conditions, primarily in the 2.4-GHz wireless band for a number of locations and conditions.

The open access to all users of the license-exempt wireless-radio bands with minimal restrictions on the control or type of emissions has resulted in a mixture of interference and noise within the bands with highly-erratic, time-varying, and frequency-varying properties. This is particularly true in the 2.4-GHz-band. All present indications are that the 5.8-GHz band will encounter similar conditions within the next few years as the cost of devices and systems for that band decreases.

Since the characteristics of a measurement system can significantly affect results, the system used for these measurements is described in some detail. For example, the amplitude of the impulsive interference and noise is a function of measurement bandwidth. A means to scale interference and noise amplitudes to the bandwidth of each specific receiving system is required. In addition, a means to cope with and define the erratic changes in interference and noise over both time and frequency band must be dealt with. A measurement in one part of a band does not represent conditions in another part, and an evaluation of the total interference and noise power in a band does not represent conditions at any specific part of a band. Thus, a deterministic approach is used to graphically show the erratic, time-varying, and frequency-varying properties of the interference and noise encountered.

Reproductions of more detailed technical memoranda for individual measurement efforts are provided in several appendices. These memoranda show the results obtained at a several locations and at various times at some locations, and they provide the basis for the summary comments in the first 27 pages of the document. A large number of examples are included in these memoranda since a large variety of interference and noise conditions were encountered.

Additional measurements are now underway at other locations and under other conditions. These additional measurements include more information on the occupancy and use of the licensed bands as well as the unlicensed bands. Also, additional measurements are underway in the 5.8-GHz unlicensed band to watch the growth in the use of that band over time. Other special measurements will continue as time permits and opportunity arises.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

1.0 INTRODUCTION

This document summarizes information gathered over several years about the occupancy and use of the license-exempt wireless-radio bands. In addition some preliminary information is provided about the occupancy and use of one licensed wireless-radio band. The main body of the document presents a summary of a large number of field measurement tasks, and extensive appendices are provided in the form of technical memoranda that were prepared for each individual field-measurement task. An attempt has been made to gather the technical memoranda into groups to make it easier for interested parties to find information pertinent to their specific interests.

The arrangement of the main body, followed by extensive appendices, is somewhat unusual for a technical document, but it is the most convenient way to summarize the primary findings and results of several years of data collection as well as provide the detailed documentation needed to support the findings and results presented in the main body of the document. The memoranda in the appendices have not been widely distributed thus their results have not been generally available to the wireless-radio community. A sufficient number of memoranda are provided in the appendices to describe the general conditions found in the various wireless-radio bands. Since these memoranda were prepared at various times and with various word processors, some differences in organization and in format exist.

The time-history presentation of the temporal and spectral details of signals, noise, and interference used in this document is somewhat different than that provided by other similar studies. The measurement technique and the instrumentation originated about three decades ago for special-purpose field-measurement tasks dealing with time- and frequency-variable signals and noise, and the instrumentation has been of considerable value to students at the Naval Postgraduate School (NPS) to obtain data for thesis projects. The instrumentation was available and had the capability to examine the occupancy and use of the license-exempt wireless-radio bands. This seemed a natural task, especially in view of the high public and commercial interests in wireless radio. No instrumentation procurement costs were encountered in conducting the measurements described in this document and its appendices.

In many ways this document is considered a detailed progress report. Further investigations of the occupancy and use of the license-exempt wireless bands are underway as well as additional similar studies in other parts of the radio spectrum. Of special concern is the need to apply non-stationary statistical analysis techniques to radio-noise and radio-interference problems, especially those encountered in the 2.4-GHz band. Unfortunately non-stationary analysis techniques have been largely ignored by the radio-interference community. Because of this neglect, effective methods are lacking to adequately describe and analyze the radio-interference problems described in this report.

This introduction is followed by a detailed explanation of the instrumentation used to collect the data in the appendices (Section 2.0). Each item of the instrumentation is described in subsections along with information about its use in the measurement program. An understanding of the capabilities, and the limitations, of the instrumentation is essential for the full interpretation of the data presented.

Since the instrumentation provides a means to identify and differentiate between signals, noise, and interference, the following terms are used in this document.

Signal: An emission from a known communications device that is intentionally trying to send a communications signal to a receiver.

Interference: Any radio signal from a communications device that interferes with the reception of a desired signal.

Noise: Any radio emission that arises from a non-communications source or a faulty communications device and interferes with the reception of a desired signal.

Emissions: A general term used for any, or all, of the above items when the specific type is not identified.

The Instrumentation section is followed by a summary of the findings of the field measurements (Section 3.0). The discussion in this section follows the order of the various appendices. First, general comments are provided about the measurements (Section 3.1). The results of measurements at a home office are presented (Section 3.2) followed by a summary of the measurements of the classroom use of wireless radio at the Naval Postgraduate School (Section 3.3). The next section describes the somewhat unusual results obtained from monitoring wireless radio use during Homeland Security field exercises (Section 3.4). Then the exploratory results of the occupancy and use of the 915-MHz band at a few locations are presented (Section 3.5) followed by a section describing preliminary measurements of one licensed wireless-radio band (Section 3.6).

The implications of the data collected are discussed in Section 4.

2.0 INSTRUMENTATION

2.1 General Approach

The instrumentation used for the field measurements is briefly described in the documents provided in each appendix. This section duplicates some of the material in the appendices, but it provides a more comprehensive description of the capabilities and limitations of the instrumentation. An understanding of both the capabilities and the limitations of the instrumentation is necessary to obtain an awareness of the details and the implications of the data obtained.

The purpose of the instrumentation was to provide a visual presentation of the primary properties of time- and frequency-varying signals and radio noise in any portion of the radio spectrum. This included a means to portray both the temporal and spectral structures of signals and radio noise in selected bands where the both the frequency span and the time of observation could be changed to best describe the signal, noise, and interference conditions encountered. One further requirement was included. The amplitude, frequency span, and time of observation must be calibrated and presented in accepted engineering terms.

Figure 1 shows a block diagram of the primary components of the instrumentation used for most measurements. Each component is described after the figure. Additional instrumentation was added to the primary components from time to time to investigate special problems. A digital oscilloscope was often added to provide an improved means to portray the temporal structure of pulse signals appearing at the video output of the spectrum analyzer. Frequency markers were added as needed to improve the frequency accuracy of the spectrum analyzers. A 120-line time-history display was sometimes used in place of a 60-line model to obtain a longer time-history axis for some special measurements. The digital-recording capability incorporated into the time-history display was seldom used because of the difficulty in obtaining meaningful statistical measures of spectrum occupancy and use.

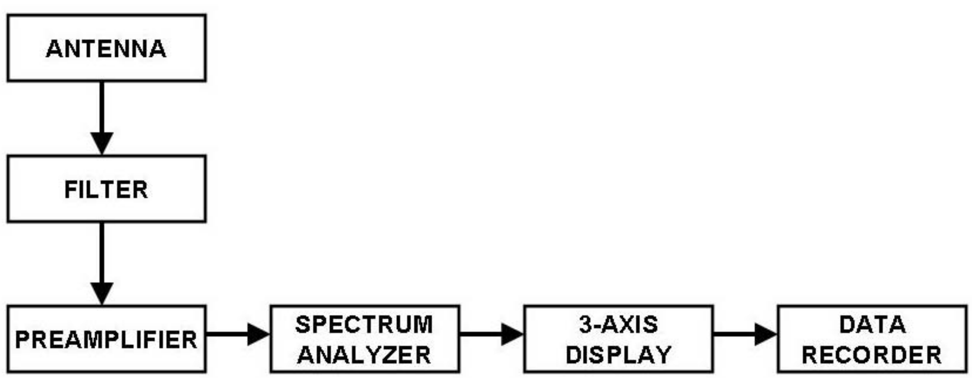

Figure 1 Block Diagram of the Instrumentation

2.2 Antennas

A type of antenna for the instrumentation was selected to optimize signal and noise collection conditions for each measurement task. In general an antenna was used that was similar to those used by the wireless radio devices. Most of the measurements described in this document used monopole antennas for each wireless-radio band. In some cases antennas with gain and directionality were used for specific diagnostic purposes such as locating an emitter.

Figure 2 provides a photograph of the three antennas most often used to examine the occupancy and use of the 5.8-GHz, 2.45-GHz and the 915-MHz bands. The antenna for the 2.45-GHz band is on the left, the antenna for the 5.8-GHz band is in the center, and the antenna for the 915-MHz band is on the right. All antennas are placed on a magnetic mount for quick and easy use with a vehicle. Short lengths of low-loss coaxial cable were used for the antenna-to-filter connection.

Figure 2 Antennas used for the 915-MHz, 2.4-GHz, and 5.8-GHz Bands

2.3 Filters:

A bandpass filter was provided for each portion of the radio spectrum to be observed. The filters were used to avoid strong out-of-band signals that might cause overloading of the preamplifier and/or the spectrum analyzer. Care was taken in the design of each filter to ensure that its dynamic range was sufficient to avoid saturation of its internal components. Many kinds of small commercially-available filters were found to be unsuitable for the measurement program because of component saturation.

Figure 3 shows a photograph of the filters used for the 915-MHz and the 2.4-GHz bands. These filters are physically large to provide linear operation for the maximum total signal power imposed onto their input terminals. Many additional high-dynamic range filters were accumulated over the years for other portions of the radio spectrum.

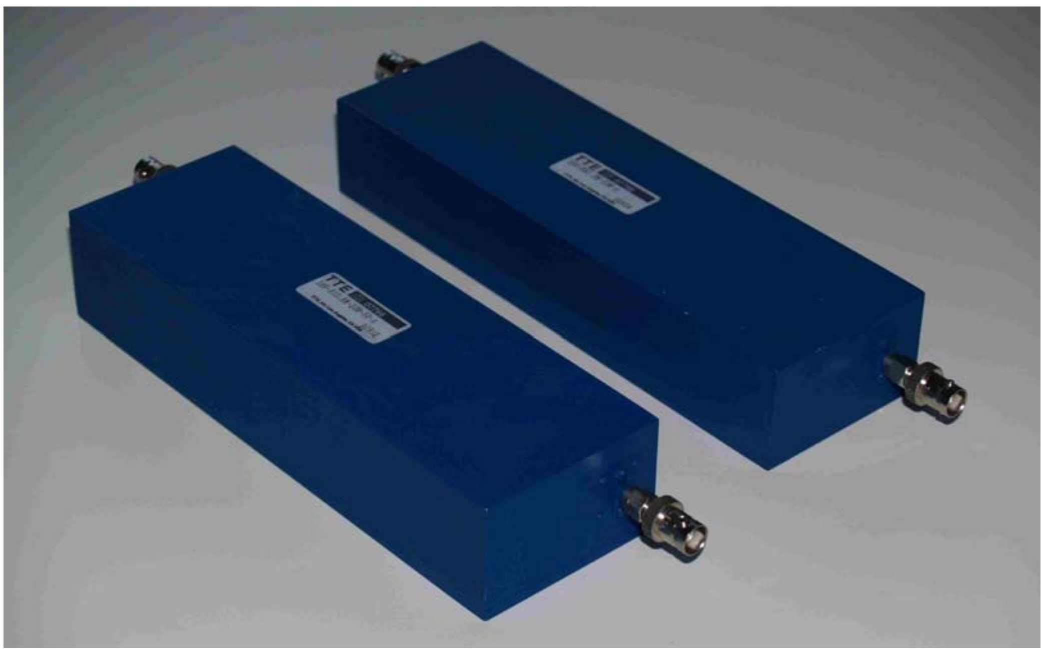

Figure 3 Bandpass Filters for the 915-MHz and 1.2-GHz Bands

Since the noise figure of most commercially available spectrum analyzers is considerably higher than that of wireless-radio receivers, a preamplifier was used between the filter and the spectrum analyzer. The low-cost preamplifiers that are commonly available for the wireless-radio bands have insufficient dynamic range to cope with high amplitude signals frequently encountered in the field. The saturation of such amplifiers results in the generation of intermodulation products and broad-band intermodulation noise. To avoid this problem, high-dynamic-range preamplifiers were provided for each wireless-radio band, and the maximum total signal power at the input to the preamplifiers was carefully examined prior to recording data to ensure that linear operation was achieved.

The signal environment frequently contained a mixture of random impulses, signals with various formats, impulsive noise, and impulsive radio interference along with a few discrete-frequency signals. High-level impulsive signals, noise, and interference can result in the production of broadband impulsive intermodulation noise. Precautions to identify instances of strong impulsive signals, noise, and interference were essential to avoid contamination of recorded data and the misleading results from such contamination.

Figure 4 shows an example of the preamplifier used for the 2.4-GHz band. Similar preamplifier assemblies were available for other bands. Spare preamplifiers were available for replacement should a preamplifier fail.

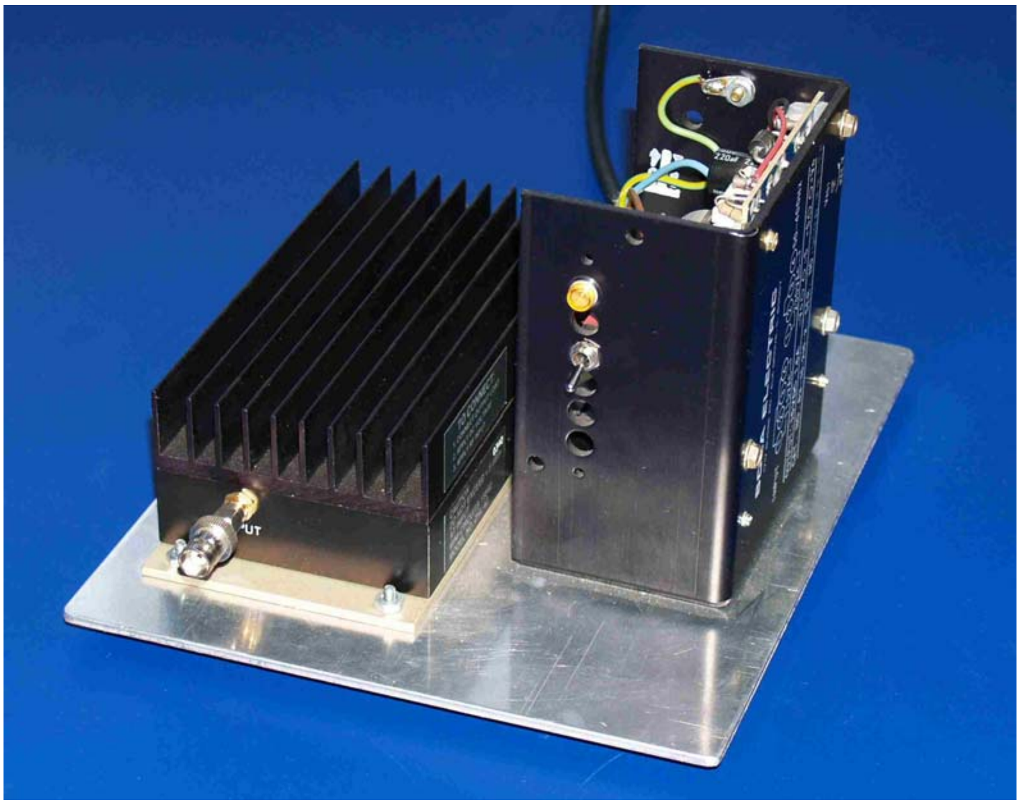

Figure 4 Example of a High Dynamic Range Preamplifier

Some sacrifice in preamplifier noise figure was necessary in order to achieve high dynamic range. Noise figures of 6 to 12 dB were provided by the high-dynamic-range preamplifiers normally used compared to the approximately 2-dB noise figures achieved by low-dynamic-range units. Additional low-noise preamplifiers were provided for special measurements, but extreme care was taken in their use to avoid intermodulation problems.

2.5 Spectrum Analyzers

Two types were used to collect data in the field. The first type was the popular scanning spectrum analyzer commonly used to examine radio signals. The second type was the FFT type of spectrum analyzer, although all of the available FFT analyzers required the use of a linear frequency translator due to their base-band operation. Both types of spectrum analyzers were employed for field measurements, although most measurements were made with the scanning type.

The selection of an appropriate model of a scanning spectrum analyzer was a major matter, and a number of models were used over past years. While modern digitally-controlled scanning spectrum analyzers were available, they were seldom used during field measurements for a variety of technical reasons. First, their dead time between scans (not specified by any of the manufacturers) was far too long to cope with the rapidly-changing signal and noise conditions found in real life. The dead time also significantly reduced the ability of a spectrum analyzer to receive and define the properties of intermittent signals, noise, and interference. In addition, the use of keypad or keyboard controls resulted in unacceptable time delays for changing the analyzer operating parameters to cope with time-changing signal, noise, and interference conditions. However, the newer digitally-controlled analyzers were preferred for the laboratory measurement of time-stable signals and noise or other similar special purpose measurement tasks.

The older knob-controlled spectrum analyzers were found to be more suitable for field-measurement purposes. The time delay between spans of the older scanning-type analyzers was considerably lower than that for the newer digitally-controlled units thus increasing their ability to detect and define intermittent emissions. The knob controls permitted the rapid adjustment of instrumentation parameters to cope with the need to define time- and frequency-changing signal and noise conditions.

The old Hewlett Packard Model 141 Spectrum Analyzer with RF heads covering the frequency ranges of 0 to 110 MHz and 0 to 1250 MHz was found to be the best available model for measurements within its frequency-coverage ranges. The Hewlett Packard Model 8565A Spectrum Analyzer was found to be the best available analyzer for the measurement of time- and frequency-changing emissions in the microwave bands. While the signal-handling dynamic range of these two models was somewhat lower than for newer models, the short dead times between spans and the ability to rapidly alter operating parameters outweighed the dynamic-range considerations. These analyzers were often modified for specific measurement tasks to improve dynamic range, provide an external synchronizing capability, and further reduce their dead time between scans.

Both spectrum analyzer models provided the ability to quickly change operating parameters such as the center frequency of a band under observation, the frequency span of that band, the scan time, and the measurement bandwidth. In addition, the analyzers could be quickly switched to operate in a zero-span mode similar to that of a fixed-tuned receiver. The scanning process could be synchronized to external synchronizing sources to aid in the fine-scale definition of the temporal structure of some repetitive signals.

The dead time between scans was carefully measured and documented for each spectrum analyzer prior to its use in the field. This was done for two reasons.

First, transients and intermittent signals can, and will often, occur during the dead time of a scanning analyzer. Such transients and intermittent signals will not be received. Also, portions of repetitive impulsive signals and noise will occur during the dead time and not be received. The probability of receiving an unknown transient is the quotient of the ratio of the scan time to the scan time plus dead time. Because of this the magnitude of the dead time compared to the scan time is a significant disadvantage of a scanning spectrum analyzer. It is essential that this ratio be known to properly understand and interpret the results of field measurements.

Second, the dead time between scans influences the duration of the time-history axis used to define the temporal properties of signals and noise. This will be described in more detail in the following section.

2.6 Time-History Display

A Model 7200B 3-Axis Display is used to portray the time-history properties of signals and noise in real time. It has been used by students and staff of the Naval Postgraduate School for a number of thesis projects and other tasks. The display is completely slaved to the operation of a spectrum analyzer, thus only visually-related adjustments are provided on the instrument. The easiest way to demonstrate its presentation and capabilities is to review an example. Figure 5 shows an example of the presentation provided by a Model 7200 display. Two views of the same data are provided. The top view shows amplitude vs. frequency in a presentation similar to that provided by most spectrum analyzers. The bottom view provides a time-history presentation of the same data as shown in the upper view.

Information from each new scan of the spectrum analyzer is shown on the bottom line of the time-history presentation. Each new scan bumps all older scans up one line, and the oldest line at the top of the time-history presentation is discarded. This process occurs in real time. Prominent aspects of emissions in the example are identified by the annotation at the top of the amplitude-vs.-time view.

Several ways are available to enhance the time-history presentation of signals, noise, and interference. For example, the time axis can be slewed (or rotated); the time axis is slightly skewed to the left in the example to better show the slanting lines across the time-history view. The amplitude can be compressed; it is almost fully compressed in the time-history view and not compressed in the upper amplitude-vs.-frequency view of the same data. The elevation of the time-history view can be varied from 0 to 90 degrees; it is at zero degrees in the time-history view and at 90 degrees in the amplitude-vs.-frequency view. In addition, any set of 4, 8, 16, or 32 lines of the time-history view can be selected for a detailed line-by-line analysis of an emission. The amplitude threshold can be varied to minimize visual interference from low-level emissions. These features can be altered in real time to aid in portraying any desired feature. Any view can be frozen for a detailed examination or to photograph the two presentations, and the viewing enhancement controls also operate with a frozen view.

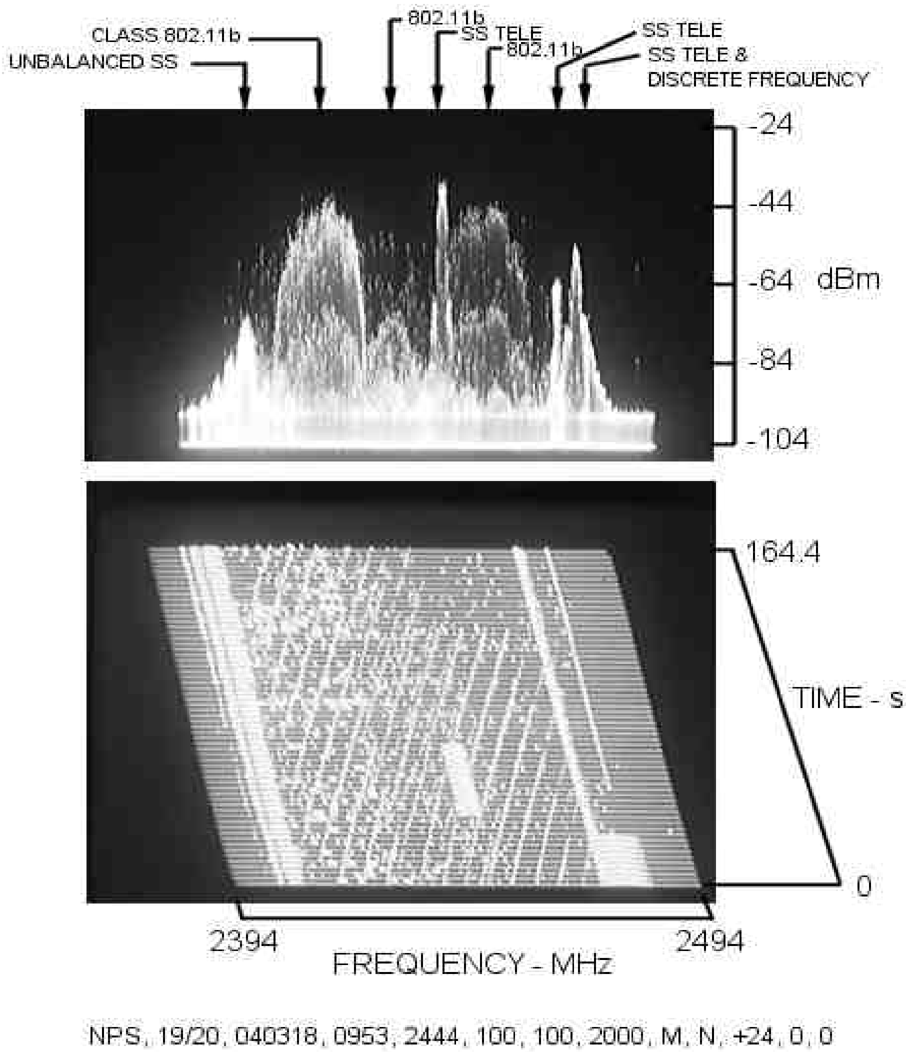

Figure 5 Example of the Occupancy and Use of the 2.4-GHz Band

The slanting lines across the time-axis presentation are a result of receiving the broadband synchronizing pulses from an 802.11b access point as the spectrum analyzer scans across the bandwidth of the pulses. The scan time of the spectrum analyzer must be longer than the repetition period of the pulses, and the analyzer bandwidth must be less than the spectral width of the pulse emission for this type of presentation. Since the data is obtained from a scanning filter, the time between impulses can be scaled from the horizontal axis which is a combination of frequency and scan time. The scan time of this axis is provided for each item of data, but it is not always added to the bottom horizontal axis to avoid excess material in the presentation.

The amplitude scale on Figure 5 refers to the amplitude of received signals at the output terminals of the antennas. The impact of receiver bandwidth on the amplitude of received signals is discussed later in Section 2.8.

Synchronizing pulses from three 802.11b access points are shown in the time-history view. The clutter between the synchronizing pulses is from the 802.11b emissions of laptop computers using the networks as well as a few random pulses from other sources. Other signal formats are also shown in the two views such as the relatively narrow-band spread-spectrum signals from portable telephones..

The data in Figure 5 was obtained during a classroom session at the Naval Postgraduate School where wireless radio was extensively used as a classroom aid. Only the signal identified as "Class 802.11b" was associated with the classroom. All other signals came from other sources on the campus.

Figure 5 shows an example of the complex variety of emissions formats found in the 2.4-GHz band. The example implies that the occupancy and use of the band is a complex matter that needs to be investigated and understood for a variety of conditions and locations. Additional examples of such data from the classroom and also other locations are provided in the appendices.

2.7 Data Recording

Until about three years ago, data was recorded by freezing the operation of the 7200B display and photographing the frozen view with a Tektronix Model C-5C Oscilloscope Camera using Polaroid film. Operating parameters were then written onto the back of each photograph. The pictures were trimmed and pasted onto white cardboard, and scales were manually added to the frequency, amplitude, and time axes. The resulting paste-up was then scanned and recorded as a computer file. While this manual process was tedious, it provided excellent examples for the documentation of the results of field measurements.

The increasing price of Polaroid film in recent years eventually became the major cost of conducting field measurements. This resulted in the modification of the Tektronix camera enclosure to incorporate a small digital camera into the C-5C case. A USB cable connection between the digital camera and a laptop computer now provides a means to place examples of the two views directly onto the hard drive of a laptop in a standard .jpg format. The two views are subsequently combined into a single file, and the frequency, amplitude, and time scales are added to each set of views along with any desired annotation using a standard photo-processing program. The end result is a compressed .jpg file ready for direct insertion into the text of a report. This process eliminated the high cost of film and the cost of the manual graphics effort needed to format the Polaroid pictures.

A digital recording capability is built into Model 7200B display. This capability was not used since useful and effective digital data-processing techniques could not be applied to much of the data accumulated for this effort.

2.8 Data Calibration and Scaling

Comprehensive records are maintained for each item of data collected in the field. These records include the following items about each item of data.

Measurement Location
Picture Number
Date in yymmdd Format
Local Time
Center Frequency of Data
Frequency Span
Measurement Bandwidth
Scan Time in ms
Signal Source (Usually an Antenna ID)
Filter ID
Preamp Gain
RF Attenuator Setting
Signal Reference Level
Comments
Additional Special Comments

An abbreviated version of the above parameters is added below each item of formatted data as shown by the line of text at the bottom of Figure 5. Sufficient information is provided in this line to add amplitude, frequency, and time scales to the data and to reference each item of data to its source.

The amplitude scales in this document are calibrated in dBm to provide a convenient means to relate recorded data to commonly accepted spectrum analyzer calibration terms. Noise temperature has not been used as a measure of interference to the reception of a desired signal. This is because of the term has not yet been defined sufficiently to describe the erratic time and frequency-varying conditions found in the wireless bands as well as the measurement bandwidth considerations.

The amplitude scales in this document provide the peak level of signals, noise, and interference as received within the measurement bandwidth of the spectrum analyzer. The peak amplitude of any emission whose bandwidth is equal to or smaller than the measurement bandwidth can be determined directly from the amplitude scale shown on the right edge of the amplitude-vs.-frequency view. Impulsive signals and broadband signals with spectral content wider than a measurement bandwidth are always higher in amplitude than shown by the amplitude scale. This is because some of the spectral content is outside the measurement bandwidth.

An empirical curve has been generated by Hodge[1] to provide an approximate means to scale the amplitude of wide-band emissions to other than the measurement bandwidth. Figure 6 shows this curve along with a second curve for wideband Gaussian noise.

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1 James W. Hodge, ***A Comparison between Power-Line Noise Level Field Measurements and Man-Made Radio Noise Prediction Curves in the High Frequency Radio Band,*** MS Thesis, Naval Postgraduate School, Monterey, CA, December 1995

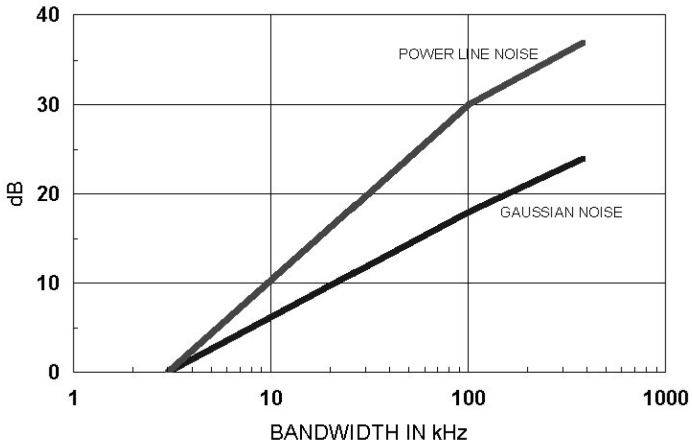

Figure 6 Impulsive Noise Bandwidth Scaling Curve

While the above Hodge curve was derived primarily from measurements of impulsive power-line noise in the HF and VHF bands, it has been shown to provide reasonable estimates for pulse emissions and impulsive noise and interference in the wireless bands. The curve is valid for receivers using Gaussian-shaped measurement bandwidths such as the bandwidth shapes used by many models of spectrum analyzers. To our knowledge similar curves have not been obtained for receivers with more rectangular IF bandpass filters.

Since the temporal structure of emissions in the wireless bands change significantly over brief intervals of time and with frequency, and are clearly non-Gaussian, one cannot provide a universal and acceptable way to define the average, root-mean-square, or other measures of amplitude other than at a selected time and for a specific small frequency band. The limitations associated with the specification of amplitude for the signals, noise, and interference presented in this document are discussed in more detail later in this document.

Finally, the duration of the time-history axis must also be determined to understand the variations of the emissions received over time and frequency. For a 60-line time-history display, the duration of the time axis, T(s), is determined by:

$$T(s) = [(\text{Scan Time in ms} + \text{Blanking Time in ms}) \times 60] / 1000$$

For a 120-line time-history display the duration of the time axis is:

$$T(s) = [(\text{Scan Time in ms} + \text{Blanking Time in ms}) \times 120] / 1000$$

The scan and blanking times are measured prior to each field use, and they are recorded along with other operating and site parameters. Tables 1 and 2 show the measured blanking times and the resulting duration of the time-history axis for two examples of instrumentation configurations. Since multiple sets of instrumentation are available, a similar chart is provided for each field measurement instrumentation configuration.

Table 1 Calibration Data – NPS HP 141 #5

Scan Time/div ms	Total Scan Time ms	Free Run Scan + Blank ms	Free Run T(s) s	Line Sync Scan + Blank ms	Line Sync T(s) s
1	10	15.1	0.91	16.5	0.99
2	20	25.1	1.51	33.7	2.02
5	50	67.9	4.07	65.6	3.94
10	100	183.0	11.0	183.0	11.0
20	200	283.0	17.1	299.0	17.9
50	500	582.0	34.9	594.0	35.6
100	1000	1,082	64.9	1,096	65.8
200	2000	2,626	157.6	2,641	158.8
500	5000	5,628	337.7	5,632	337.9
1000(1 s.)	(10 s.)	10,624	637.4	10,632	637.9

Table 2 Calibration Data – WRV HP 140

Scan Time/div ms	Total Scan Time ms	Free Run Scan + Blank ms	Free Run T(s) s	Line Sync Scan + Blank ms	Line Sync T(s) s
1	10	14.7	0.88	19.9	1.2
2	20	24.7	1.48	33.7	2.03
5	50	54.7	3.28	65.8	3.95
10	100	185.0	11.1	199.0	12.0
20	200	285.0	17.1	285.0	17.1
50	500	584.0	35.1	587.0	35.2
100	1000	1,084	65.0	1094	65.7
200	2000	2,084	125.0	2092	125.5
500	5000	5,084	305.0	3088	185.2
1000(1 s.)	(10 s.)	10,090	605.4	10,090	605.4

3.0 DATA SUMMARY

3.1 General Approach

The presentation of a precise and orderly summary of the data provided in the appendices is extremely difficult because of the diversity of the measurement tasks, variations in the data from one field-measurement task to another, changes in the data from one time to another time, differences from one wireless-radio band to another, and differences from one part of a band to another part. An attempt has been made in subsequent subsections to provide a useful itemized summary of the key findings of the Technical Memoranda provided in each appendix.

Early in the measurement program it was recognized that the occupancy and use of the unlicensed wireless radio bands could not be described by standard statistical descriptors such as percent of time a band is occupied; percent of time a channel in a band is occupied; the average or root-mean-square (RMS) power of signals, noise and interference in a selected band; amplitude probability distributions; or other similar descriptors. This is because the durations, amplitudes, and temporal properties of signals, noise and interference changed significantly and suddenly over similar time periods and over different parts of each band. The erratic nature of signals, interference, and noise was remarkable. The non-stationary statistical properties of signals, interference, and noise dominated the results observed for each unlicensed band. Any reader must consider this key problem when trying to describe and define the occupancy and use of the licensed-exempt wireless-radio bands.

Nevertheless, it was often possible to relate the reception success of a desired signal to the interference and noise present over some specific short interval of time during which conditions were briefly stable. This required knowledge of the time history of the signals, interference, and noise for each specific time interval of interest. But, it was not possible to provide a meaningful overall measure of the impact of noise and interference on communications success. The reader must take into account the highly erratic time- and frequency-variable nature of signals, interference, and noise. Of special interest is that the temporal structure of interference and noise varied significantly over short periods of time and with frequency.

The occupancy and use of the licensed bands appears to be much more orderly than that of the unlicensed bands, but sufficient information is not yet available to fully understand their state. Additional field measurements are planned that include data on the occupancy of the licensed bands.

3.2 Home Office Measurements

The series of measurements presented in the Appendices started with an examination of the occupancy and use of the 2.4-GHz bands at a home office (see Appendix A). The home office was located in a typical medium-size university town (Davis, California) consisting of a mixture of individual houses, duplexes, and small apartment buildings. The home office was located in a residential area that was about one-half mile from a small business complex and about 2 miles from the University.

The home-office measurements started in the year 2001, and they continue to the present time. Initial measurements were made in 2001 in an attempt to understand the implications of radio interference encountered during use of the 915-MHz and 2.4-GHz bands in the home and in the home office. One portable telephone utilizing frequency-hopping modulation in the 2.4-GHz band was located in the home office along with an 802.11b data link between the office computer and two laptop computers, a wireless mouse, and wireless keyboard. A second portable telephone using spread-spectrum modulation in the 2.4-MHz band was used in the nearby living room of the residence. A third portable telephone using frequency-hopping modulation in the 2.4-GHz band was also available in the home for general use and for tests in that band.

The documents in Appendix A present the detailed results of the home office measurements. Undocumented measurements were made prior to formal field tasks to become familiar with the various signal formats in the bands and to cope with some early confusion resulting from the ever changing temporal and spectral properties of the ambient emissions. Numerous examples of ambient conditions are provided in Appendix A. In all cases the amplitude is provided in dBm at the input terminals of the preamplifier (or the output terminals of the antenna since cable loss was small and can be ignored).

The measurements provided a number of interesting observations and results. They are summarized as follows.

- Very high occupancy and use of the 2.4-GHz band was found during the daytime, and very low occupancy and use at nighttime.
- Stable occupancy and use conditions were not encountered except at nighttime when the band occupancy and use was minimal.
- Emissions were found from multiple 802.11b devices along with other emissions with similar, but not identical, characteristics. While the synchronizing pulses from one particular source with a similar emission were continuously present, the occurrence of all 802.11b emissions varied with time of day and from day to day. The frequency of the 802.11b emissions also changed with time.
- Radio interference from microwave ovens was immediately encountered. Several examples of the duration and spectral content of this interference are provided in Appendix A. The duration of this interference often lasted in increments of 1 minute, as expected from the operating settings provided by the oven’s controls.

- Harmful interference was noted to home-office 802.11b operation from microwave ovens located over a radius of about one city block although many instances of low-level interference from microwave ovens were not investigated due to the difficulty of tracing the sources of such intermittent emissions. The spectral content of microwave oven noise varied from oven to oven, and it usually extended across the entire 2.4-GHz band and into the adjacent bands allocated to other services.

- The frequency-hopping telephone in the home produced intermittent and very high interference levels across the entire band. Several times during the tests, low-level to medium-level frequency-hopping signals from other portable telephones were observed.

- Band-limited signals from portable telephones using spread-spectrum modulation were encountered at random times throughout the day and evening. These signals appeared throughout the band and often within the spectral width of 802.11b emissions.

- Communications-related emissions were found from a variety of sources using a variety of signal formats. Sources varied from short-distance users with omni-directional antennas to point-to-point users with high-gain and directional antennas.

- A primary aspect of the occupancy of the 2.4-GHz band at the home office was the time- and frequency-variable nature of most of the emissions. Time-stable conditions were never found.

- The interference and noise encountered in the home office use of 802.11b erratically reduced the throughput of the home-office wireless system at times to unacceptable levels. The use of 802.11b in the home office was eventually abandoned and replaced with cables because of excessive interference and noise. The removal of the home-office emissions from the band also lowered the interference level encountered by other nearby communications systems.

- Eventually a new portable telephone was put in the home office that used the 5.8-GHz band, and a 915-MHz band telephone was used in the living room. Both remain in use today, several years after their installation.

- Reflections from nearby buildings and objects made it extremely difficult to obtain valid direction to a source using directional antennas in and around the home office. Successful indications of direction to a source were obtained while in open terrain.

3.3 Classroom Measurements

A series of short courses in Wireless Radio were conducted at the Naval Postgraduate School during the years of 2004 through 2005 (see Appendix B). These courses were provided to naval and other personnel who wished to use wireless radio for a broad variety of purposes. An 802.11b access point was installed in a classroom, and each student was provided with a laptop computer at his desk and for after class work. Each laptop was equipped with 802.11b. The conduct of the short courses provided an excellent test bed to observe the operation of a classroom network operating within the ambient emission environment of an engineering building that was surrounded by other buildings.

The courses were usually conducted in a classroom located on the second floor of a four story building. Figure 7 shows the classroom configuration. Tables were provided for the students with electrical outlets and with sufficient space for their laptops (shown in blue) and study material. An Access Point was located on the left wall of the classroom as shown by the small red rectangle. The Access Point was connected to the NPS student server. The right wall consisted of large windows overlooking other buildings on the campus.

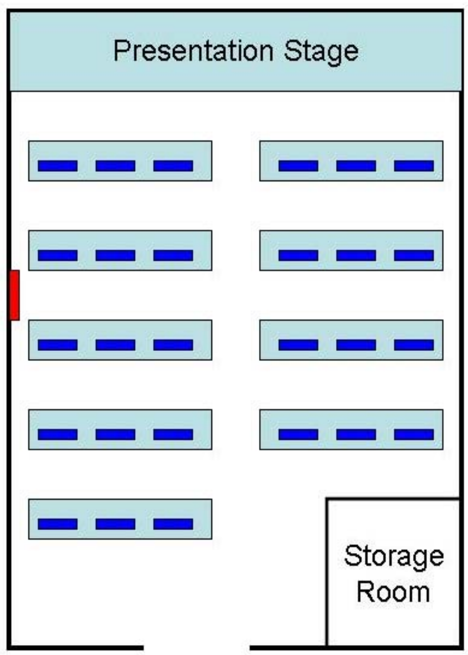

Figure 7 Configuration of Classroom

A small storage room was located at the right rear of the classroom. The measurement equipment was located in this room to avoid adding a distraction to the normal classroom activities. Pick-up antennas were located within the storage room and/or in the classroom as desired.

The class size varied from about 25 to 27 students, each with a laptop. Some interference was expected from other access points and wireless networks in the same building and from wireless networks in other nearby buildings. In addition some interference was expected from specialized experiments typically being tested at a university. Since the campus was fairly large, interference from outside sources in the City of Monterey was not anticipated. Only minimal data on the ambient interference levels was available prior to conducting the first class.

Four documents in Appendix B provide examples of the occupancy and use of the 2.4-GHz band during different class periods. The result from the classroom measurements are summarized in the following statements.

- The classroom wireless-network hardware (Access Point and laptops) performed as expected during the classes. No significant hardware problems were noted. Signal levels were high as expected from the short distance between the laptops and the Access Point.
- The location of the measurement equipment in the small adjacent room provided an ideal way to observe signals, noise, and interference in the 2.4-GHz band without interfering with normal classroom activities.
- Large changes occurred in the occupancy and use of the 2.4-GHz band during each class period and from day to day during the week-long classes.
- While daytime occupancy and use of the 2.4-GHz band was very high, nighttime occupancy and use was very low.
- A very large variety of emissions were noted including those from 802.11b, spread-spectrum, and frequency-hopping devices. In addition many instances of microwave oven noise and other unusual and nonstandard emissions were observed at intermittent and unpredictable times.
- Instructors and students had no control over the sources of interference and noise. At times it completely blocked the operation of the classroom 802.11b wireless network. At other times, it lowered the throughput to noticeably low levels. Yet, normal operation was also frequently achieved. No part of the band was free of interference and noise.
- The interference and noise varied significantly in spectral and temporal content with time and differed significantly across the band. Stable conditions were not found except during the low activity time of the night.

3.4 Homeland Security Measurements

Two memorandum describing the occupancy and use of the 2.4-GHz band for two homeland security exercises are provided (see Appendix C). These measurements also examined the ambient occupancy of the band from 600 to 800 MHz. The first memorandum describes the occupancy and use of these two portions of the radio spectrum during an exercise where the exercise was conducted in a deep valley in the middle of a remote area called MOUT. Supplemental measurements were made near an aircraft hangar where communications systems associated with drone aircraft used to support field exercises were being tested.

The first memorandum provides a wealth of information about the utilization of the 2.4-GHz band during a field exercise of only modest size. This exercise was conducted in part to test the effectiveness of new communications devices and systems designed specifically for use by homeland security personnel. Comments are as follows:

- A few very low-level ambient signals were found in the 2.4-GHz band prior to the start of the MOUT exercise. These ambient signals were traced to emissions from a distant mountain top site used to provide commercial wireless-radio coverage to a residential area also located some distance from the MOUT site.
- Measurements during the field exercise showed extensive use of the 2.4-GHz band. Many signals with overlapping spectral content were found (e.g. see Figure 12 of the first memorandum in Appendix C). Interference varied across the band with severe interference in portions of the band and little or none in other portions of the band. The temporal structure of the emissions changed significantly with time and with frequency.
- The occupancy of the 2.4-GHz band changed significantly with time as the exercise proceeded and the need for various communication devices and systems changed. Very low occupancy existed prior to the exercise, very high occupancy, with significant interference conditions, occurred during the exercise, and very low occupancy was found immediately after the exercise.
- Several of the communications devices used frequency-adaptive techniques to avoid or minimize radio interference. These adaptive techniques could not cope with the high interference conditions existing during the exercise.
- Unfortunately, throughput for the various communications devices was not measured during the exercise. Such measurements would have been highly useful in assessing the results of the exercise.
- Some communication devices exhibited significant spurious emissions, especially at turn on.
- Only normal ambient signals were observed in the 600 to 900-MHz band.
- No signals were observed in the 5.8-GHz band although one point-to-point system was intermittently used during the exercise. Since the measurement system was used in a time-share mode to observe each band, it is believed the 5.8-GHz emissions occurred while the instrumentation was used to observe emissions in the 2.4-GHz band.
- The supplementary measurements near the airport hangar also showed the high occupancy and use of the 2.4-GHz band. Serious interference conditions were encountered in the band from overlapping emissions containing different signal formats and different channel arrangements.

The second memorandum describes the ambient occupancy and use of these two bands in another even more remote area prior to the conduct of extensive field exercises. This measurement was completed in an attempt to understand potential interference problems that might be encountered from existing users during the conduct of extensive field exercises. Comments follow:

- Only one unusual high-amplitude pulse emission was observed near 700 MHz during this exercise.
- The 2.4- and 5.8-GHz bands were free of all emissions in the test exercise area.
- A single 802.11b emission was observed at the headquarters area. The coverage of this emission was minimal, and it was not received outside the small headquarters area.

3.5 915-MHz Band Measurements

The occupancy and use of the 915-MHz band was examined periodically over the years. One technical memorandum is provided in Appendix D that summarizes measurements made at a number of locations and over a few years time. While the amount of data is not as exhaustive as that for the popular 2.4-MHz band, it is sufficient to illustrate the general nature of its use.

The 915-MHz band was the first band where low-cost wireless devices became available, but its small width of 13 MHz is insufficient for widespread use. Nevertheless, a number of users were found at all locations examined. Comments follow:

- The 915-MHz license-exempt band is tucked between licensed bands where high occupancy of the licensed bands was noted at all locations. No indication of out-of-band emissions from the adjacent bands into the 915-MHz band or from 915-MHz users into adjacent bands was noted.
- The erratic appearance of signals from portable telephones using spread-spectrum modulation occurred at all locations examined. These signals were usually of relatively short duration, and long duration signals (longer than a few minutes were unusual) were seldom encountered.
- High-level frequency-hopping emissions were encountered at some locations. These were traced to either commercial or government users, commonly for data transmission.
- A continuous spread-spectrum emission was found coming from a shopping center. Further investigation identified this as a commercial data-transmission service used by a local business. Frequency-hopping interference from a second nearby data-transmission system was also encountered at this location.

3.6 Licensed-Band Measurements

A small effort was devoted to obtain initial understanding of the occupancy and use of the licensed bands used for wireless radio. This effort was limited to the frequency bands between 800 and 950 MHz and at only one residential area. Nevertheless, the measurements were sufficient to obtain a general understanding of the occupancy and use of the some of the licensed bands. Comments follow:

- The frequency limits for the band and its sub bands are established by the Federal Communication Commission, and they are provided in the appendix. Each small frequency sub band was used by a particular commercial or government entity, and the entity using each sub band employed its chosen signal format.
- Only the occupancy of the band was investigated. The efficiency and use of each sub band was not investigated since that larger task was not a part of the objectives of the work described in the appendix. Nevertheless, the use of each band appeared to be high.
- A variety of signal formats was found in the various sub bands, and only one format was used within each sub band. Overlapping signals commonly found in the license-exempt bands were not encountered.
- No instance of out-of-band or spurious emissions were noted. For example the presence of spectral sidebands of spread-spectrum emissions commonly found in the license-exempt bands was not found in the licensed bands. Also, no spurious emissions were found at any time. It was noted that some sub bands were subdivided either in frequency or in time, and multiple signals were efficiently packed into each sub band without mutual interference or without interfering with a neighbor. Each user designed their signal format to most efficiently use the sub band allocated for their purpose.
- The data clearly suggest that the operators of the licensed bands used better designed equipment and complied with established rules in their use of the bands. While some changes in signal formats were noted over time, these changes were made in an orderly manner. The changes did not impact or have any effect on the use of adjacent or other bands.
- No example of radio interference was found except for one onerous case of local interference that was traced to the instrumentation. Severe radio interference was noted in 700- to 1000-MHz portion of the radio spectrum during early measurements. This interference was traced to radiation from a USB cable running from the digital oscilloscope camera to the laptop computer used to record data. Radiation from this cable was intercepted by the measurement-system antenna. The temporal and spectral content of this interference is described in the appendix since USB devices and cables are widely used in modern data-collection and data-processing devices.
- The measurement technique used to obtain data in this document did not provide the capability to demodulate and read, or record, the content of messages. It was limited to the ability to examine the temporal and spectral structure of signals, noise, and interference.

4.0 IMPLICATIONS OF THE DATA

The measurements described in the appendices provide a number of key items of information that need to be considered during any evaluation of the occupancy and use of the license-exempt wireless-radio bands and for the efficient spectrum management of such bands. These items have been boiled down into a series of statements as follows.

4.1 The 2.4-GHz License-Exempt band

- The daytime use of the 2.4-GHz band is clearly overcrowded except at remote and rural locations. A large variety of users were noted in the band, and they operate with a large variety of signal formats. This has resulted in considerable band-occupancy and band-use disorder. Plain old-fashioned radio interference is a major problem for signal reception in this band, especially in the daytime.
- A complex mixture of users can be found the 2.4-GHz band. They include individuals, a wide variety of commercial enterprises, and departments of local, state, and national government. Many users, especially those with 802.11a,b,g devices, feel they are the sole occupiers of the band. They are often completely unaware of the signal-sharing aspects of the band.
- To further complicate band occupancy, a variety of communications systems use the band including short range 802.11a,b,g systems, point-to-point data links, point-to-area data services, point-to-point video services, area-coverage telephone systems, portable telephones, medical monitoring systems, and more.
- A complex mix of modulation formats were found in the 2.4-GHz band. They include pulse signals from 802.11a,b,g devices; pulse signals from other devices with similar but not quite identical pulse formats; spread-spectrum devices, frequency-hopping equipment; video emissions; and other emission formats including unusual formats. Topping this off is microwave-oven noise; spurious emissions from many devices, and erratic noise from other odd devices operated by experimenters and developers of new gear.
- While some users attempt to operate in a time-stable mode, most generate signals of short durations, at unpredictable times, and at unpredictable frequencies in and sometimes out of the band.
- No attempt to hide the old-fashioned radio-interference problem under new terminology, or marketing hype, will cover up and solve its harmful impact to all users.
- Most interference and noise in the 2.4-GHz band is highly impulsive, and it is rarely Gaussian. Thus, its amplitude is a function of receiver bandwidth.
- From a technical standpoint, interference and noise in the 2.4-GHz band is a complex time- and frequency-varying problem that cannot be described with conventional stationary statistical terms such percentage of band occupancy, percentage of channel occupancy, peak power, average power, root-mean-square power, amplitude probability distributions, or other standard measures often used

to describe and assess the effects of statistically stationary interference and noise on communication systems. The radio interference encountered by a daytime user of the 2.4-GHz band is a complex nonstationary statistical problem.

- The use of adaptive receivers in the 2.4-GHz band (that can sense the presence of interference or noise and move a communications link to another channel with less interference or noise) was rarely successful except for cases of low-band occupancy such as at nighttime and in remote unpopulated areas (when they are not needed). In general daytime interference and noise is so pervasive that all portions of the band contain interference. Adaptive receivers merely move to another channel containing what is sensed as slightly less interference and noise. The interference and noise encountered on an old channel, or a new channel, can change rapidly to a better state, or a worse state, at a time scale comparable to short signal durations.
- The relatively new term *Interference Temperature* introduced to define noise in the wireless bands is based on Gaussian noise, and it has not yet been defined in scientific terms that apply to the erratic and nonstationary interference and noise found in the 2.4-GHz band.
- Unfortunately, most users of the band do not have an understanding of the interference and noise problem since they rarely have a means to identify, examine, or assess interference and noise conditions. The band users suffer, usually unknowingly, with erratic and time-varying throughputs obtained with the assistance of error-correction techniques.
- Numerous examples of spurious emissions from poorly-designed and inexpensive equipment were found in and around the 2.4-GHz license-exempt frequency band, and this acerbates the interference problem. For example the spectral sidebands of spread-spectrum signals are rarely suppressed in present devices (they are suppressed in the licensed bands), resulting in the occupancy of wider portions of the band than necessary. Numerous cases of erratic impulsive emissions and spurious emissions were also noted.
- From the positive side, the open availability of the 2.4-GHz band along with low-cost devices and systems has resulted in new communications techniques and systems previously not available to the general public, commercial organizations, and all levels of local, state and federal government. Many cases of the highly-effective and profitable use of the band were encountered during these measurements. Countering this is the growing understanding that interference is a significant problem, and quick and inexpensive solutions are desired by the users, but they are simply not available. There is no effective spectrum management mechanism to identify and resolve interference problems, thus higher transmitter power is often the most convenient and most effective remedy. This remedy is spreading, and it merely exacerbates the interference problem faced by other users.

4.2 The 5.8 GHz License-Exempt Band

The occupancy and use of the 5.8-GHz band was examined at most of the locations used for the investigation of the 2.4-GHz band. Very few signals were found in this band, and no instance of radio interference has so far been found, thus no interference data is presented in this particular document. Several comments follow:

- Low-cost devices and systems for this band have not been available in past years, and the cost of devices and systems is still considerably higher than for equivalent devices in the 2.4-GHz band. Competitive price issues seem to be responsible for the ongoing high use of the 2.4-GHz band, and it is a major reason for the slow migration of users into the 5.8-GHz band.

- In addition, only a limited number of devices and systems are available at this time; however this appears to be changing. The cost of devices is decreasing and the variety of devices and systems is increasing. This suggests that the occupancy and use of the 5.8-GHz band will increase in the near future. It is not the purpose of this document to attempt to predict the timing of this increase.

- The rules for entry into the 5.8-GHz band are the same as those for the 2.4-GHz band. As the cost of devices and systems becomes comparable to that for the 2.4-GHz band, a rapid increase in the use of the band will certainly occur. While the band is much wider than the 2.4-GHz band, it still will not support completely interference-free operation. Similar interference conditions and degradation in performance conditions similar to that experienced in the 2.4-GHz band are certain to occur. It is only a matter of time for this band to encounter the same problems as those of the 2.4-GHz band.

- Consideration should be given to new rules for the use of the band. For example, a portion of the band could be reserved for point-to-point users and another portion to the low-power and short-range office users. Some control over signal formats would also minimize many interference problems.

- Portable telephone users could be assigned to a portion of the band or portable telephones employing narrow-band modulation techniques could be moved to the 915-MHz band where longer ranges can be achieved and less interference encountered (this would require that some point-to-point users and other high-power users in that band be eventually migrated into the 5.8 GHz band).

4.3 The 915-MHz License-Exempt band

The limited width of this band (26 MHz) is a primary factor preventing the widespread use of the band. It is not practical to expect industry to develop extensive new devices and systems for the band. Nevertheless a number of users were noted at most urban locations, including point-to-point business users. Many of these users employed special devices and systems assembled by small businesses to meet individual needs. This is the reason for the variety of special signal formats found in the 915-MHz band at many locations. Equipment for each communication task is designed in the best manner to meet specific needs rather than conforming to standards for signal formats.

While the 915-MHz band is not suitable for the wide-band emissions used by pulse signal formats such as 802-11a,b,g devices, the band could accommodate a large number of limited bandwidth systems using narrow channels. For example the band can accommodate more than 250 100-kHz channels, a number that would provide a means for interference-detection techniques used by adaptive receivers to become effective. Since the number of users is presently limited, the cost of changing the band into a new channel format would not be high.

4.4 The Licensed Bands

While the examination and evaluation of the occupancy and use of the licensed bands was not an objective of this effort, some data was collected over the past decade to provide an initial comparison of the unlicensed to the licensed bands. Comments follow:

- In all cases examined the licensed bands were used in an orderly matter. No case of radio interference was noted.
- All emissions originated from well-designed sources. No case of spurious or out-of-band emissions was found during the short time of the measurements.
- All emissions were tightly packed into allocated bands. Unused spectrum space was not detected.
- The data clearly suggest that good engineering practices are employed by the operators of each band examined.
- While interference from USB cables and devices was noted in the 800- to 900-MHz region, this interference was not generated by the licensed entities. It was generated by radiation from poorly-designed computer-related digital devices. This kind of interference was not pervasive and would not affect most users of the licensed bands. Nevertheless, it will be encountered by some special users of the band as it did during the collection of data for this document.

4.5 Other Issues

The data collected and provided in the appendices has raised other issues that have not been adequately summarized in prior sections. They are:

- The terms of *radio noise* and *radio interference* are used throughout this document. In this document *radio interference* means the reception of radio signals originating from communications devices other than that producing a desired signal. *Radio noise* is used to describe radio emissions from non-communication sources such as that from microwave ovens, spurious emissions from poorly-designed equipment, and emissions from experimental devices. The measurement technique allowed the identification and classification (in most cases) of emissions into these two categories.

- Many individuals consider all unwanted emissions appearing at the input terminals of a radio receiver to be radio noise. Thus, *radio interference* and *radio noise* are lumped into a single category also called *radio noise*. This is also an acceptable means to define radio noise at the input of a receiver as long as it is understood that interference and noise are combined.

- Of special concern is that the radio noise and radio interference described in the appendices is so intermittent in time and can change so significantly across narrow frequency spans that it cannot be described by conventional stationary statistical means. These changes were often comparable with the duration of message transmissions. The noise and interference encountered is a nonstationary statistical problem that has been largely ignored by the wireless-radio community.

- Obtaining an understanding of the impact of interference and noise on the reception of a desired signal was complicated by the wide variety of emission formats found in the band. The variety of spectral and temporal structures of the various emissions in the band and the changes of these with time and with frequency was amazing. New emission formats often appeared during the measurement sessions along with the popular 802.11a,b,g formats. Some control over the spectral and temporal parameters of the emissions allowed in the band would simplify the assessment of the impact of interference and noise on communications throughput.

- Erratic noise pulses not associated with a specific communications system or a specific device were noted at most measurement locations, especially those locations and bands with high occupancy. This high-level noise often covered the entire band under examination, and it was mostly found in the 2400- to 2483.5-MHz band. The spectral content of these pulses rarely extended outside the frequency limits of the 2400- to 2483.5-MHz band. The source(s) of this noise are of concern. While similar impulsive intermodulation products have been noted during other measurements due to the saturation of an amplifier or a nonlinear device near a transmitting antenna, such a source was not responsible for the erratic noise pulses. Intermodulation pulses do not have distinct frequency limits such as documented during the measurements described in this document. The high amplitude and frequent occurrence of these pulses is already a source of significant interference to the reception of desired signals, and the source and the source-to-victim path needs to be identified.

- Comprehensive communication system throughput measurements did not accompany the noise and interference measurements described in this document. Cases of total loss of communications links were encountered during the measurements and high-levels of loss in throughput were observed but not documented. Thus, these measurements did not establish a good relationship between noise and interference and system performance.
- The use of techniques to measure the impact of radio noise and interference conditions on the throughput of selected wireless-radio systems in the unlicensed bands would be a valuable addition to further field measurements. Since the spectral and temporal properties of interference, noise, and a desired signal can be defined for short periods of time, it should be possible to provide a reasonable assessment of the impact of time-varying interference and noise on a time-varying signal for selected short intervals of time.
- Computational techniques are often effectively used to determine the impact of noise and interference on communications system performance. This approach was not undertaken during this effort because of the lack of techniques to deal with the nonstationary characteristics of the noise and interference.
- A review of the devices now available commercially for the 5.8-GHz license-exempt wireless-radio band show that devices with multiple RF signal formats and multiple kinds of applications are available. Short distance equipment is available as well as long-distance point-to-point systems. Because the band is much wider than the 2.4-GHz band, and equipment costs are decreasing, it is anticipated that this band will become a major target of manufacturers and their marketing personnel. Given time, this band will encounter the same interference problems now encountered in the 2.4-GHz band.

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APPENDIX A. HOME OFFICE MEASUREMENTS

Three documents are provided in this appendix. They are:

- Technical memorandum 021006, ***Emissions in the 2.4-MHz License-Exempt Band at one location***, October 6, 2002
- Technical Memorandum 040628, ***Occupancy and Use of the 2.4-GHz Wireless Band at a Residence,*** *July 2004*
- Technical Memorandum 041230, ***A Reexamination of Emissions in the 2.4-GHz License-Exempt Wireless-Radio Band at Davis, California***, December 2004

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Technical Memorandum 021130
Signal Enhancement laboratory
Department of Electrical and Computer Engineering
Naval Postgraduate School
Monterey, CA 93943

November 2002

EMISSIONS IN THE 2.4-GHz LICENSE-EXEMPT BAND AT ONE LOCATION

by:
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ABSTRACT

The availability of portions of the radio spectrum for low-power license-exempt devices coupled with the recent widespread availability of low-cost wireless radios has raised the issue of saturation of the available allocated bands. While cases of harmful interference to existing and new users have been reported, very little factual information is available to determine the extent of such interference or about the actual occupancy and use of the present license-exempt bands. This paper explores the occupancy and use of the 2400- to 2500-MHz band and potential radio interference to a new wireless radio system in that band at one location, a home office, in a small city in central California.

INTRODUCTION

The portion of the radio spectrum at and near 2400- to 2500-MHz frequency band is allocated to a variety of services in the United States. For example, amateur radio is authorized to use the band from 2390 to 2450 MHz, the Industrial Scientific and Medical (ISM) Service from 2400 to 2500 MHz, and a variety of low-power and license-exempt wireless-radio users also use the band. A detailed listing of the authorized users of this band in the United States is provided in the reference.[2]

The widespread availability of low-cost wireless radio devices for use in the license-exempt bands has raised the issue of congestion in these bands. This is particularly true of the 2400- to 2483.5-MHz band since a large variety of low-cost devices are available for this band. While reports of harmful interference have been noted, little factual evidence is available to understand the extent of the interference problem or the use of the license-exempt bands.

A series of measurements of the spectrum environment was undertaken at the location of a new 802.11b wireless-radio system to evaluate the interference problem. The location of the measurement was at a home office in a city of modest size (Davis, California), a university town with a population of about 60,000 people. Because of the relatively small size of the city and the location of the home office in a residential area about 2 miles from downtown and the university, neither a high nor low density of emissions was expected.

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[2] The FCC's On-line Table of Frequency Allocations, Revised as of February 28, 2002

INSTRUMENTATION

The instrumentation was similar to that previously used for the measurement and definition of radio noise in other parts of the radio spectrum.[3] It consisted of available components assembled on a laboratory cart for portability. Figure 1 shows a block diagram of the instrumentation.

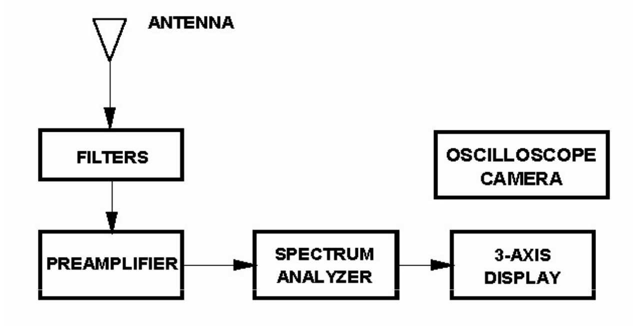

Figure 1

For most measurements a small stub antenna, similar to those used on wireless radio systems, was used to collect emissions. In one case a reflector with a dipole feed (a gain of 14 dB) was used. In most cases a filter was used to exclude high-level out-of-band signals and ensure that no component in the measurement system was saturated. A high-dynamic-range preamplifier with a gain of 24 dB was used for all measurements to achieve measurement-system sensitivity about equal to that of a standard VHF/UHF radio receiver. While the 12-dB noise figure of the preamplifier was higher than desired, it was used in preference to a lower noise figure preamplifier to ensure that amplifier saturation did not occur at any time during the measurements.

A relatively old spectrum analyzer (HP Model 8565A) was used since its time between scans was considerably lower than for newer models, and its manual controls permitted the rapid adjustment of the analyzer to cope with frequent changes in the content of emissions. An ELF Engineering Model 7200B 3-Axis Display was used to provide a visual time-history presentation of emissions in the band or in any desired portion of the band. It provided the ability to observe and document the detailed spectral and temporal structure of received emissions.

A small table containing pertinent measurement parameters accompanies each item of data. The parameters are listed in Table 1.

Table 1
Measurement Parameters

Line 1	Local time in 24 hr. format, date in yymmdd format
Line 2	Site identification, antenna identification, antenna direction
Line 3	Center frequency, scan width, IF bandwidth, scan time*
Line 4	Filter, preamplifier gain, RF attenuation, IF gain
Line 5	Additional information

* (LS) is appended when line synchronization is used

[3] Wilbur R. Vincent, Richard W. Adler, and George F. Munsch, ***An Examination of Man-made Radio Noise at 37 HF Receiving sites***, Document No. NPS-EC-05-003, Signal Enhancement Laboratory, Department of Electrical and Computer Engineering, Naval Postgraduate School, November 2004

BAND OCCUPANCY

The first step in the investigation was the examination of emissions within and around the 2400- to 2500-MHz frequency range commonly called the 2.4-GHz Industrial, Scientific, and Medical (ISM) band and/or the 2.4-GHz license-exempt band.

Figure 2 shows emissions received at the home office over the frequency range of 2400 to 2500 MHz. The upper view shows the spectral shape of the three dominant emissions in the band. The amplitude of each emission, referenced to the 50-Ohm input of the preamplifier, is provided in dBm. The lower view provides a time-history view of the emissions over a 121.1-second measurement period for this example.

A dominant feature in the middle of the time axis of the lower view is the erratic emission from a microwave oven. The oven was located 30 feet (and in a different room) from the stub antenna used to receive signals. The oven emissions extended above and below the band limits, and the total frequency range of the microwave-oven emission is provided in a later example.

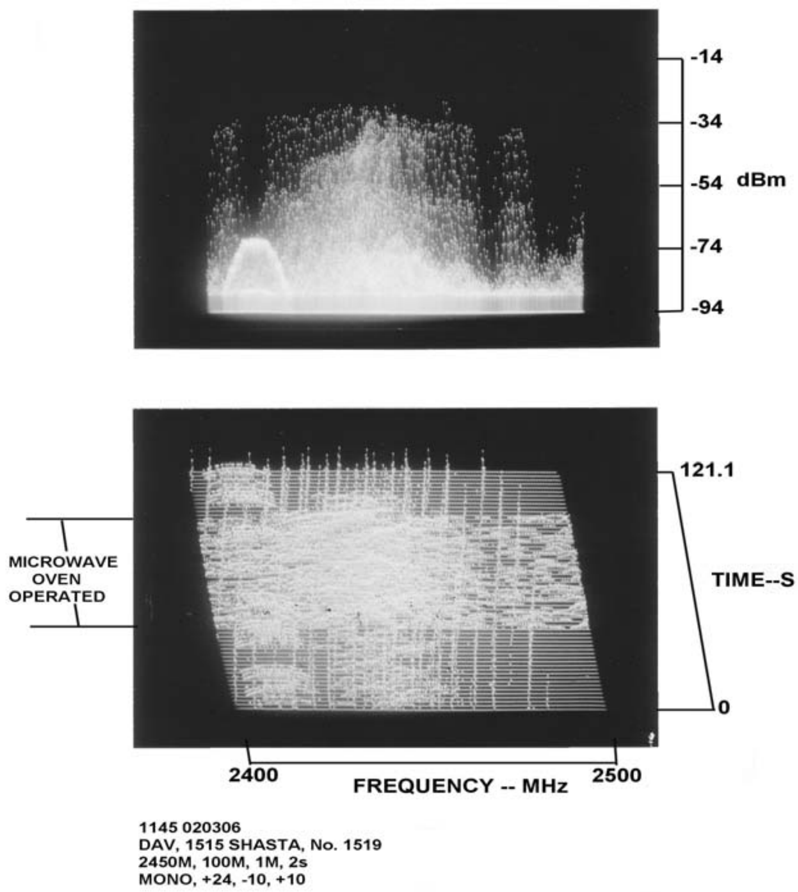

Figure 2 Example of Emissions in the 2400- to 2500-MHz Band

Another dominant feature in Figure 2 is the slanting lines across the time-history view. These lines are caused by the wide-bandwidth pulse emissions from a frequency-hopping portable telephone used in and around the home office. In this case the scan time of the analyzer is much longer than the hopping period of the portable phone, and the measurement bandwidth is considerably less than the total spectral width of the emission. This allows several hops to be received during each slow scan. The repetitive and orderly scan process of the spectrum analyzer allows the multiple impulses received during successive scan to build up into the slanting lines.

The emission near the left edge of the frequency range (in the upper view with a trapezoidal shape) is from the base station of a wireless radio transmitter associated with an area-coverage telephone system of a nearby business. The wireless telephone system provides employees of the business with hand-carried telephone service when in the vicinity of the business. The base-station antenna for this system is located on the roof of a four-story building about 250 feet from the home-office measurement location. The coarse-scale measurement parameters used to obtain this example do not show the fine-scale temporal and spectral aspects of this emission.

Figure 3 on the next page shows the total spectral width of the emission from the microwave oven. The frequency range of the example is 2120 to 2620 MHz although the spectral width of the emission did not quite cover the total measurement range. The primary emission component is centered at about 2450 MHz. Three additional broad bands of noise are shown at lower amplitudes where one is higher in frequency than the primary emission and two are at lower frequencies. Of special interest to the authors is that the microwave oven produced sufficient noise in the 2300- to 2310-MHz and 2390- to 2450-MHz amateur bands to prevent the reception of low-level signals whenever the oven was operated.

During the measurements radio noise from other microwave ovens was also noted at intermittent times. These emissions came from microwave ovens in nearby residences and apartments. One apartment resident located 175 feet from the office was requested to operate his microwave oven for a series of one-minute intervals. Emissions from the oven were examined using a directional antenna with 14 dB of gain and located outside the wall and windows of the home office. It was pointed directly at the apartment containing the microwave oven. Figure 4 shows emissions received from the distant oven. The spectral and temporal structure of its emission is similar to that from the oven in the residence containing the home office, and the total spectral width is about the same.

The amplitude of the primary emission and the secondary spectral components from this and other nearby microwave ovens is sufficiently strong to cause significant intermittent interference to initial tests of wireless radio systems at the home office location as well as amateur radio operation in the same residence.

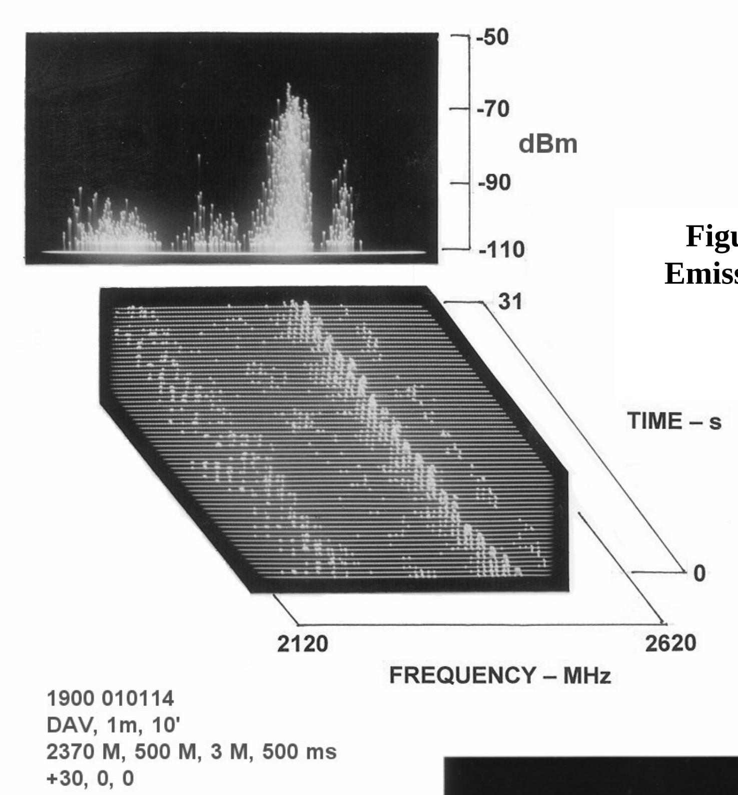

Figure 3 Spectral Width of Emissions from a Microwave Oven

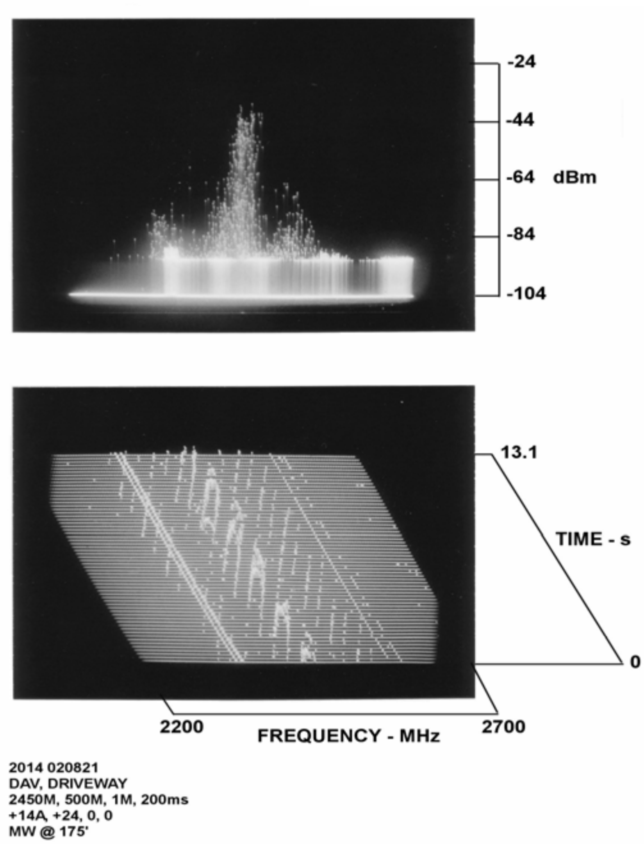

Figure 4 Emissions from a Distant Microwave Oven

Figure 5 shows emissions in the 2400- to 2500-MHz band when the microwave oven was not operated. In this case another frequency-hopping emission with different hopping parameters is shown in the center of the frequency range. A careful examination of the upper view shows that two emissions are present from this source. A few very strong pulses were traced to the base unit of a portable telephone operating in a nearby home while the lower-level emissions are from the portable unit. This signal and other similar signals appeared at erratic times and amplitudes during all measurement sessions.

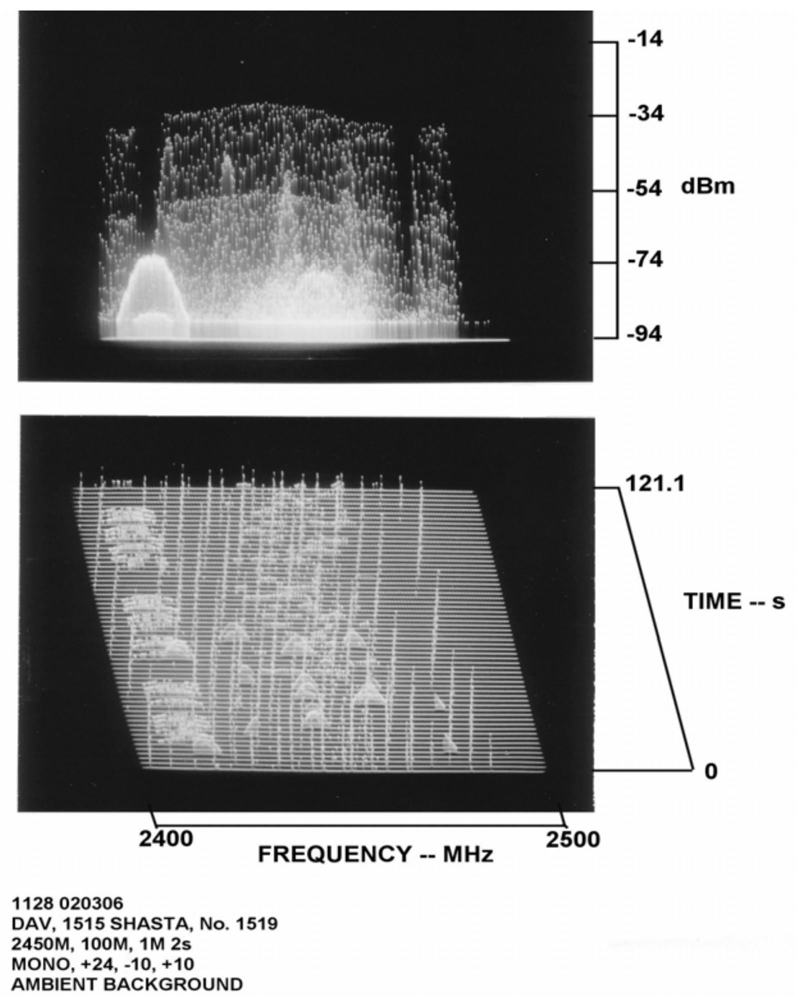

Figure 5 Example of Emissions in the 2400- to 2500-MHz Band without Microwave Oven Noise

FINE SCALE EXAMINATION OF INDIVIDUAL EMISSIONS

To better understand the properties of emissions in the band, the fine-scale spectral and temporal characteristics of each individual emission were examined. Examples are provided in this section.

Microwave Oven Noise

Figure 6 shows the fine-scale spectral and temporal structure of the primary spectral component emitted by the microwave oven located close to the home office. For this example, the scanning process of the spectrum analyzer was synchronized to the power-line frequency. The straight lines parallel to the time-history axis shows that the microwave-oven emission consists of bursts of noise that are synchronized to the power-line frequency. The temporal structure indicates the oven's magneton was powered by a half-wave voltage waveform. This suggests that the magnetron was its own rectifier. Note that the temporal structure changes with both frequency and with time.

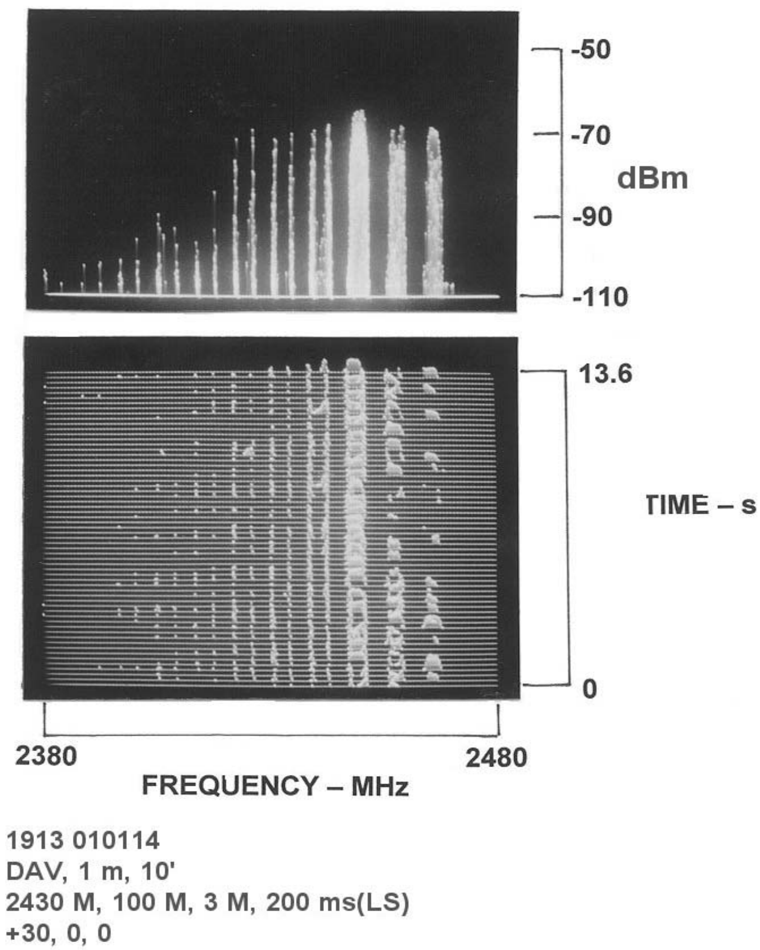

Figure 6 Fine-Scale Temporal and Spectral Structure of Microwave Oven Emissions

Frequency-Hopping Portable Telephone

The fine-scale spectral and temporal structure of the frequency-hopping portable phone whose coarse-scale properties are shown Figures 2 and 3 was examined, and Figure 7 shows the detailed structure of emissions from its base station. The frequency channelization of the emission is evident from the spectral view and can be found in the time-history view by careful examination. Nineteen primary frequency hops or channels are employed over the 80-MHz width of the emission. Only small variations in amplitude occur across the emission width. Additional data indicates the hopping-pattern repeated in an orderly process at 4.5 second intervals.

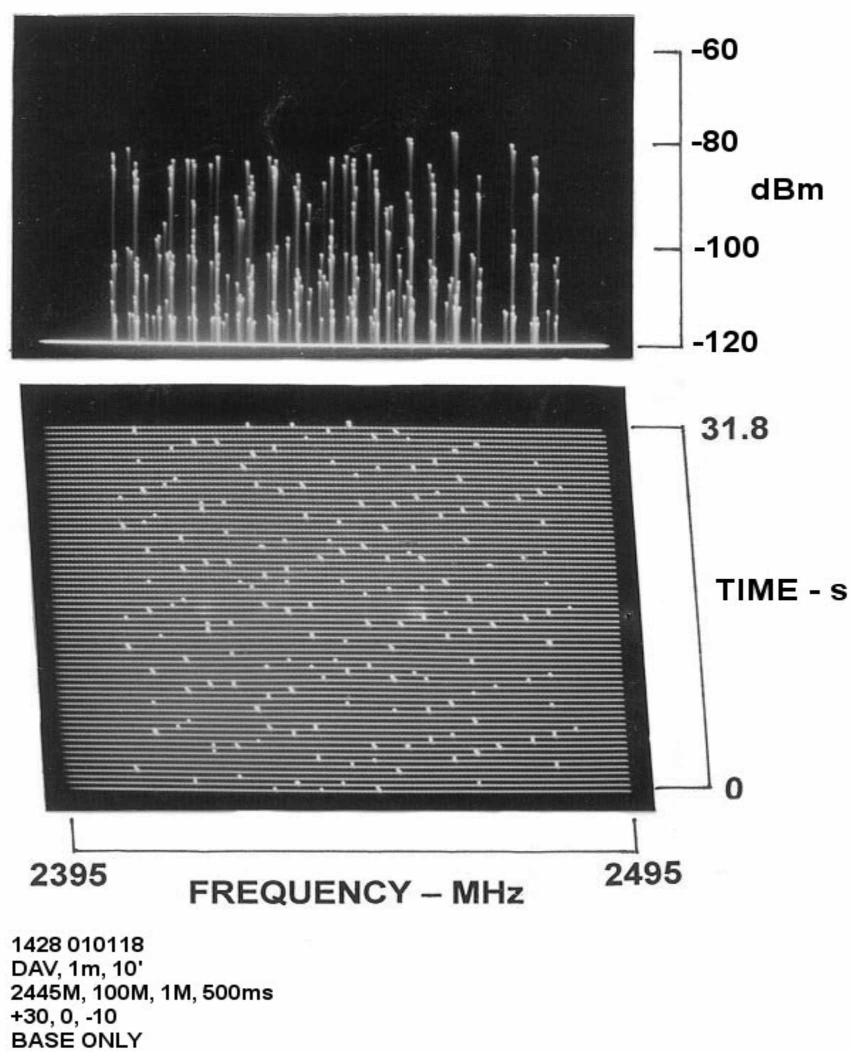

Figure 7 Fine-Scale Structure of a Frequency-Hopping Signal from a Portable Telephone

Figure 8 shows the relationship between emissions from the base-station and the portable unit. Signals from only the base station are shown at the top of the time-history view. The pulses are aligned parallel to the time-history axis due to the line synchronization of both the spectrum analyzer and the pulses from the base station. When the portable unit is turned on, additional pulses synchronized to the base unit signals appear immediately after the base station pulses. Each pulse is modulated with speech from the user of the portable and base units

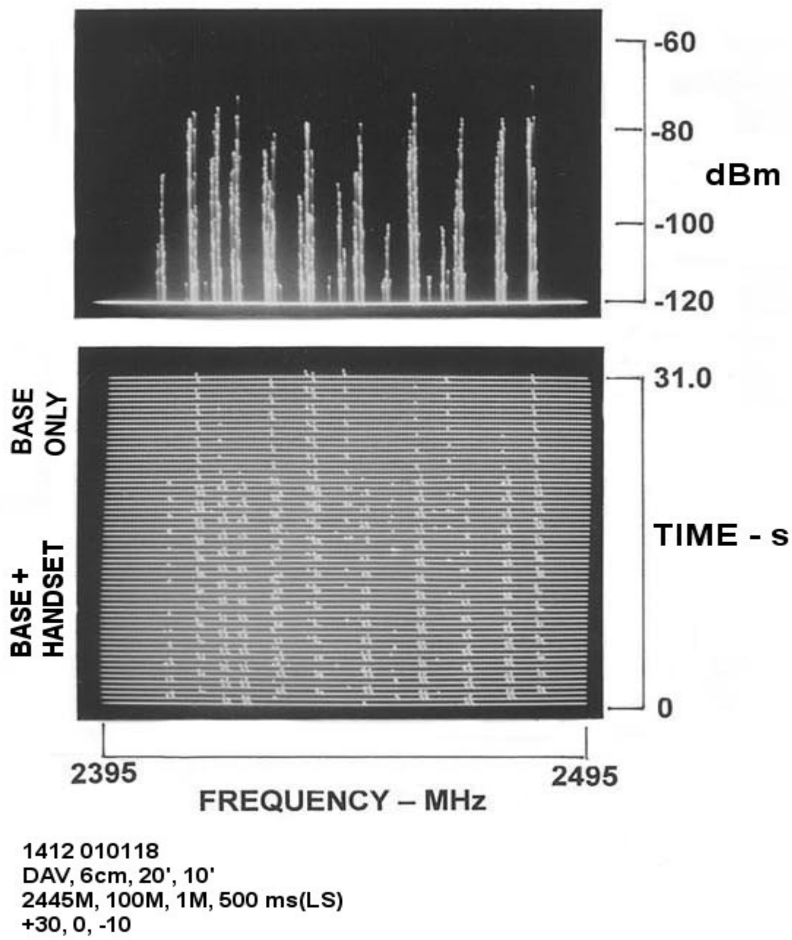

Figure 8 Fine-Scale Structure of Frequency-Hopping Signal from a Portable Telephone

Area Wide Telephone System

Next, the fine-scale structure of the area-wide telephone system previously shown in Figure 2 is examined. Figure 9 provides the usual two views of the signal with a center frequency at 2420 MHz and a frequency span of 20 MHz. The spectral shape of the emission is shown in the upper view. In this case, the received level of the emissions was highest at the center of the emission and lower above and below its center frequency.

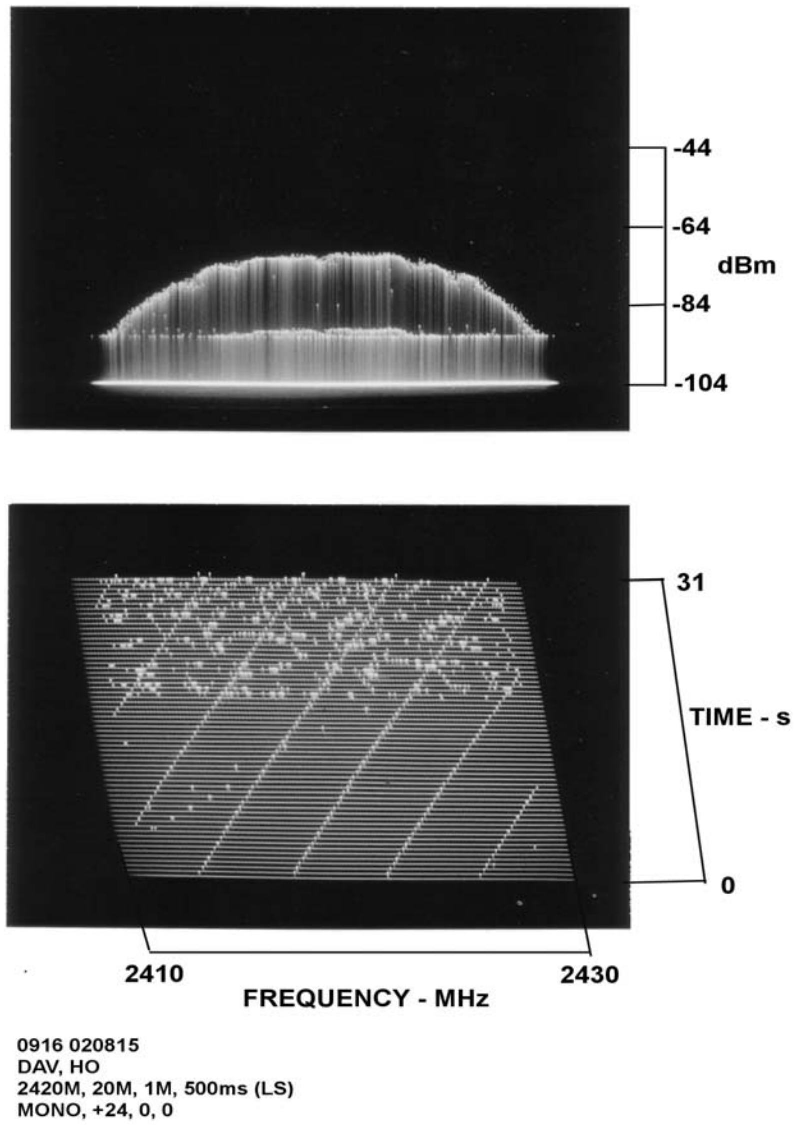

Figure 9 Base-Station Emissions of a Frequency-Hopping Area-Wide Telephone System

In the upper part of the time-history view of Figure 9, the system was in use. In the lower part of the time-history view, all portable units were silent, and the dense pulse emissions from the base station changed into a low-repetition-rate-synchronization signal. The spectrum analyzer was operated in the line-synchronization mode, and the resulting slanting lines indicate the pulses were not synchronized to the power-line frequency. The synchronizing pulses occur at one hundred millisecond intervals. The more complex pulse pattern reappears each time the area-wide telephone system is activated by either a base or portable user.

Of interest is that a few stray pulses from another source are shown on the left half of the lower portion of the time-history view of Figure 9. This source was not identified.

During the collection of data the synchronizing pulses occasionally appeared to change in duration. A closer inspection indicated they were considerably more complex than implied by the single pulse format implied in Figure 10. Figure 11 shows the time-domain properties of the synchronization signal when a single pulse was replaced with a short series of pulses. The purpose of the occasional more complex synchronization pulse code was not determined.

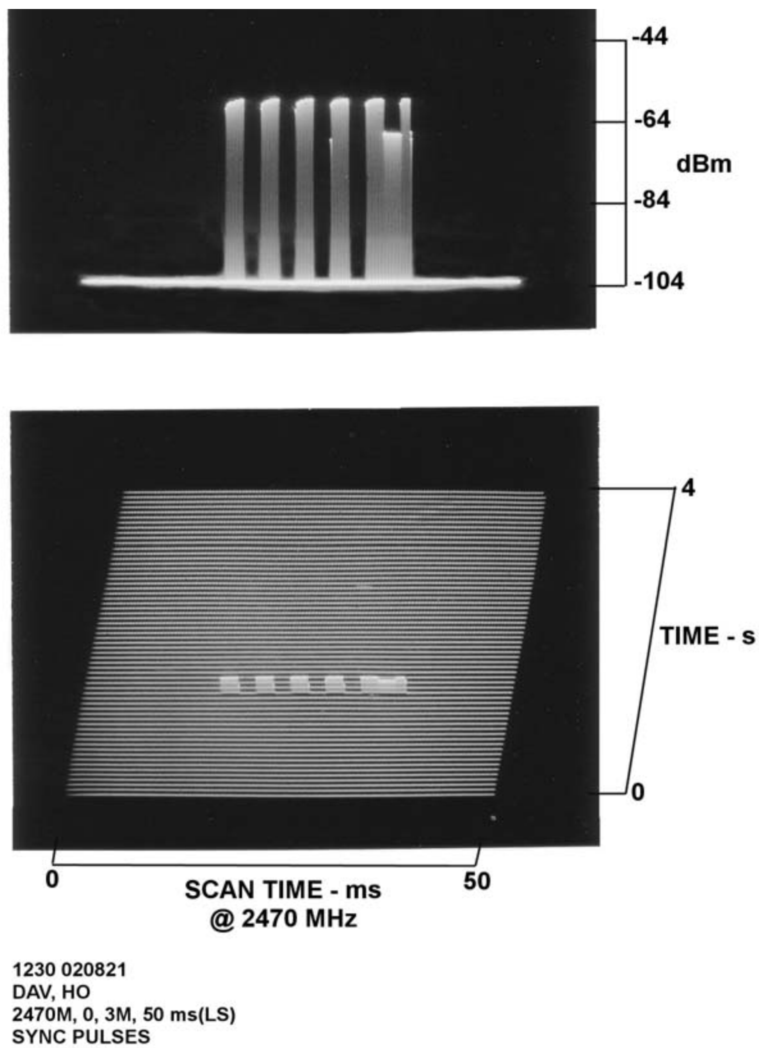

Figure 10 Time-domain Coding of Synchronizing Signal from the Area-Wide Telephone System

Spread-Spectrum Portable Telephone

A second portable telephone was used on the home telephone of the residence containing the home office. Its base station is located in another room about 35 feet from the stub antenna used for signal collection at the office location. This telephone used spread spectrum modulation, and the spectral and temporal structure of its emission is shown in Figure 11. The upper view shows two signals at different strengths but with nearly identical spectral characteristics. The strongest signal is from the portable unit that was used in the home office near the stub antenna. The lower signal is from the more distant base unit. Both have a deep null at the center frequency of their emissions and both have second-order emissions on each side of the primary emission. The fine-scale structure is nearly identical for signals from both the base-station and the hand-held unit. It is apparent that both use the same transmitter components. The time-history view shows that the base and hand-held unit timeshare the same frequency channel using bursts of signal one millisecond in duration and spaced by one millisecond.

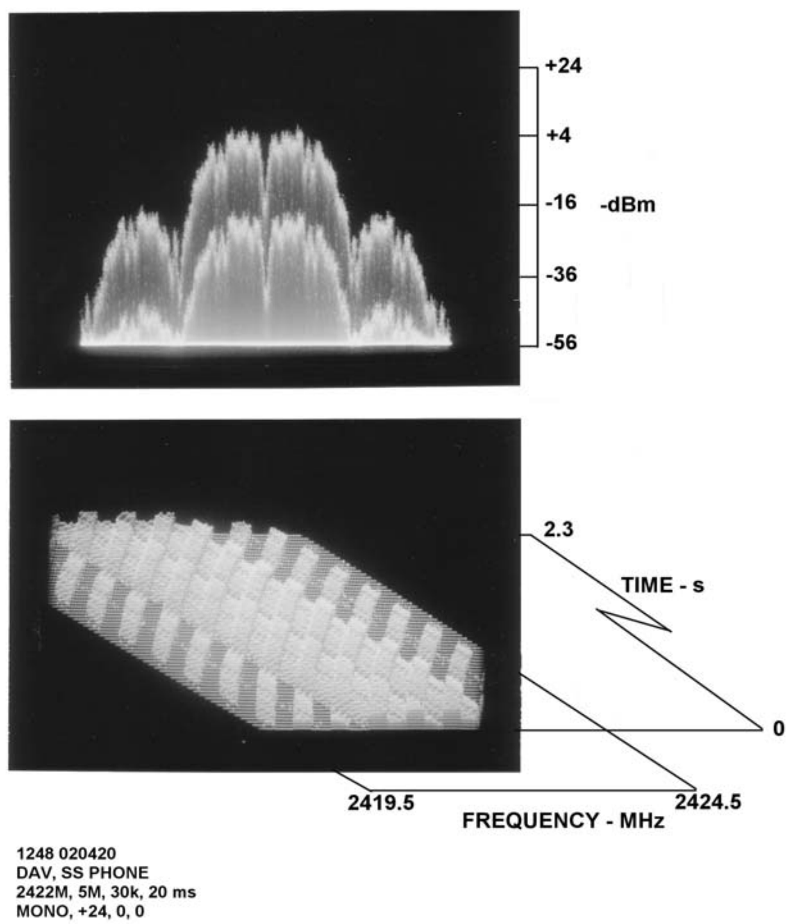

Figure 11 Fine-Scale Structure of a Spread-Spectrum Signal from a Portable Telephone

Point-to-Point Data Link

A low-level pulse emission was found in the upper frequency portion of the band centered at about 2460 MHz. Figure 12 shows its spectral and temporal structure. This emission was traced to a nearby point-to-point data-transmission system. Only synchronizing pulses spaced at one hundred millisecond intervals were found on this emission. At times, a synchronization pulse would change from a single pulse to a short series of multiple pulses of various widths. While it is suspected the system employed an 802.11b-type signal format for the transmission of data, but this was not confirmed due to the low usage of the system.

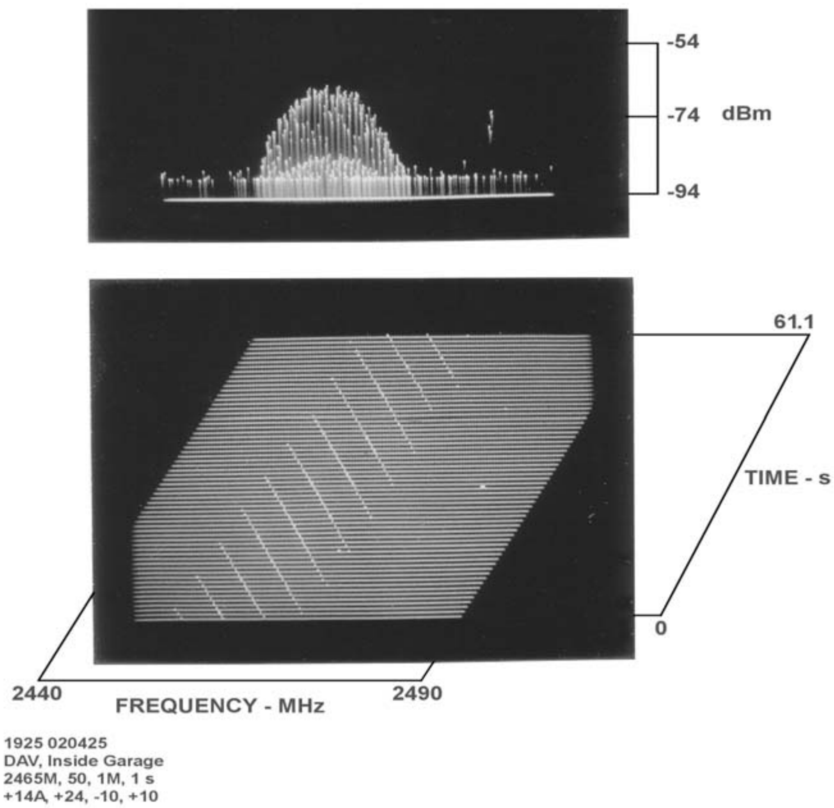

Figure 12 Synchronizing Pulses from a Point-to-Point Data Transmission System

A single pulse from an unknown source is shown about one-half way along the time axis of the time-history view and near the upper end of the frequency range of Figure 12. This pulse also appears in the upper view about –70 dBm in amplitude. Such pulses were occasionally noted at erratic times of the day. These intermittent pulses were generally ignored and no attempt was made to catalog their occurrence, although each pulse represents potential interference to any system operating in this portion of the band.

DISCUSSION

The result of this investigation of the occupancy and use of the 2400- to 2500-MHz band at one location is summarized below. The general occupancy of the band was first explored. Next, the detailed spectral and temporal structure of each primary emission was examined.

The measurement series was conducted primarily to determine the feasibility of installing a new wireless data transmission system in a home office. The occupancy measurements and the more detailed examination of each emission provide considerable insight into the present use of the band at the home-office location and potential interference to a new 802.11b system in the home office. Comments about each the overall band occupancy and the fine-scale structure of emissions follow.

Band Occupancy:

The examples of band-occupancy data (see Figures 2 through 5) show that a variety of emissions exist at the location examined. These ranged from one frequency-hopping system occupying 80% of the total band to intermittent microwave-oven noise with a spectral content extending well outside the band to frequencies used by other radio services. No part of the 2.4-GHz wireless band was free from emissions during weekdays. Only sporadic emissions were noted during nighttime hours and on weekends. While one emission associated with an area-coverage telephone system was almost continuously used during the weekday daytime hours, all other emitters were sporadic in operation, typical of the use of portable telephones, the domestic use of microwave ovens, and the operation of other intermittent sources.

All radio emissions observed at this location used different signal formats. Several emissions used various forms of frequency-hopping modulation, some used direct-sequence spread-spectrum modulation, and others used the common 802.11b signal format. The intended wireless radio signals along with microwave oven noise resulted in a curious mixture of time-varying emissions. Time-stable occupancy conditions never occurred during any of the measurement periods.

The more conventional statistical measurements of channel and band occupancy were not conducted since the objectives of this effort were limited to obtaining a general understanding of band use at the location of interest. The data show that obtaining meaningful statistical measures of band use will be difficult due to the erratic nature of band occupancy and the time-varying nature of each individual emission.

The band-occupancy data also provides useful information about the dynamic range of the received emissions. Due to the power restrictions imposed on each license-exempt wireless-radio emitter by the by the Federal Communications Commission, the maximum signal levels at the office location were lower than those found in and around most other communications bands. This provides wireless-radio designers and users greater freedom from receiver overloading than for many other radio services. Even with this limitation, sensitive low-noise preamplifiers were found to be susceptible to overloading under some conditions. It was necessary to use a high dynamic range preamplifier to avoid overloading and the contamination of measured results with intermodulation products.

Individual Emissions:

The variety of emissions found during the band-occupancy measurements made it difficult to fully understand the time-varying aspects of the composite mixture of various signals and noise. Thus, the band-occupancy measurements were supplemented by an examination of the spectral and temporal details of each individual emission. Examples are provided to illustrate the primary properties of each emission. All emissions originated from standard and widely-available commercial devices which were purchased from local electronic stores. No special or non-standard sources were found or included in the survey.

Microwave Oven Noise: The spectral properties of a large number of microwave ovens were investigated by the Institute of Telecommunications Sciences in 1994.[4] The spectral data obtained from our more limited measurements is consistent with the ITS data. Both investigations show that radio noise from microwave ovens must be considered when investigating performance degradation of wireless-radio systems in home offices and at many other locations.

Figure 2, 3, 4 and 6 show the spectral and temporal properties of emissions from microwave ovens located in and near the residence used for the measurements. Figures 2 through 4 show that noise levels extend well below and above the band limits. Microwave oven noise significantly degraded the reception of signals in the amateur radio bands of 2300 to 2310 MHz and 2390 to 2450 MHz. Emission levels were surprisingly high from microwave ovens which are located up to several hundred feet away, and they have the potential to degrade the performance of systems over the frequencies shown.

The distinctive temporal structure of the primary spectral component of microwave oven emissions shown in Figure 6 illustrates the complexity of such noise. The temporal structure varies considerably with time and frequency and becomes erratic at some frequencies. Nevertheless, the data shows that portions of the temporal structure are completely free of noise, and this aspect of microwave oven noise apparently was taken into account in the design of the signal format of Portable Telephone No. 1.

Portable Telephone No. 1: A dominant emission at the home-office location is the broadband signal from the frequency-hopping portable telephone used in the residence. Signals from this telephone occupied 80% of the band (see Figures 7 and 8) where each figure shows some aspect of the hopping pattern of this emission. Figure 8 is of special interest since it shows the relationship between signals from the base-station and the hand-carried unit. Figure 8 also show that the pulses from the base station were synchronized to the power-line frequency and that the portable-unit emissions were slaved to the base-station pulses. This particular portable telephone allows multiple hand-carried units to be simultaneously operated. Each additional hand-carried unit adds an additional set of frequency-hopping emissions into the time interval between the base-station pulses.

[4] Philip E. Gawthrop, Frank H. Sanders, Karl B. Nebbia, and John J. Sell***, Radio Spectrum Measurements of Individual Microwave Ovens***, U.S. Department of Commerce, Boulder, CO, NTIA Report 94-303-1

The data also show that the synchronization of the portable-telephone emissions to the power-line frequency allowed the designer to place its pulses into the dead time of the temporal pattern of emissions from microwave ovens (whose emissions are also synchronized with the power-line frequency). Thus, this particular telephone system was immune to high-levels of radio noise from microwave ovens. Tests confirmed this immunity.

Area-Wide Telephone System: Figures 9 and 10 show the primary aspects of emissions from the local area telephone system operated by a nearby business. Its emissions were about 20-MHz wide, occupying about 20% of the band. The shaped spectral structure as shown in the upper view of Figure 9 is considerably different from the flat spectral structure of the frequency-hopping emissions of portable telephone No. 1. It is evident that the designers of the system were concerned about the strength of emissions at the band edges of the signal.

During the daytime the telephone system was highly used resulting in the addition of numerous data pulses within the 20-MHz band. During the nighttime hours and on weekends, the system was only occasionally used, and the emissions often reverted to only synchronization pulses spaced 100-ms apart as shown in the lower part of the time-history view of Figure 9.

While the synchronizing signal usually consisted of series of pulses, occasionally its pattern changed into a more complex form of the pulse-time coding as shown in Figure 10. The purpose for this coding was not determined from the measurements.

Portable Telephone No. 2: Figure 11 shows the spectral and temporal structure of spread-spectrum emissions from this telephone. Its emissions were limited in width to about 5 MHz thus it occupied only 5% of the band. About sixteen such telephones could be operated in the band at or near one location without generating interference to each other.

The unusual spectral structure of the spread-spectrum emission is puzzling. The deep null at the center frequency of the signal and the fine-scale variations in the amplitude of the spectral structure are not consistent with the spectral structure of a well-designed spread-spectrum signal source. No obvious reason for these unusual aspects of the signal could be discerned from the measured data.

Other Emissions: A variety of other low-level and random-occurring emissions were noted during the measurements. Some of these could be traced to microwave ovens in neighboring residences. Others were from portable telephones operated in nearby residences. Still other odd pulse sequences could not be attributed to known sources. To further confuse band occupancy, wide-band emissions from video-surveillance systems are now appearing in the band. Since such emissions were only occasionally noted during the measurement times, no attempt was made to identify their sources. They are mentioned because additional sources were observed, and they may become more prevalent at other times.

IMPLICATIONS OF THE DATA:

Starting in 1995, the Institute of Telecommunication Sciences (ITS), Boulder CO conducted a detailed and lengthy series of broadband spectrum surveys at a number of locations in the United States. [5, 6, 7, 8] These surveys included occupancy information for the 2400- to 2500-MHz band. At the times of the various ITS surveys, occupancy of the band was found to be low, but the ITS data was obtained prior to the widespread availability of low-cost wireless-radio devices. While the ITS data for the 2400- to 2500-MHz band is of considerable historical interest, it does not provide a good basis for determining present-day band-occupancy conditions. A similar survey at this time would produce much different results, and such a comprehensive survey is long overdue.

The data contained in this paper is direct evidence that the occupancy and use of the 2400- to 2500-MHz band has changed dramatically since the earlier ITS surveys. The allure of the license-exempt use of portions of the radio spectrum along with the availability of low-cost devices is apparent from even a cursory examination of the band-occupancy data. The removal of bureaucratic procedures and licensing costs from users is a major reason for in the rapid expansion of emitters in the 2400- to 2500-MHz band. Given these favorable conditions, many wireless-radio users have already appeared in the band and more will flock into it and into any additional license-exempt spectrum provided. This was aptly demonstrated many years ago by the rapid occupancy of the 27-MHz Citizens Band along with its massive interference problems.

All of the emitters identified in this paper, including microwave ovens, perform a desirable and highly useful service to the public. While no gross misuse of the band was detected during the measurements, the question of efficient spectrum use was clearly raised. For example signals from one of the portable telephone system uses about 80 MHz of the radio spectrum for the transmission of a single 3–kHz wide voice signal. This cannot be considered an efficient use of the crowded radio spectrum by any reasonable and meaningful standard. The information supplied with this particular telephone stated that it was a frequency-hopping spread-spectrum (FHSS) system, but no additional information about its signal format was provided to allow the purchaser to evaluate its interference potential to other nearby systems. Measurements were required to understand how it and the other wireless radios use the band and how to cope with the interference they generate.

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5 Frank H. Sanders, Bradley J. Ramsey, and Vincent S. Lawrence***, Broadband Spectrum Survey at San Diego, California***, Institute of Telecommunication Sciences, National Telecommunications and Information Administration, U.S. Department of Commerce, Boulder, CO, March 1995

6 Frank H. Sanders and Vincent S. Lawrence, ***Broadband Spectrum Survey at Denver, Colorado***, National Telecommunications and Information Administration, U.S. Department of Commerce, Boulder, CO, NTIA Report 95-321, September 1995.

7 Frank H. Sanders, Bradley J. Ramsey, and Vincent S. Lawrence, ***Broadband Spectrum Survey at Los Angeles, California***, National Telecommunications and Information Administration, U.S. Department of Commerce, Boulder, CO, NTIA Report 97-336, May 1997

8 Frank H. Sanders, Bradley J. Ramsey, and Vincent S. Lawrence***, Broadband Spectrum Survey at San Francisco, California,*** National Telecommunications and Information Administration, U.S. Department of Commerce, Boulder, CO, NTIA Report 99-367, July 1999

In addition to signals from wireless radios, the presence of additional and unwanted emissions from microwave ovens must be considered. These devices are found in most kitchens as well as in office coffee rooms, restaurants and many other places. Intermittent radio noise from these devices is a practical aspect of the 2400- to 2500-MHz band-use issue.

A careful review of the types of users of the 2400- to 2500-MHz band at the location described in this paper is of interest. Only six wireless radio systems were identified during the measurements as primary band users. It is estimated that a total of about thirty people use these six systems. This is a small number of systems and users for a total of 100 MHz of spectrum space. While a few more systems might be added into the band with minimal additional interference problems, no massive expansion of users can be accommodated at or near this specific location using the variety of signal formats found on existing systems. Compare this with the ability of the band to accommodate users with differently organized band-use plans. The band can accommodate more than ninety 1-MHz channels, more than three thousand 30-kHz channels or ten thousand 10-kHz channels. Alternatively, the adoption of compatible modulation schemes would permit the reuse of the spectrum with minimal interference from existing signals. A review of more-effective band-use techniques is suggested by the results.

Of concern is that no good way presently exists to adjudicate interference problems in the bands presently allocated for wireless radio. It is unrealistic to expect the Federal Communications Commission to investigate and resolve massive numbers of interference problems at locations remote from their offices and monitoring stations. It is a *caveat emptor* situation where only a few of the licensed users of the band and a few wireless-radio users will have the expertise and the instrumentation to understand and cope with their individual time-changing interference problems. Most wireless-radio users will not understand why one wireless-radio system performs exceptionally well while other similar systems perform erratically and poorly due to an unfavorable and intermittent radio-noise environment. The variety of signal formats, each with its own susceptibility to time-variable noise, greatly complicates the interference/performance issue. Coping with *old fashioned radio-interference* problems will become a costly aspect of wireless radio under the existing wide-open ground rules for the use of the wireless bands.

This brief investigation only scratches the surface of the wireless-radio issues. Additional information at other locations is required to fully understand the extent of the radio-interference problem, to develop spectrum-use techniques to minimize radio interference, and to provide a meaningful technical basis for the improved use of spectrum space allocated to wireless radios.

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Technical Memorandum
No. DAV 040628

OCCUPANCY AND USE of the 2.4-GHz WIRELESS BAND at a Residence

Prepared By:

Wilbur R. Vincent
Richard W. Adler
George F. Munsch

1. INTRODUCTION

This is the second examination of the occupancy and use of selected frequency bands assigned to Wireless Radio Communications at a location in Davis, California. The results presented are preliminary and they represent conditions found at the time and location of the measurements.

Considerable background was accumulated before the start of this series of measurements. The occupancy and use of the 2.4-GHz license-exempt band had previously been explored while setting up a wireless network at a home office (located at 115 Shasta Drive in Davis, CA). In addition the occupancy and use of the 2.4-GHz band was examined during a series of short courses in Wireless Radio Communications at the Naval Postgraduate School held in the years 2003 and 2004. Other less extensive and more exploratory measurements were made in the 915-MHz license-exempt band and in other bands allocated to cell phones and business users.

Only emission properties were examined during these preliminary measurements, and no attempt was made to monitor content.

Simple equipment was used to obtain the occupancy and use results, and this equipment is described in other similar memoranda.

The results described in this memorandum were obtained at a convenient location, the driveway at 1515 Shasta Drive in Davis, CA. This location is about 30 feet from the office measurements described in the first memorandum. One would expect similar results with the exception of changes in emitters in the near vicinity with time. All office wireless equipment was turned off during these new measurements to obtain information about the ambient radio environment. Other local sources such as microwave ovens, portable telephones, amateur radio equipment, and video monitoring devices were also turned off during these measurements. This approach was undertaken to permit the examination of the erratic band-wide pulses that have appeared in the data obtained at the Davis and the Naval Postgraduate School locations with minimal interference from emissions from known and controllable sources.

2. THE 2.4-GHz LICENSE-EXEMPT BAND

The occupancy and use of the 2.4-GHz License-Exempt band was reexamined at the 1515 Shasta Drive, CA location on 28 July 2004. The frequency range of 2400 to 2500 MHz is commonly refered to as the ISM band (allocated to Industrial, Scientific and Medical users). It is also allocated to radio amateurs, government purposes, and other users, and consumer products such as microwave ovens operate in this band. License-exempt wireless radio has been allocated the 2400- to 2483.5-MHz portion of this band, but the users must not interfere with other licensed users and must accept interference from all other authorized services.

Figure 2.1 shows the occupancy and use of that portion of the band allocated to wireless radio along with additional small bands at lower and higher frequencies. Two views of the same data are provided in Figure 2.1. The upper view is similar to the amplitude-vs.-frequency presentation of a scanning spectrum analyzer. The amplitude of each emission at the output terminals of the antenna is provided in dBm across a 50-Ohm load.

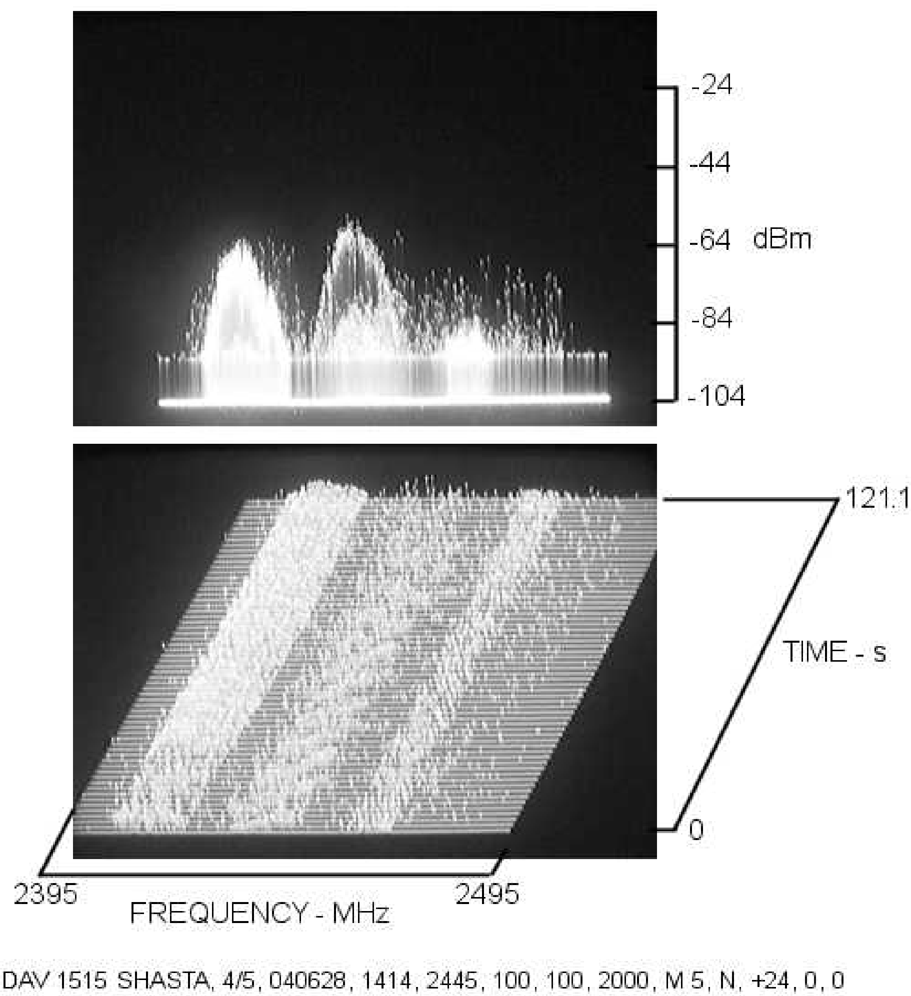

Figure 2.1

Emissions in the 2395- to 2495-MHz Frequency Range, Example 1

The lower view shows a time-history view of 60 successive scans of the spectrum analyzer where new scans are entered into the bottom line and old scans are discarded off the top of the view. The amplitude is severely compressed in the lower view. The frequency range is shown on the bottom view in MHz along with the time required to accumulate 60 successive scans. Since a scanning receiver is used, the frequency scale also represents scan time, a feature highly useful in examining the properties of repetitive pulse signals and impulsive noise.

Since the time-history display is slaved to the spectrum analyzer, the frequency range, time duration, and amplitude range is set by the analyzer controls. The azimuth, elevation, and threshold level of both views is controlled by the display. Thus one can rapidly adjust the analyzer and display controls to best present the characteristics of the emissions received.

A line is provided at the bottom of the view. This line provides the measurement location and the time of the measurement needed to identify each view as well as key instrumentation parameters needed to add frequency, amplitude, and time scales to each item of data.

The bright appearing signal at the lower frequency end of the view is from a nearby telephone system used by the maintenance staff of a nearby business. When not in use the base station emits synchronization pulses at 100-ms intervals. In Figure 2.1, the system was in use and the resulting data pulses fill in the time between the synchronizing pulses. Near the bottom of the time scale of the time-history view, some users quit the system and the synchronizing pulses are distinguishable. The peak amplitude of this signal is about –64 dBm.

The next highest signal is from a nearby point-to-point data-transmission system used by another part of the same business. This system emits synchronization pulses also spaced at 100 ms-intervals. Data pulses obscure the synchronization pulses in this view. The peak amplitude of this emission is about –60 dBm at the measurement location.

Synchronization pulses from a more distant 802.11b wireless radio access point are shown about ¾ the way up the frequency scale. Their peak amplitude is about –83 dBm.

A careful examination of the upper view also shows intermittent and erratic pulses in the upper half of the frequency range and also around the telephone system signal. These impulsive signals were not present during early measurements at this location. Similar erratic pulses have been noted during wireless radio classes at the Naval Postgraduate School in Monterey. The source of these erratic pulses is not known at this time, and they will be investigated during additional measurements at other locations.

Figure 2.2 shows another view of emissions in the same frequency range but at a different time of day. The use of the telephone and data systems was lower during this early evening measurement thus the synchronizing pulses for both emitters are more clearly shown as slanting lines across the time-history view. A fewer number of data pulses occupy the time between the synchronizing pulsed of both signals.

The erratic pulses shown in Figure 1 are also present in this example. In addition, erratic noise from another unidentified emitter covered up the 802.11b signal for about half of the measurement time. It is possible that this additional erratic noise was from a microwave oven located elsewhere in the neighborhood.

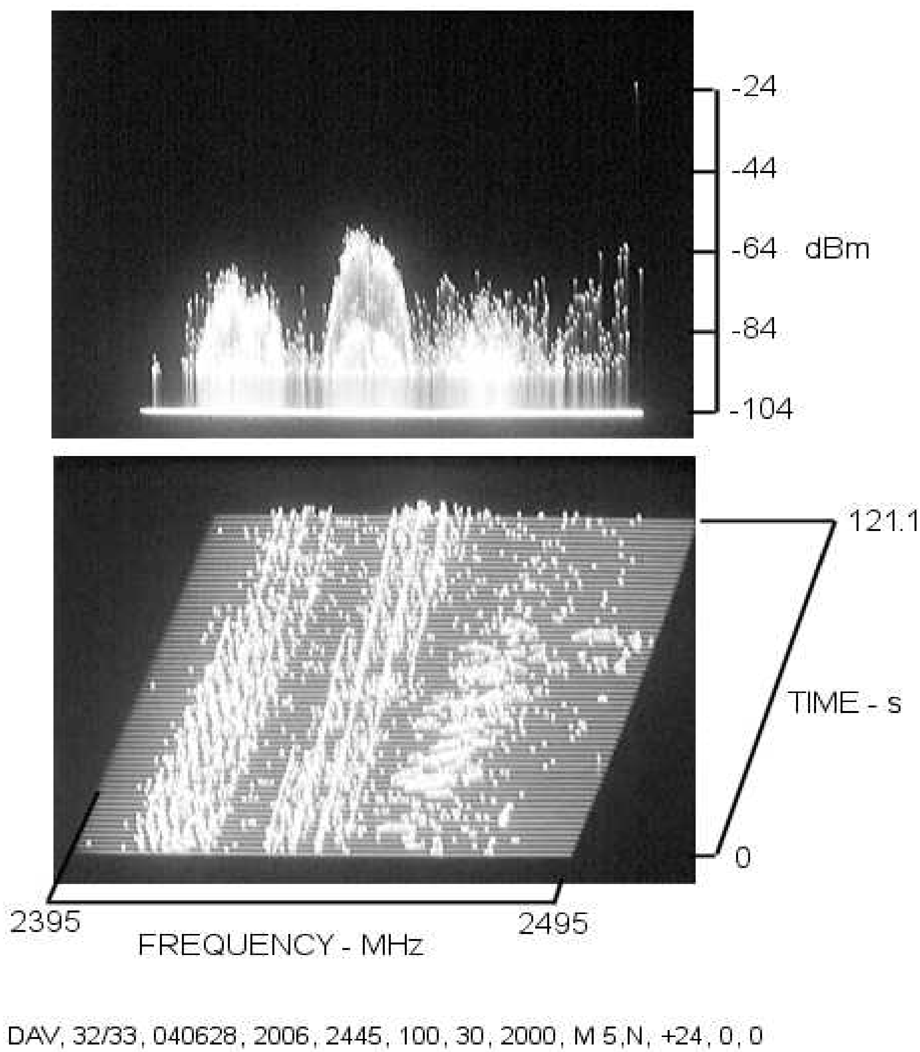

Figure 2.2
Emissions in the 2395- to 2495-MHz Frequency Range, Example 2

The erratic pulses in the upper end of the band were examined in some detail over a period of several hours since their characteristics and sources are not understood. Figure 2.3 shows an example of these pulses over the frequency range of 2470 to 2480 MHz at 1429 local time.

The time-history view shows a high population of single pulses along with a few bursts of multiple close-spaced pulses. The upper view shows their amplitude of is somewhat erratic and with a peak of about –65 dBm. Rotating the azimuth of the time-history view did not reveal any discernable set of synchronizing pulses. The shutdown of all instrumentation components except the preamplifier and the spectrum analyzer suggest that instrumentation sources were not involved.

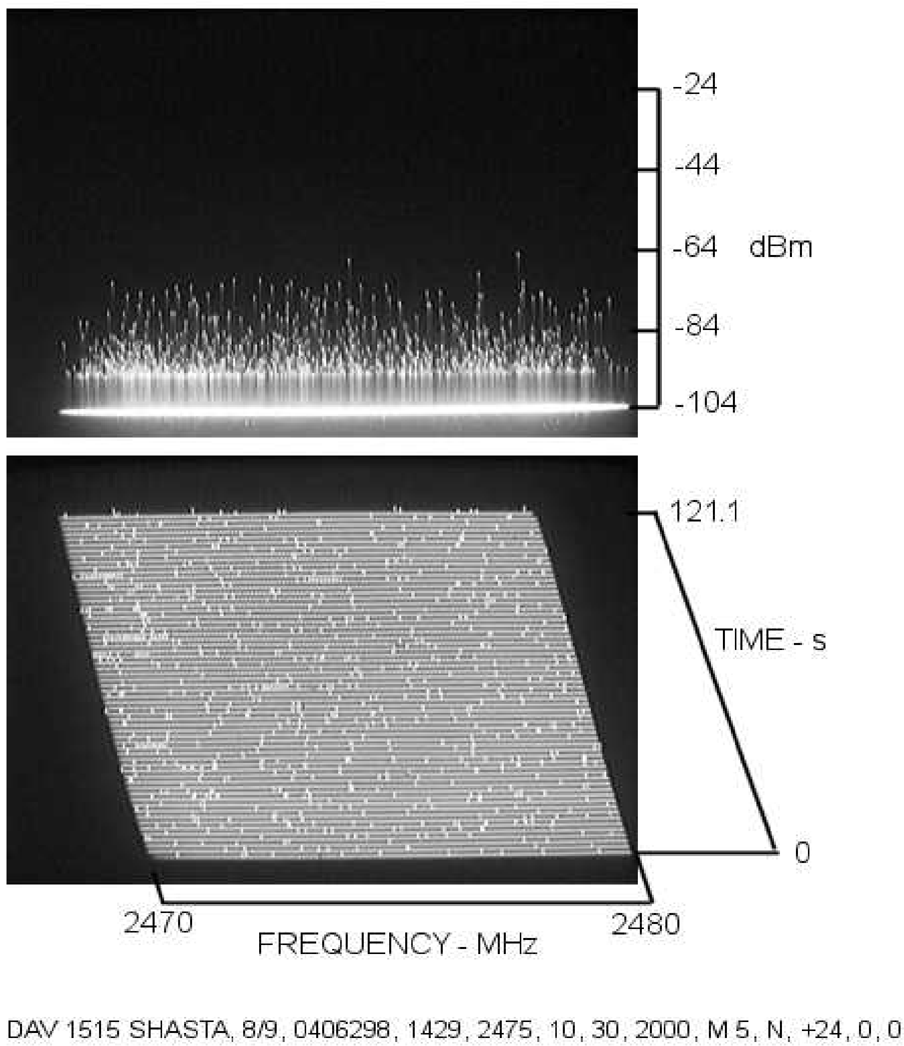

Figure 2.3

Erratic Pulses, 2470 to 2480 MHz, 1429 LT

Figure 2.4 shows another example of the intermittent pulses observed in the upper part of the band. In this example the population of pulse groups was much higher than in the previous figure. The similar properties from group to group suggest they are intended transmissions for some unknown purpose. In this case the amplitude of the pulse groups was generally higher than the more random pulses which also appear in the view. The two emissions appear to be from different sources and for a different purpose. Both cause erratic interference to 802.11b systems operating in the area where the impact is the corruption of data pulses from collisions between the three sources.

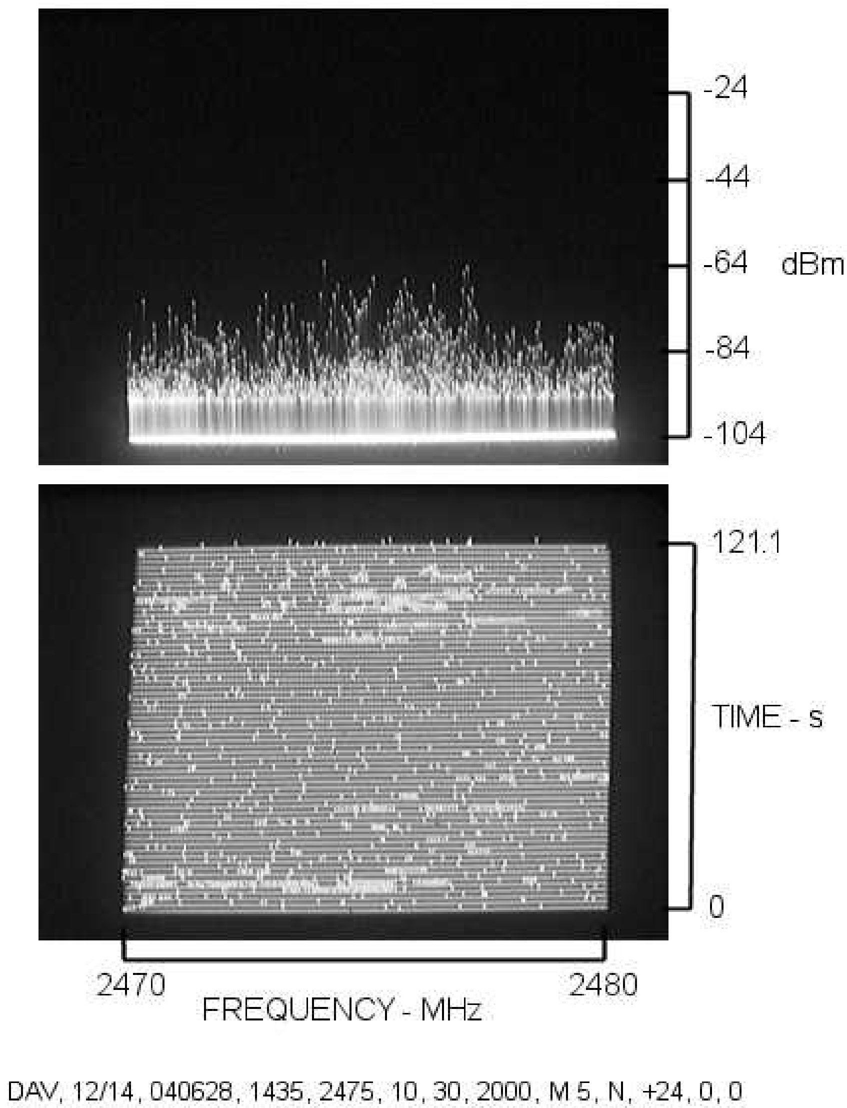

Figure 2.4
Erratic Pulses, 2470 to 2480 MHz, 1435 LT

To better understand the gross temporal structure of the two emissions, four scan lines near the upper part of the time-history view were examined in more detail. Figure 2.5 shows the four scan lines. The upper view shows the amplitude of all pulses in the four scan lines. In the lower view the amplitude of the pulses is compressed about 60 percent. The temporal structure of the bursts of pulses is shown for each scan mixed in with the individual pulses.

The data suggest that the duration and amplitude of the pulse groups is variable. This suggests that multiple sources of the pulse groups may be present. The amplitude variation within a group is likely from reflections from objects in the propagation path between the source and the measurement system.

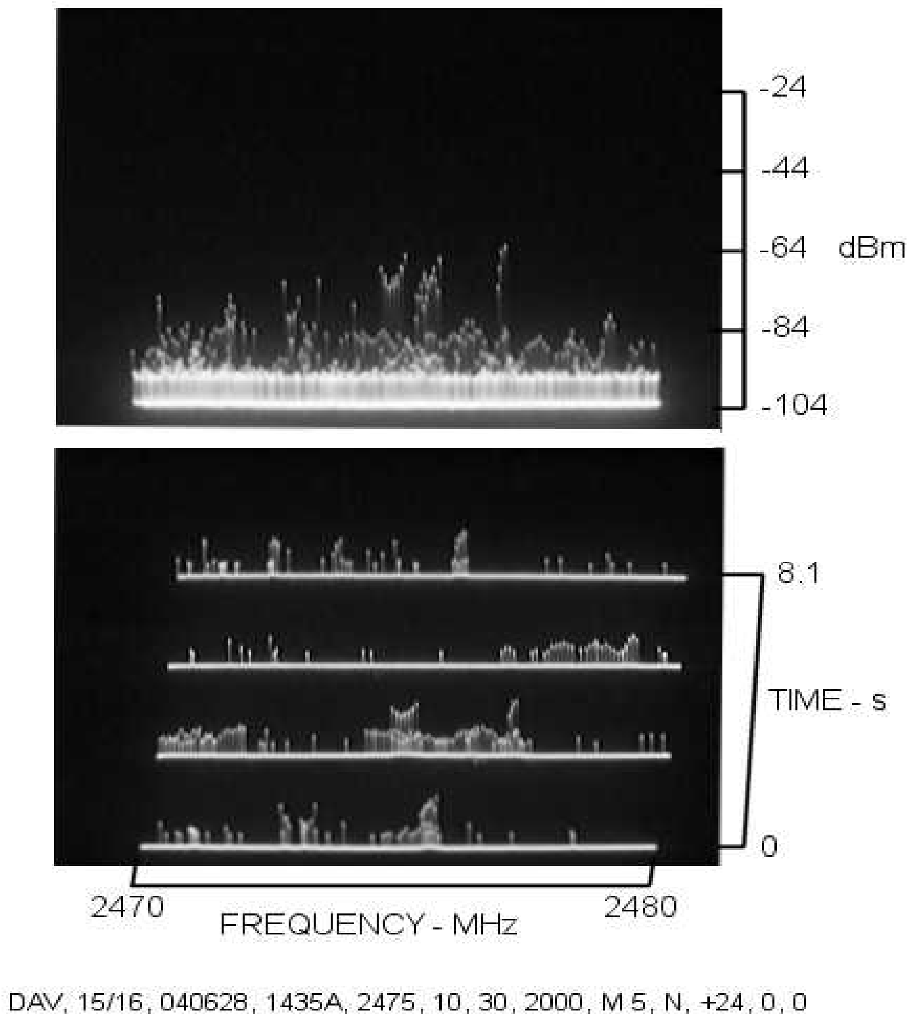

Figure 2.5
Expanded View of Four Scans from Figure 4

Figure 2.6 shows a time of excessive interference in the upper part of the 2400- to 2483-MHz license-exempt band. Two amplitude views are provided in Figure 2.7. The upper view represents the amplitude of emissions in the upper two-thirds of the time-history view. The middle view shows the amplitude of emissions in the lower one-third of the time-history view.

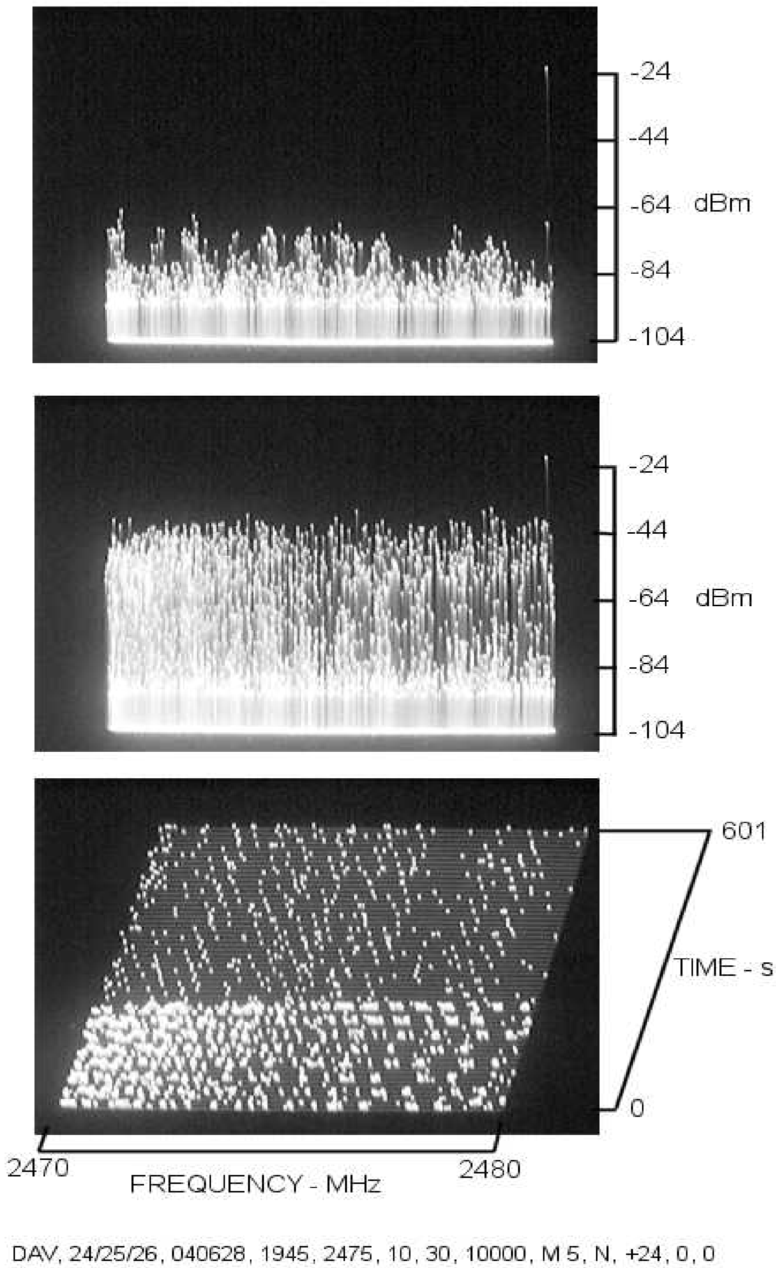

Figure 2.6

Excessive Interference in the Upper Portion of the 2.4 GHz Band

The time-history view of Figure 2.6 shows a continuous record of emission over the 601 seconds duration of the data. During the upper two-thirds of the view impulsive emissions appear as somewhat confused slanting lines, but the lines are not perfectly straight. This implies that the emissions occurred at a nominal spacing close to 450 ms. Some pulse-to-pulse jitter is indicated by the data.

An examination of the top amplitude-vs.-frequency view indicates that the pulses maximized in amplitude in 12 separate frequency bins across the 10-MHz wide band. The peak amplitude of the pulses was about –70 dBm. Pulses between these bins appear to be the random occurring pulses shown in the previous examples.

About two-thirds of the way down the time-history view another set of pulse emissions appeared with a period similar to the lower level pulses. The pulse width of the new emission was considerably wider than that of the narrow pulses of the upper portion of the time axis. Because of the large value of scan time used to obtain the data, the detail of the temporal structure of these wide pulses in not well defined. The peak amplitude of these new pulses was about –42 dBm, almost 30-dB higher than the prior pulses. The clustering of the new pulses into frequency bins was not as apparent as for those in the upper part of the time-history view.

The full width and the gross spectral shape of these pulses are not known because their spectral content was much wider than the scan width used for this example. This is a case where it would have been advantageous to have two instrumentation suites operating in parallel where one could remain with the present settings and the other could be adjusted to define the full spectral content of the two emissions and to explore their fine-scale temporal structures.

Figure 2.8 shows still another example of emissions in the upper end of the band. The erratic pulses continued to be present, but the pulse groups were absent at the time of this example. The amplitude of the pulses was variable, and no distinctive timing pattern could be found.

A single spread-spectrum signal appeared for about 12 seconds near the upper end of the frequency range. The signal is typical of an emission from a portable telephone, but the duration was unusually short for a typical telephone call.

This example is included to show the wide variety of conditions found in the upper part of the 2400- to 2483-MHz license-exempt band which range from a few random pulses to extreme interference levels.

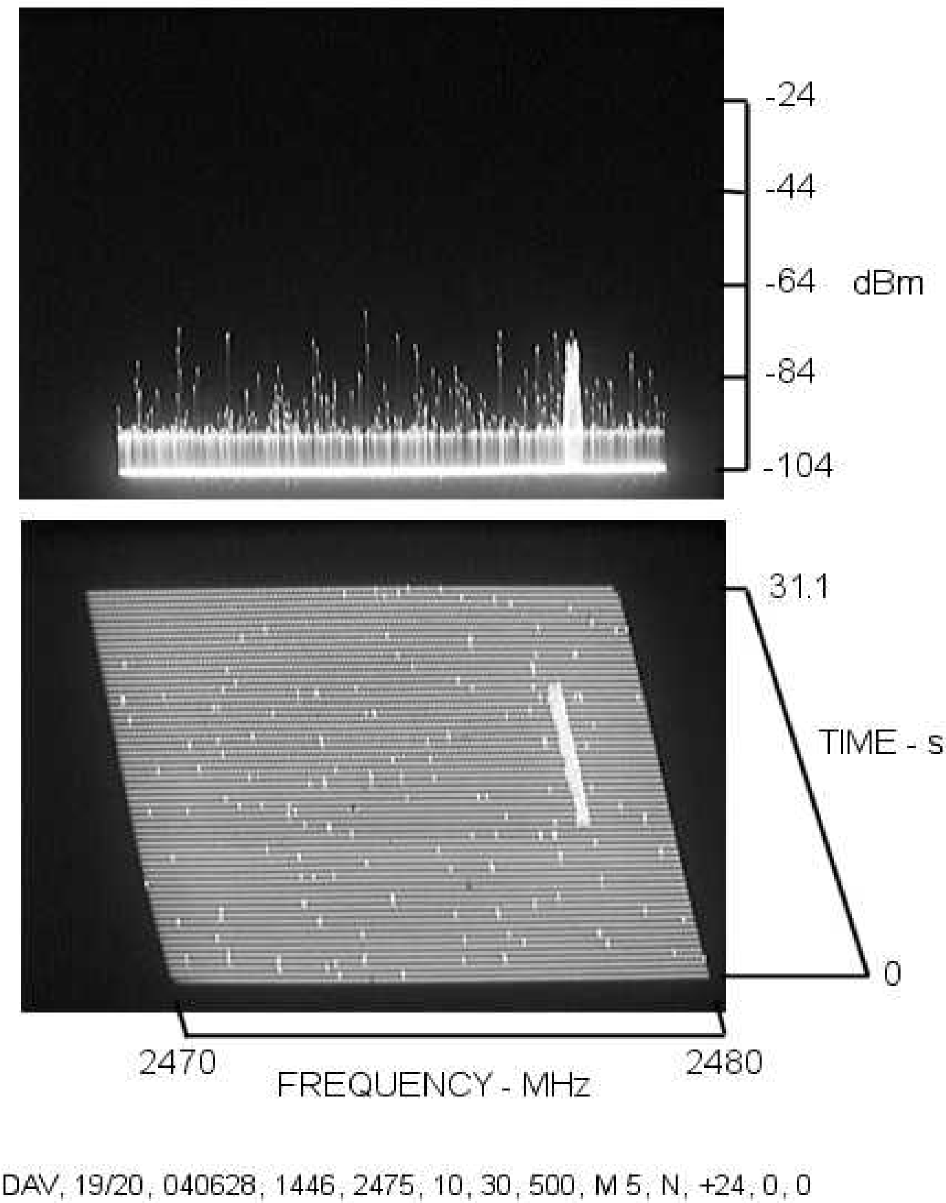

Figure 2.8

Erratic Pulses and a Spread Spectrum Emission, 2470 to 2480 MHz, 1446 LT

SUMMARY COMMENTS

Two items of interest appear in the data for this measurement. First, the erratic appearance of microwave oven noise and other emissions from unknown sources were present. Second, the erratic pulses observed during prior measurements at this location and at other locations were present. Both kinds of emissions caused significant radio interference to the reception of desired 802.11b signals at the driveway measurement location and at the nearby home-office location.

While the sources of some interference and noise are becoming apparent (e.g. microwave oven noise and interference from other 802.11b systems operating on the same portion of the band), the source of the erratic band-wide pulses is not understood. Yet they are a significant source of radio interference to users of the 2.4-GHz band. Several possible sources of these pulses are under investigation as time and resources permits. At first it was assumed they were impulsive intermodulation products similar to those observed from the saturation of non-linear sources near radars on ships. However, these pulses are limited to the frequency width of the 2.4-GHz band. Since filters were not used to limit the frequency range of the instrumentation and the operating bandwidth of the preamplifiers was much larger than the 2.4-GHz band, it is highly unlikely that some other mechanism would limit the spectral width of intermodulation products to the precise width of the 2.4-GHz wireless-radio band. It is more likely that these pulses are emitted from specific devices using the 2.4-GHz band or they are spurious radiation from existing users.

While this measurement effort was limited in the time available for diagnostic purposes, it is clear that the major unidentified impulsive source of noise to signal reception at several locations needs to be identified and understood.

Technical Memorandum
No. WRV 041230

December 2004

A REEXAMINATION OF EMISSIONS IN THE 2.4-GHz LICENSE-EXEMPT WIRELESS-RADIO BAND AT DAVIS, CA

By:

Wilbur R. Vincent
Richard W. Adler
George F. Munsch

INTRODUCTION

A technical memorandum dated October 6, 2002 summarized the occupancy and use of the 2.4-GHz band at a home office location in Davis, CA[9]. The occupancy and use of the band at this location was reexamined in late December of 2004. This memorandum provides the results of the revisit.

The instrumentation and measurement procedures were identical to those used for the initial examination, but the measurement location was slightly different. While the original data was obtained within the home office at 1515 Shasta Drive, the revisit measurements were obtained with the instrumentation in a van that was parked in the driveway of the residence containing the home office. The driveway location is about 30 feet from the home office location along with one intervening exterior wall containing large windows. Only minimal differences in signal strengths were noted for the two locations.

Figure 1 shows a photograph of the van and the roof-mounted receiving antennas.

Figure 1 Photograph of Instrumentation Van

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[9] Wilbur R. Vincent, George F. Munsch, and Richard W. Adler, *Emissions in the 2.4-GHz License-Exempt Band at One Location*, Technical Memorandum, October 6, 2002

Three simple monopole antennas are shown on the roof of the van. They are mounted on a cross arm which is fastened to the roof with two heavy-duty magnets. The 2.4-GHz band antenna is on the left, the 5.6-GHz antenna is in the center, and the 915-MHz antenna is on the right end of the support. Short coaxial cables run from each antenna through the roof vent and down to preamplifiers. The preamplifiers are directly below the antennas to minimize cable lengths.

Figure 2 shows the 2.4-GHz instrumentation mounted on a work table in the van. Standard instruments are strapped to the table to prevent movement and for safety during travel.

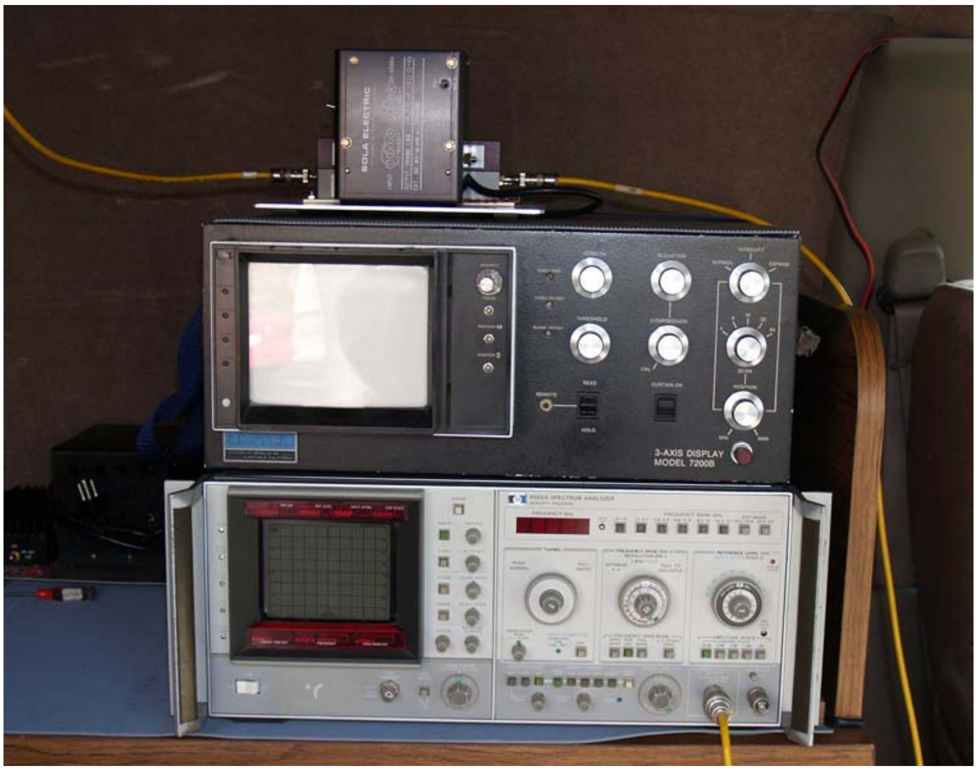


Figure 2 Instrumentation for the 2.4-GHz Band

A high dynamic range preamplifier with a gain of 24 dB is at the top of the instrumentation. The time-history display is the large black instrument, and a Hewlett-Packard Model 8565 Spectrum Analyzer is on the bottom of the suite. A laptop computer and a digital oscilloscope camera is located to the immediate left of the above instruments. Similar instrumentation suites are installed further to the left of the 2.4-GHz suite when simultaneous multi-band operation is desired.

As data is accumulated and recorded, an entry is made in a log. The log contains information such as location, time, and instrument parameter settings. The logs for this measurement period are provided at the end of this memorandum.

As data is prepared for use in a document, information from the log is placed on a line located immediately below the data. Each item of information in this line is separated with a comma. This line contains the following information.

Measurement location, detailed location, picture numbers, date in yymmdd format, local time, center frequency in MHz, frequency span in MHz, scan time in ms, IF bandwidth in kHz, antenna type, filter identification, preamplifier gain, RF attenuation, and IF reference.

A somewhat different format was used in some past data records where the measurement information is listed on four sequential lines. The content is similar to the single line now used.

All temporal and spectral records of data are obtained, processed, and maintained in digital formats. The examples of data shown in this document were recorded with a digital oscilloscope camera developed for this type of data recording. Formatting the views used in this document was accomplished on a computer using standard commercial software.

BAND OCCUPANCY AND USE DATA

The total frequency span of the license-exempt band (2400 to 2483.5 MHz) was examined to obtain some initial information about the number and kinds of signals present at the location and to compare the results with previous measurements. Figure 3 shows the result of the first measurement.

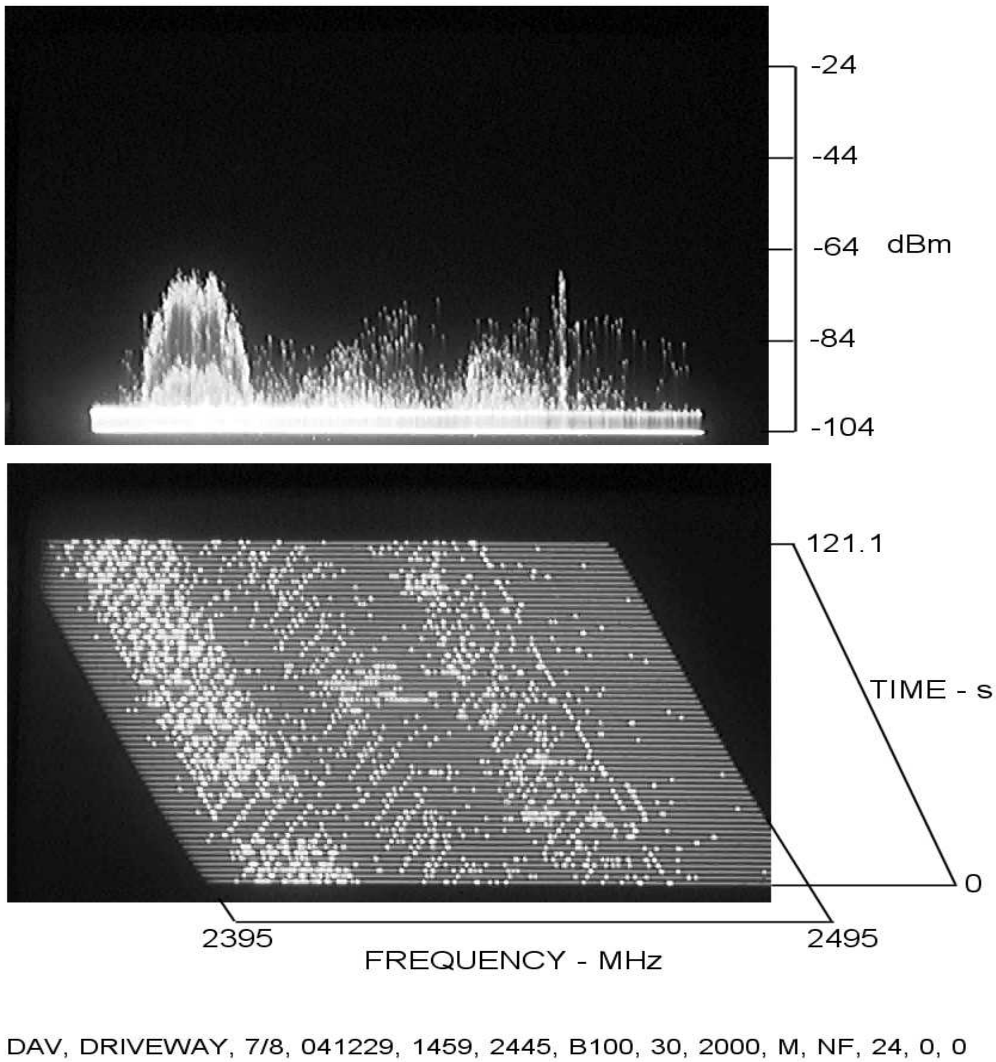


Figure 3 Occupancy and Use, 2395 to 2495 MHz

Two views of the same data are provided where the upper view is similar to the conventional amplitude-vs.-frequency presentation of a scanning spectrum analyzer. The amplitude of all emissions is provided on the right edge of the upper view in terms of signal power delivered by the antenna to the 50-Ohm input of the preamplifier.

The lower view of Figure 3 shows 60 successive scans of the analyzer where new scans are entered into the bottom of the view and the 61st scan is discarded off the top of the time-history view. The amplitude is severely, but not completely, compressed in this view. The slanting lines are generated by the repetitive synchronizing pulses of 802.11b signals interacting with the slow scanning of the spectrum analyzer.

The signal on the left end of the frequency scale is from the base station of a local area telephone system used by the maintenance department of a nearby business. The telephone system was in use for most of the 121.1-second time of the example. Near the bottom of the time-history view the synchronizing pulses from the base station are visible during a brief period of no use. The spectral shape of this emission is shown in the upper view. The amplitude and gross spectrum shape are consistent with prior measurements at this location.

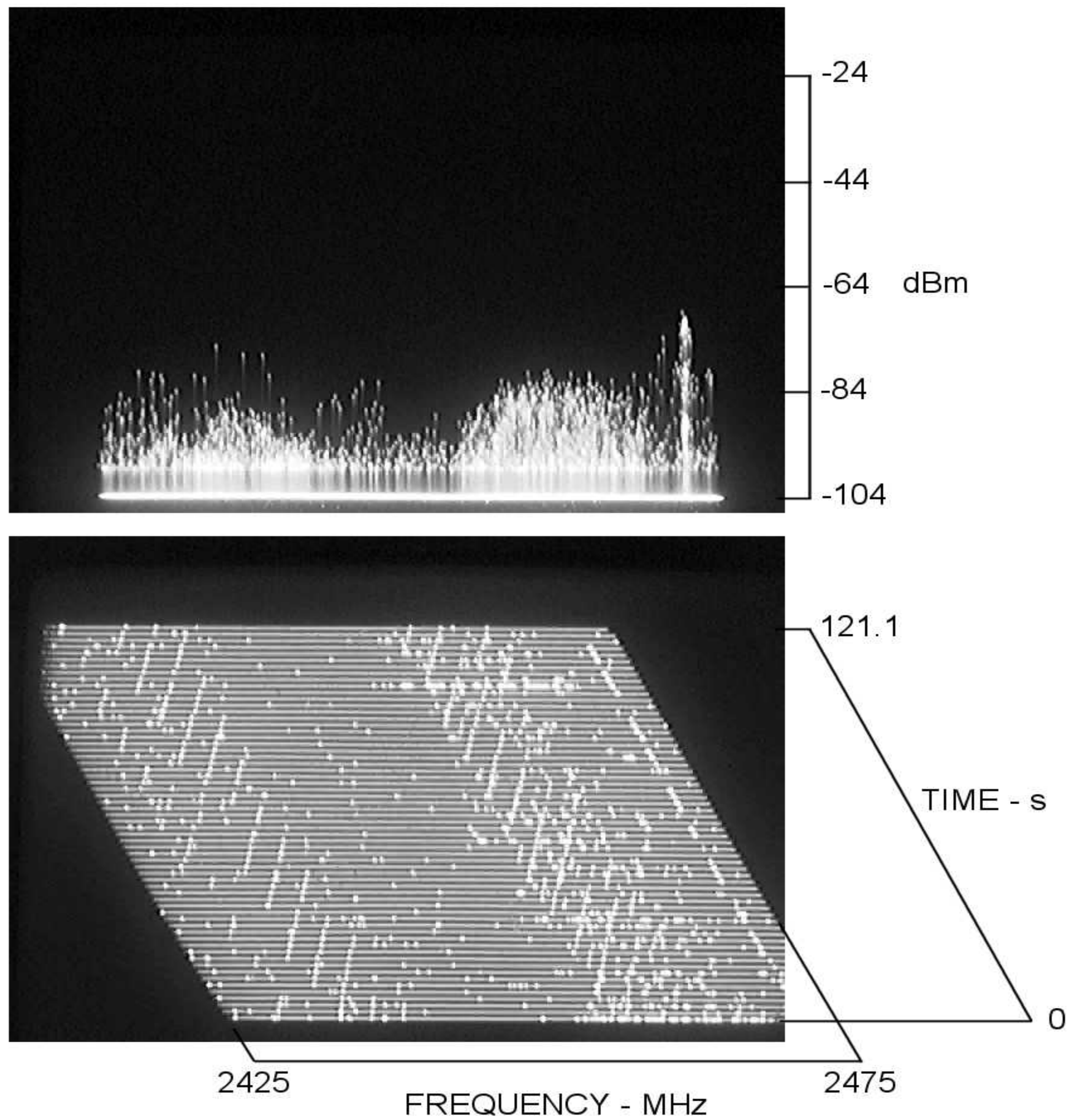
Synchronizing pulses from two 802.11b systems are present in a portion of the band slightly lower in frequency than the center frequency. The shape and spectral width of the two 802.11b emissions is shown in the upper view. It is apparent that neither of the access points for these systems can be accessed at the measurement location because of interference, although the signal strength of both is sufficient for normal reception and synchronization. Any additional system on the same channel, or an adjacent channel, will also experience unacceptable interference. Additional and different appearing impulses can be seen near the center of the time-history axis. These signals overlap a portion of the spectral width of the two 802.11b emissions. This appears to be brief interference from a microwave oven. The location of the microwave oven was not determined.

Two and possibility three overlapping 802.11b signals appear in a frequency band above the center frequency of the data. The spectral shape of these signals is shown in the upper view. These signals are sufficiently separated in frequency from the lower-frequency pair that no mutual interference exists between the two channels. While all individual signals were sufficiently strong that connection with their access points should be possible, such a connection was not feasible due to interference. Again, this channel was unusable at the Davis location.

What appears to be a discrete-frequency signal at an level of about -69 dBm is shown at a frequency near 2472 MHz. This signal appears to turn on and off, but not at even intervals. It will be examined in more detail later in this memorandum.

Still one additional feature is shown by the data. Erratic impulses exist across the entire license-exempt band. These impulses are best viewed in the upper view. Of interest is that these impulses are limited to the 2400- to 2500-MHz portion of the spectrum. These erratic pulses did not appear at this location during earlier measurements, and their source is not known at this time. Such impulses can be caused by very strong in-band or out-of-band pulses that overload the instrumentation, but a careful check of the entire collection of signals impinging on the antenna did not reveal any that would generate impulsive inter-modulation products. Also, It is unlikely that the spectral content of pulses generated by inter-modulation would be limited to the 2400-to 2500-MHz band. They appear to be valid pulses that occur at random times and at random amplitudes. Similar erratic pulses have been noted at other measurement locations, and they are a part of the normal ambient background in this band at many locations. Of interest is that some 802.11b devices have been noted to radiate spurious emissions, including pulses, outside their normal emission bandwidth.

The frequency range was changed to examine a 50-MHz portion of the band centered at 2450 MHz. This range included the 802.11b emissions and the discrete-frequency emission at 2472 MHz. The signal-amplitude threshold of the time-history view was set to show only the strongest synchronizing signals for the lower-frequency 802.11b system. Two sets of synchronizing pulses are shown for the higher-frequency 802.11b signals. Note that random high-amplitude impulses that appear across the entire band.



DAV, DRIVEWAY, 12/13, 041229, 1510, 2450, 50, 30, 2000, M, NF, 24, 0, 0

Figure 4 Occupancy and Use, 2425 to 2474 MHz, Example 2

Five minutes after Figure 4 was obtained, severe microwave-oven interference appeared for one minute. The microwave oven interference is clearly shown in the time-history view, and its erratic amplitude is shown in the upper view. Similar interference from microwave ovens was noted throughout the measurement period.

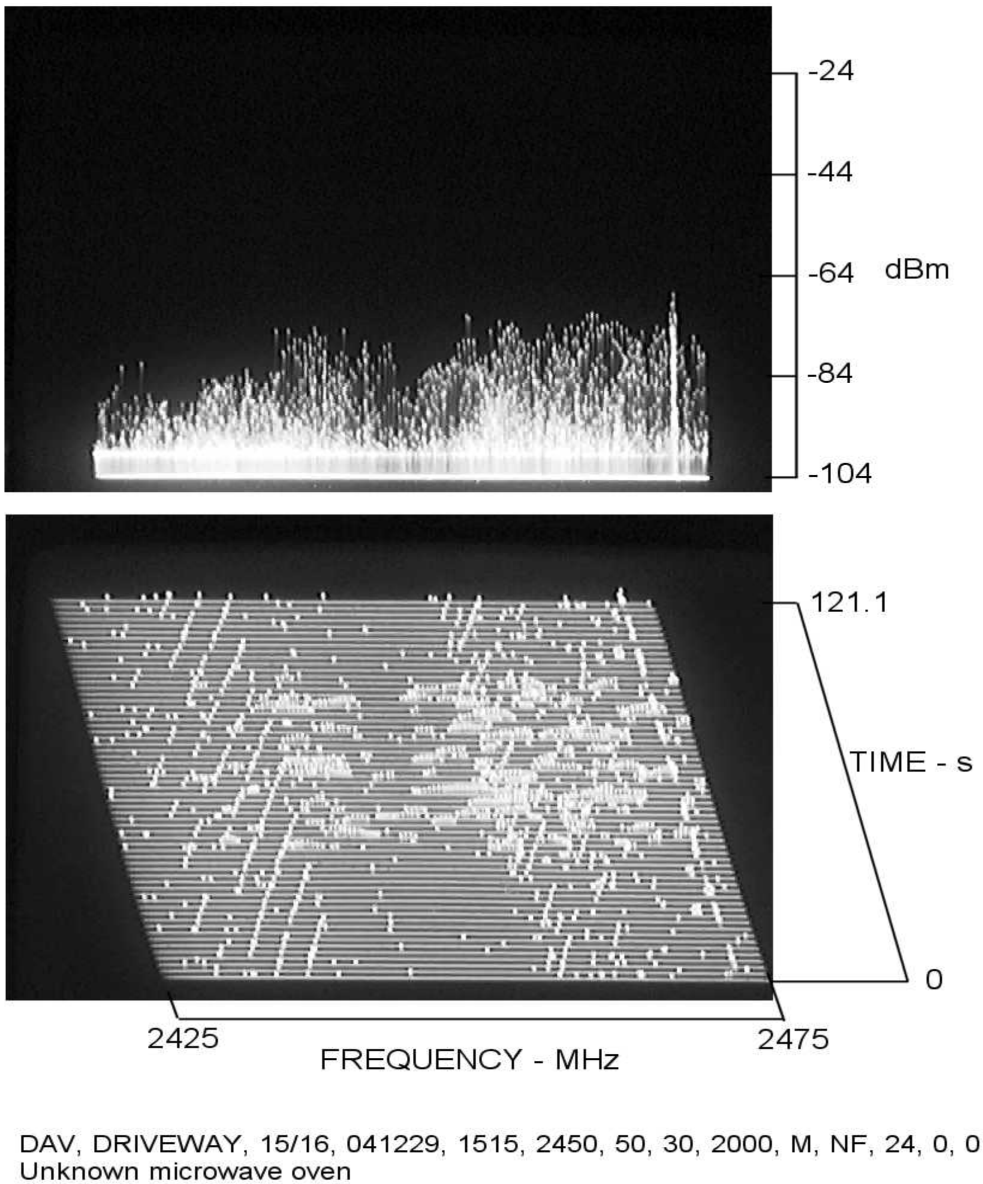


Figure 5 Occupancy and Use, 2425 to 2475 MHz, Example 2

Since several instances of interference from microwave ovens were noted during the measurement period, and the microwave oven in the residence containing the home office was operated. This microwave oven was located 50-ft. from the van's antennas, and the direct path from the oven to the van included a garage and two walls with no windows. Figure 6 shows the result using the same operating parameters as the previous two examples. Severe interference obliterated any possibility of receiving 802.11b signals in the frequency range shown while the microwave oven was operated.

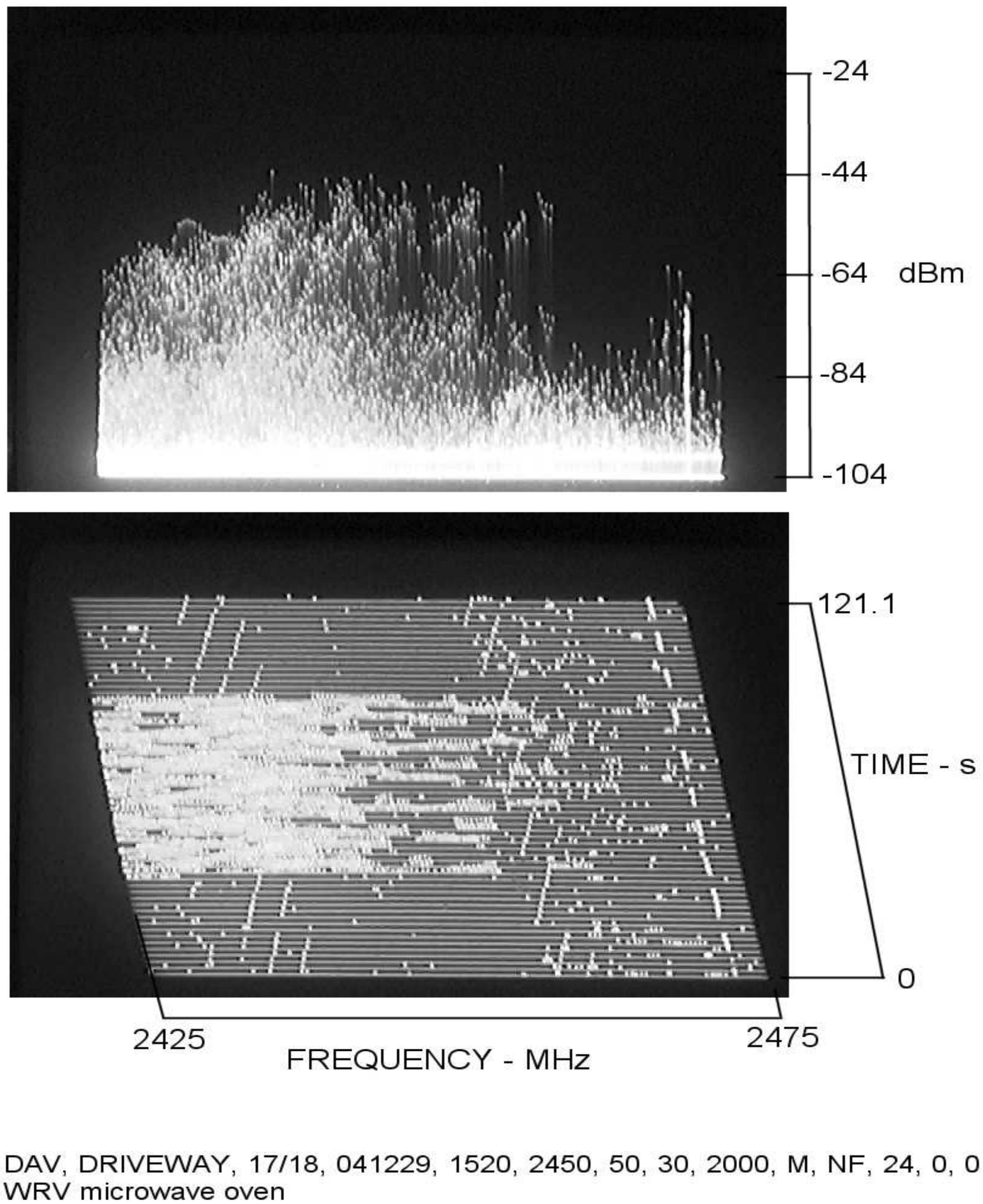


Figure 6 Occupancy and Use, 2425 to 2475 MHz, Example 3

Since only a portion of the license-exempt band was covered in Figure 6, a second run of microwave-oven interference was made using a frequency span of 2400 to 2500 MHz. Figure 7 shows the result. Interference from this microwave oven peaked in amplitude near the center of the license-exempt band, but spectral components of microwave noise were present across the entire band and probably outside the band at both higher and lower frequencies.

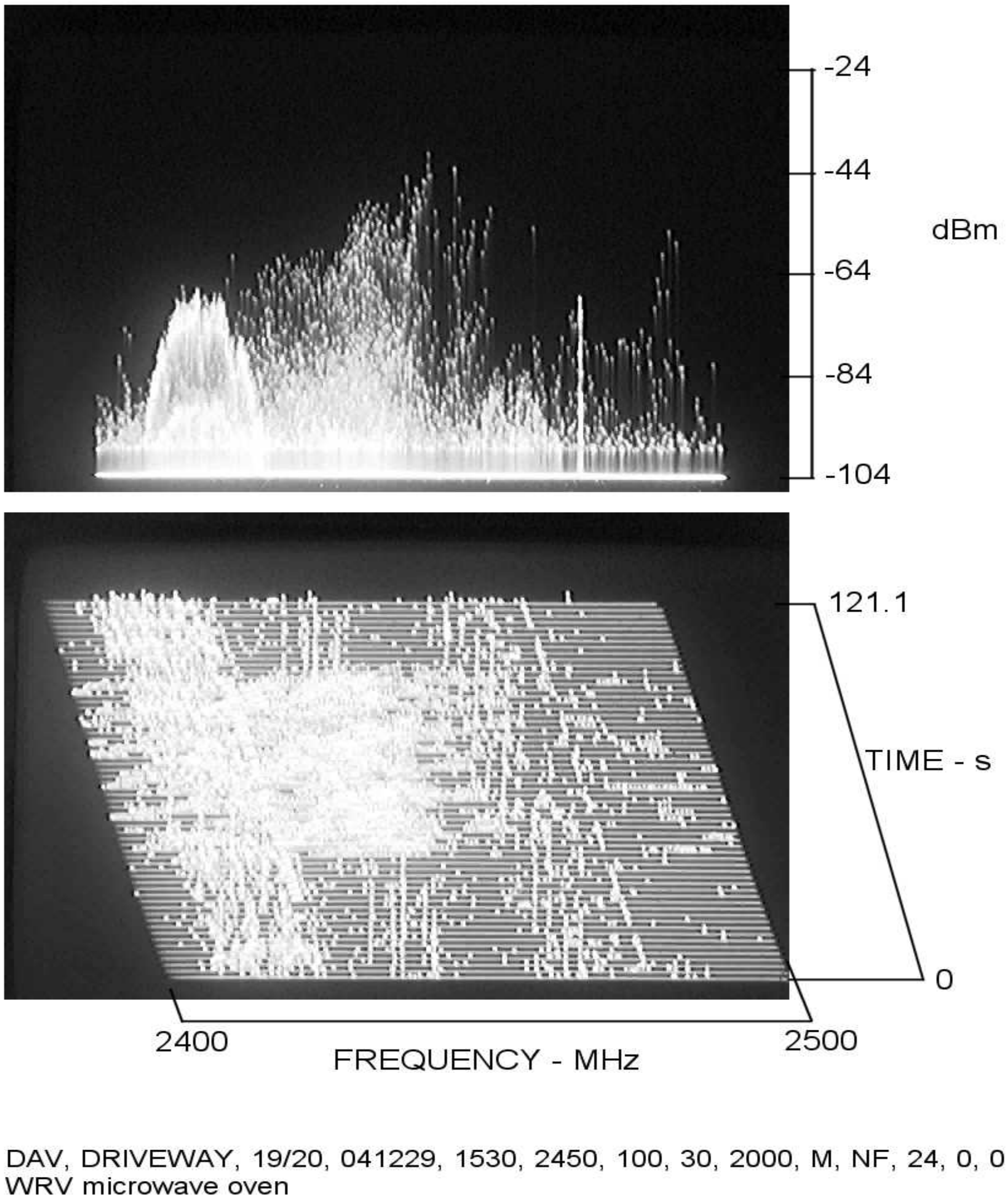
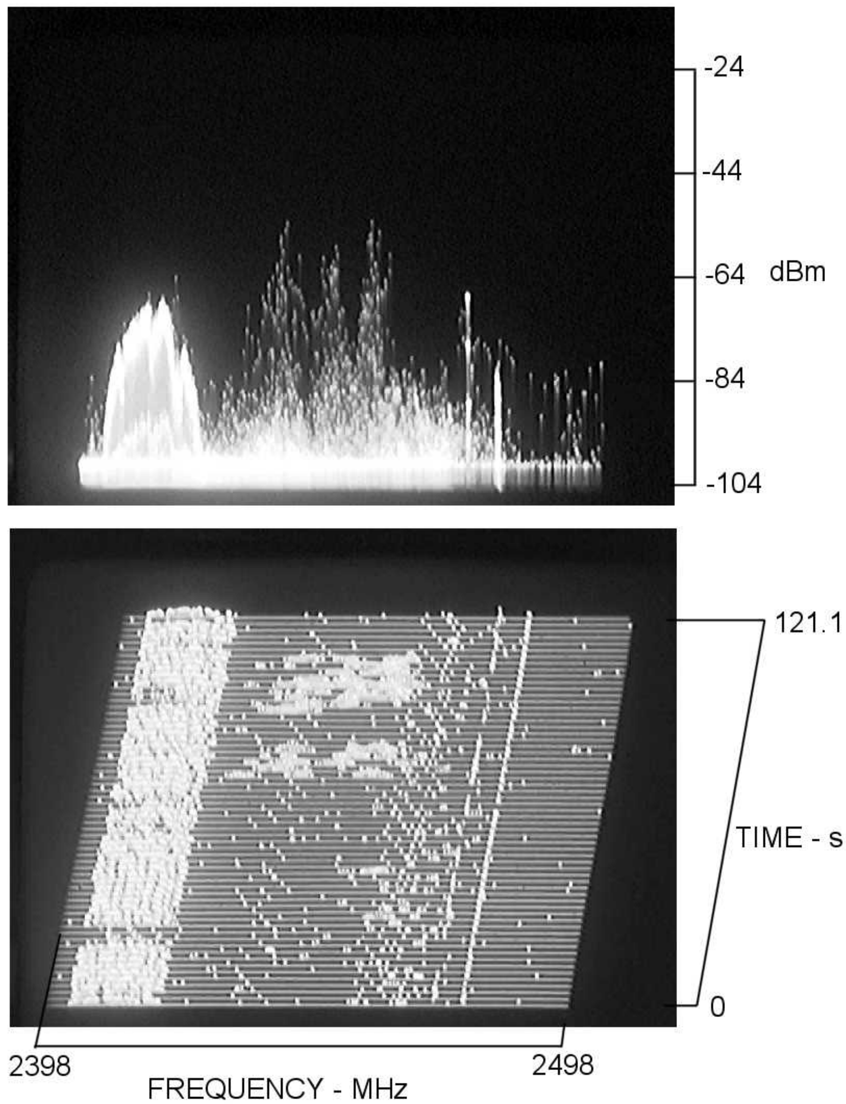


Figure 7 Occupancy and Use, 2400 to 2500 MHz

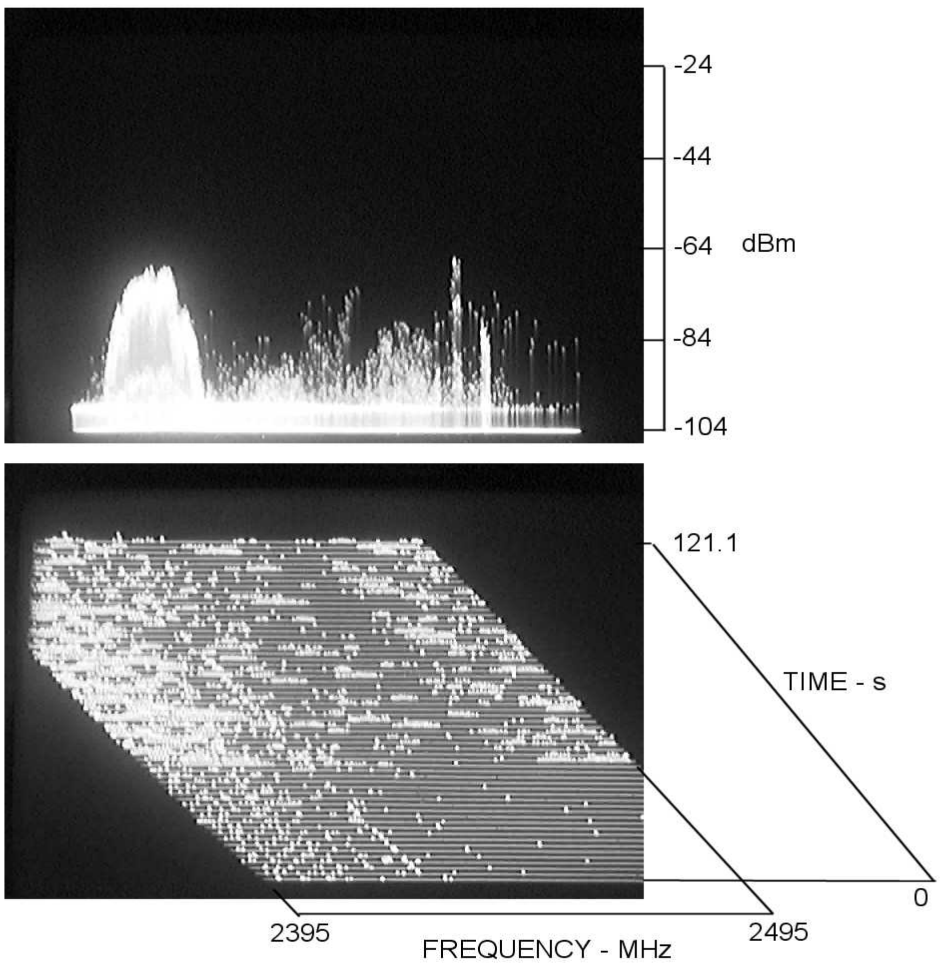
Additional measurements were made on the morning of December 30. Figure 8 shows the result. The signals from the local telephone system and the 802.11b sources were present as well as a two brief periods of interference from a microwave oven. The width of the spectral emission from this particular microwave oven was much narrower than those shown in previous examples, and it did not interfere with the reception of signals from the base station of the local telephone system. A second discrete-frequency signal appeared above the 2472-MHz emission observed on the previous day.



DAV, DRIVEWAY, 22/23, 041230, 1018, 2448, 100, 30, 2000, M, NF, 24, 0, 0
Unknown microwave oven

Figure 8 Occupancy and Use, 2398 to 2498 MHz

The erratic nature of the signal population and interference in the 2.4-GHz band is shown in the next example. Figure 9 shows the state of the band seven minutes after the data in Figure 8 was obtained. Highly erratic microwave-oven interference was found across the entire band for more than five minutes. The example shows when the interference stopped. Of interest is that the spectral content of microwave oven interference is much different than all previous examples noted during this and prior surveys of this band at this location. Since the unusual spectral content of the interference obviously extended to frequencies above and below the 2.4-GHz band, it suggests that a faulty microwave oven probably is within line of sight of the measurement location.



DAV, DRIVEWAY, 24/25, 041230, 1025, 2445, 100, 30, 2000, M, NF, 24, 0, 0

Figure 9 Occupancy and Use, 2395 to 2495 MHz

The temporal and spectral properties of the emission at 2472 MHz were examined in more detail. Figure 10 shows the rather complex result of the examination. The time-history view shows that nine bursts of signal occurred during the 7.1-second measurement period. The duration and spacing between bursts was not constant. Wide-band noise was noted at the start of some bursts but not at other bursts. Each burst was amplitude modulated with a sine wave with a period of about 14 ms (about a 71-Hz rate). The source or purpose of this unusual signal is not known or understood at this time. It is another unusual emission that has recently appeared in the 2.4-GHz band at the Davis location.

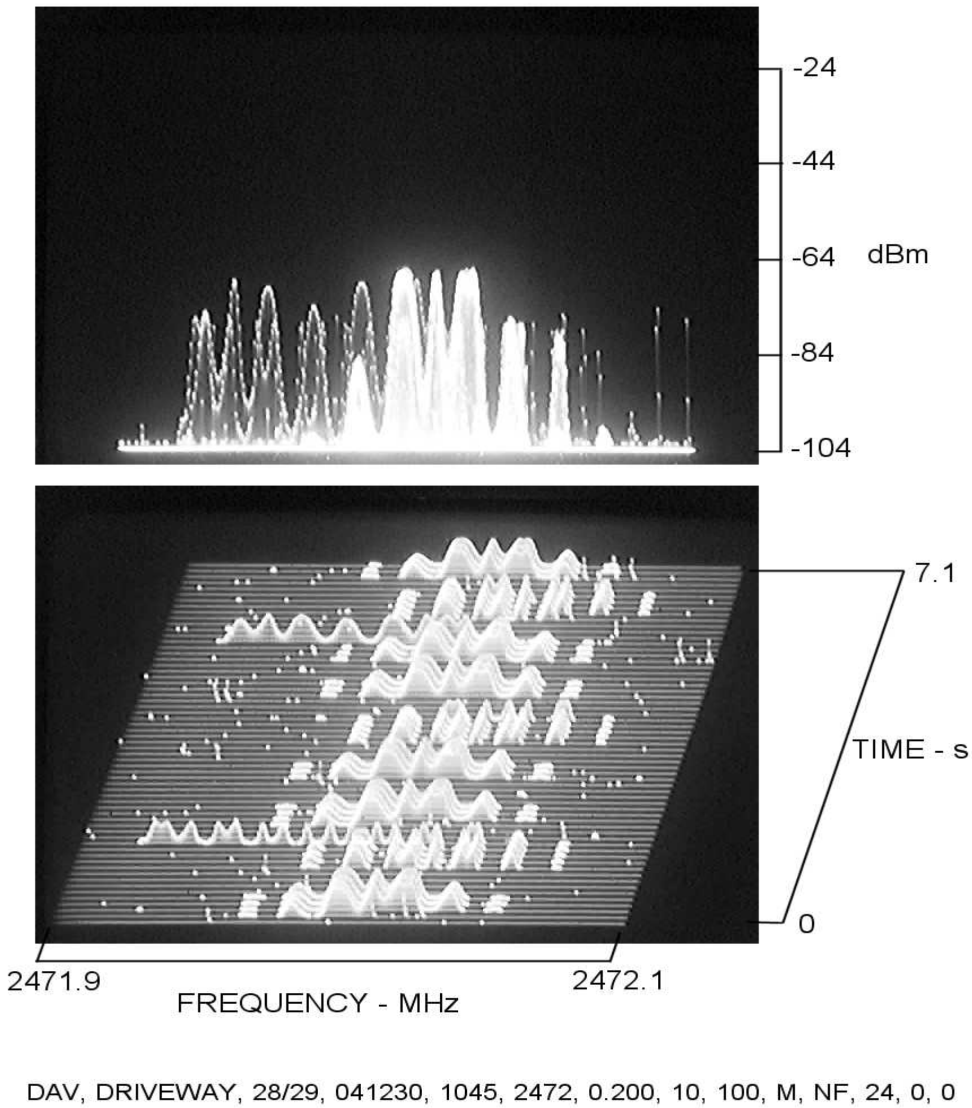


Figure 10 Fine-Scale Temporal and Spectral Structure of 2472-MHz Emission

During the examination of the fine-scale structure of the emission at 2472 MHz a number of unusual bursts of interference were noted. The frequency span was increased from the 0.2-MHz value used for Figure 10 to 1.0 MHz to better examine these bursts. Figure 11 shows the 2472-MHz emission as well as numerous erratic impulses. A few distinctive blobs of white in the time-history view are impulsive interference associated with the 2472-MHz emission. The source of the other impulsive bursts is not known at this time.

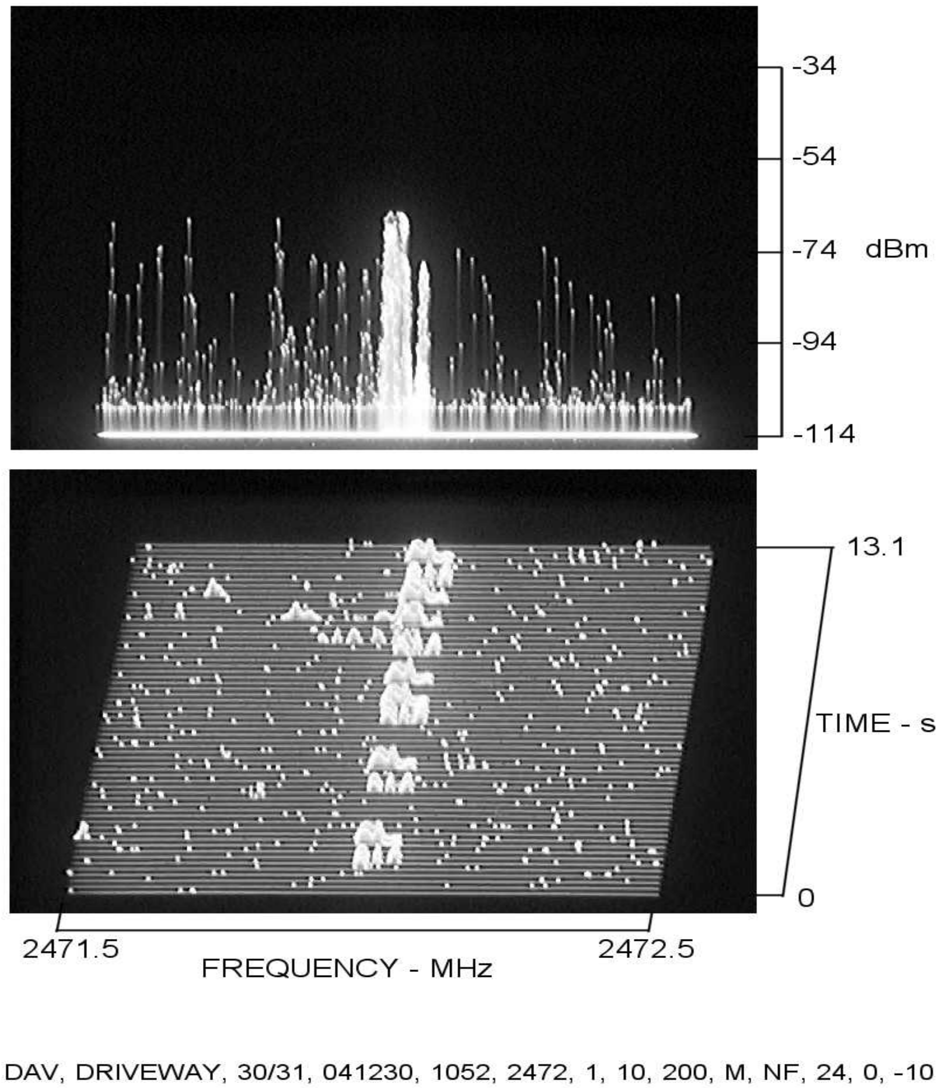


Figure 11 Impulsive Noise Near the 2472-MHz Emission

DISCUSSION AND FINDINGS

The location at 1515 Shasta Drive in Davis, CA has been used for a large number of measurements of the occupancy and use of the license-exempt wireless-radio bands over the past three years. This has included the periodic examination of emissions in each band, a test location for new and modified instrumentation, and as a checkout place prior to making measurements at other locations. Measurements have been made in a home office, at a workbench in the garage, and with the instrumentation installed in a van for mobility. Supplementing this are extensive measurements of the occupancy and use of the 2.4-GHz band during wireless-radio classes at the Naval Postgraduate School in Monterey, CA[10, 11, 12, 13] and special measurements at other urban and remote locations[14, 15]. This particular document describes the results of a revisit to the popular license-exempt 2.4-GHZ band at the Davis, CA location.

A very large number of devices are available at retail stores at low cost for the 2.4-GHz band. They range from the various versions of the popular 802.11 series of wireless-communications devices, video links, portable telephones, special short-range telephone systems, infant-monitoring devices, home-security and business-security devices, and many special purpose devices. Emissions are present in this band from low-power short-range devices using omni-directional antennas as well as point-to-point communications systems using high-gain antennas. Topping this off are the erratic-occurring emissions from microwave ovens the entire 2400- to 2500-MHz band along with random impulsive noise.

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10 Wilbur R. Vincent, Richard W. Adler, and Andrew A. Parker, ***Occupancy and Use of the 2.4-GHz License-Exempt Band during the Wireless Communications Class of March 2003***, Technical Report NPS-03-04, Signal Enhancement Laboratory, Department of Electrical and Computer Engineering, Naval Postgraduate School, Monterey, CA, October 2003

11 Wilbur R. Vincent and Richard W. Adler, ***Occupancy and Use of the +2.4-GHz License-Exempt Band during the Wireless Communications Class of September 2003***, Technical Report NPS-03-05, Signal Enhancement Laboratory, Department of Electrical and Computer Engineering, Naval Postgraduate School, Monterey, CA, October 2003

12 Wilbur R. Vincent and Richard W. Adler, ***Occupancy and Use of the 2.4-GHz License-Exempt Band during the Wireless Communications Class of March 2004***, Technical Report NPS-04-02, Signal Enhancement Laboratory, Department of Electrical and Computer Engineering, Naval Postgraduate School, Monterey, CA, April 2004

13 Wilbur R. Vincent and Richard W. Adler, ***Occupancy and Use of the +2.4-GHz License-Exempt Band during the Wireless Communications Class of June 2004,*** Techncial Report NPS-04-03, Signal Enhancement Laboratory, Department of Electrical and Computer Engineering, Naval Postgraduate School, Monterey, CA, October 2003

14 Wilbur R. Vincent, Richard W. Adler, and Andrew A. Parker, ***Signal Population in the License-Exempt Wireless-Radio Bands at the Mout Site,*** Technical Report NPS-05-01, Signal Enhancement Laboratory, Department of Electrical and Computer Engineering, Naval Postgraduate School, Monterey, CA, April 2004

15 Wilbur R. Vincent and Andrew A. Parker, ***Ambient Signal Population at Three Locations on Camp Roberts,*** Technical Report NPS-04-04, Signal Enhancement Laboratory, Department of Electrical and Computer Engineering, Naval Postgraduate School, Monterey, CA, April 2004

A number of tentative, but important, findings have been reached from this measurement and from supporting data from other measurements. These are:

- The daytime occupancy of the 2.4-GHz band at the Davis location is saturated. While a few narrow-band emissions might be squeezed into the band with proper frequency selection and some tolerance to interference, additional broadband emissions such as another 802.11b emission cannot be accommodated at this location.
- The use of 802.11b devices in the 2.4-GHz band at the home office in Davis has been terminated because of the low data throughput from interference.
- Microwave ovens are a major source of radio noise. Since the temporal and spectral content of this noise changes from one oven to another, its impact on communication-system performance is intermittent and erratic.
- The high amplitude of ambient signals and the high levels of background impulsive noise indicates that any new user at a location must significantly increase received signal strength to obtain sufficient signal-to-interference margin for useful communications success. The most convenient solution is more transmitter power.
- A search of the Internet for high-power amplifiers for the 2.4-GHz band has revealed a number of sources for 5-, 10-, 25-, and 50-Watt amplifiers. It is clear that those determined to join in a signal-to-noise contest can easily obtain the needed amplifiers.
- Some limited success can be obtained using antenna gain at some receiver locations where multi-path propagation is minimal, but this is not the case at the Davis location where most interference paths contain reflections. Antenna directivity at this location was not a practical or effective means to obtain increased signal-to-interference levels.
- This effort was limited to the examination of the occupancy and use of the 2400- to 2483.5-MHz band, with emphasis on the Davis, CA location. A companion and supplementary diagnostic effort including the identification of sources of emissions is required to fully understand the implications of the odd emissions found in the band. Such an effort would necessarily include laboratory work to understand spurious emissions from some sources. This additional effort is beyond the scope of the present work.
- The imprecise term "***interference fog***" is an apt term sometimes used to describe the erratic aspects of radio noise and interference encountered by an existing or a new user. The fog varies with location, time, direction, altitude, density of sources, and receiver bandwidth, where results are usually intermittent, erratic and disorderly.
- Finally, there is no escaping the conclusion that "***old-fashioned radio interference***" is the dominant problem in the use of the 2.4-GHz band at the Davis location. There is much evidence that this is also the case at many other locations. The band is now beginning to be called the "***junk band***", a term that seems appropriate.

Data Log, DAV 1515 Shasta 041229

Location	Pic No.	Date yyy/mm/dd	Time Local	Freq. MHz	Span MHz	BW kHz	Scan T ms	Source	Filter id	Preamp dB	RFAttn dB	Ref. dBm	Comments
Driveway	1	041229	1439	2474	0.200	30	1000	M	NF	24	10	0	
Driveway	2	041229	“	“	“	“	“	“	“	“	“	“	
Driveway	3	041229	1444										Cal Shot
Driveway	4	041229	1454	2445	100	30	1000	m	nf	24	0	0	
Driveway	5	041229	“	“	“	“	“	“	“	“	“	“	
Driveway	6	041229	“	“	“	“	“	“	“	“	“	“	
Driveway	7	041229	1459	2445	100	30	2000	m	nf	24	0	0	
Driveway	8	041229	“	“	“	“	“	“	“	“	“	“	
Driveway	9	041229	1505	2470	50	30	2000	m	nf	24	0	0	
Driveway	10	041229	“	“	“	“	“	“	“	“	“	“	
Driveway	11	041229	“	“	“	“	“	“	“	“	“	“	
Driveway	12	041229	1510	2450	50	30	2000	m	nf	24	0	0	
Driveway	13	041229	“	“	“	“	“	“	“	“	“	“	
Driveway	14	041229	1515	2450	50	30	2000	m	nf	24	0	0	Unknow Microwave Oven
Driveway	15	041229	“	“	“	“	“	“	“	“	“	“	
Driveway	16	041229	“	“	“	“	“	“	“	“	“	“	
Driveway	17	041229	1520	2450	50	30	2000	m	nf	24	0	0	WRV Microwave
Driveway	18	041229	“	“	“	“	“	“	“	“	“	“	
Driveway	19	041229	1530	2450	100	30	2000	m	nf	24	0	0	WRV Microwave
Driveway	20	041229	“	“	“	“	“	“	“	“	“	“	
Driveway	21	041229	“	“	“	“	“	“	“	“	“	“	

Data Log, DAV 1515 Shasta 041230

Location	Pic No	Date dd/mm/yy	Time Local	Freq. MHz	Span MHz	BW kHz	Scan T ms	Source	Filter id	Preamp dB	RF Attn dB	Ref. dBm	Comments
Driveway	22	041230	1018	2448	100	30	2000	m	nf	24	0	0	Unknown Microwave Oven
Driveway	23	041230	“	“	“	“	“	“	“	“	“	“	
Driveway	24	041230	1025	2445	100	30	2000	m	nf	24	0	0	Unknown Microwave Oven
Driveway	25	041230	“	“	“	“	“	“	“	“	“	“	
Driveway	26	041230	1034	2480	50	30	2000	m	nf	24	0	0	Unknown Microwave Oven
Driveway	27	041230	“	“	“	“	“	“	“	“	“	“	
Driveway	28	041230	1045	2472	0.200	10	100	m	nf	24	0	0	Source Not Identified
Driveway	29	041230	“	“	“	“	“	“	“	“	“	“	
Driveway	30	041230	1052	2472	1	10	200	m	nf	24	0	-10	Source Not Identified
Driveway	31	041230	“	“	“	“	“	“	“	“	“		“

APPENDIX B. CLASSROOM MEASUREMENTS

Four documents are provided in this appendix. They are:

Technical Memorandum 0304, ***Occupancy and Use of the 2.4 GHz License-Exempt Band during the Wireless Radio Class of March 2003***

Technical Memorandum 0309, ***Occupancy and Use of the 2.4-GHz License-Exempt Band during the Wireless Communications Class of September 2003***

Technical Memorandum 0403, ***Occupancy and Use of the 2.4-GHz License-Exempt Band during the Wireless Communications Class of March 2004***

Technical Memorandum 0406, ***Occupancy and Use of the 2.4-GHz License-Exempt Band during the Wireless Communications Class of June 2004***

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Technical Memorandum 0304
Signal Enhancement Laboratory
Electrical and Computer Engineering Department
Naval Postgraduate School
Monterey, CA

March 2003

Occupancy and Use of the 2.4-GHz License-Exempt Band during the Wireless Communications Class of March 2003

by:
Wilbur R. Vincent,
Richard W. Adler, and
Andrew A. Parker

INTRODUCTION

This technical memorandum provides a record of the use and occupancy of the 2.4-GHz license-exempt band during a class on Wireless Communications at the Naval Postgraduate School during the month of March 2003. Room 221 of Spanagel Hall was used for the class. Wireless-radio equipped IBM laptop computers were provided for each student, an additional laptop for the instructor, and two spare laptops for class monitors (a total of 28 laptops). The twenty-eight laptops operated into a single 802.11b Access Point located on the wall of the classroom. The Access Point was connected to a server at NPS that stored all instruction and class-generated material, and made the material immediately available to each student.

The data in this memorandum supplements similar data provided in earlier documents.[16, 17] The purpose of these documents is to obtain an understanding of the use and occupancy of the license-exempt wireless-radio bands at a number of locations. Additional memorandum will be added to the list as new locations and new situations are examined.

The widespread availability of low-cost wireless-radio devices and the absence of the cost of obtaining a traditional license for each user or group of users has resulted in a flood of emitters into the license-exempt bands. Fortunately, the limited coverage of each emitter allows for the geographic reuse of each band, but little is known about the actual use and occupancy of the bands at any specific location or area. While numerous anecdotes of both successes and problems with license-exempt wireless radio have been reported, few are supported by sufficient technical data to permit a realistic evaluation of either the successes or the problems.

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[16] Wilbur R. Vincent, George F. Munsch, and Richard W. Adler, ***Literature Search of the Impact of Noise on Wireless Communications,*** Technical Report, June 2002, Prepared for the Federal Communications Commission, Washington D.C., Signal Enhancement Laboratory, Department of Electrical and Computer Engineering, Naval Postgraduate School, Monterey, CA.

[17] Wilbur R. Vincent, George F. Munsch, and Richard W. Adler, ***Emissions in the 2.4 GHz License-Exempt Band at one Location,*** Technical Memorandum, November 2002, Signal Enhancement Laboratory, Department of Electrical and Computer Engineering, Naval Postgraduate School, Monterey, CA

INSTRUMENTATION

The instrumentation used to collect classroom data is similar to that previously used for the measurement and definition of radio noise in other parts of the radio spectrum.[18] It consists of available components assembled on a laboratory cart for portability. Figure 1 shows a block diagram of the instrumentation.

For most measurements a small stub antenna similar to those used on wireless radio systems was used to collect emissions. Other antennas can be used for special measurements. When necessary a filter can be used to exclude high-level out-of-band signals and ensure that no component in the measurement system is saturated. A high-dynamic range preamplifier with a gain of 24 dB was used for all measurements to achieve a measurement system sensitivity about equal to that of a standard receiver. While the 12-dB noise figure of the preamplifier was higher than desired, it was used in preference to a lower noise figure preamplifier with less dynamic range to ensure that saturation did not occur at any time during the measurements.

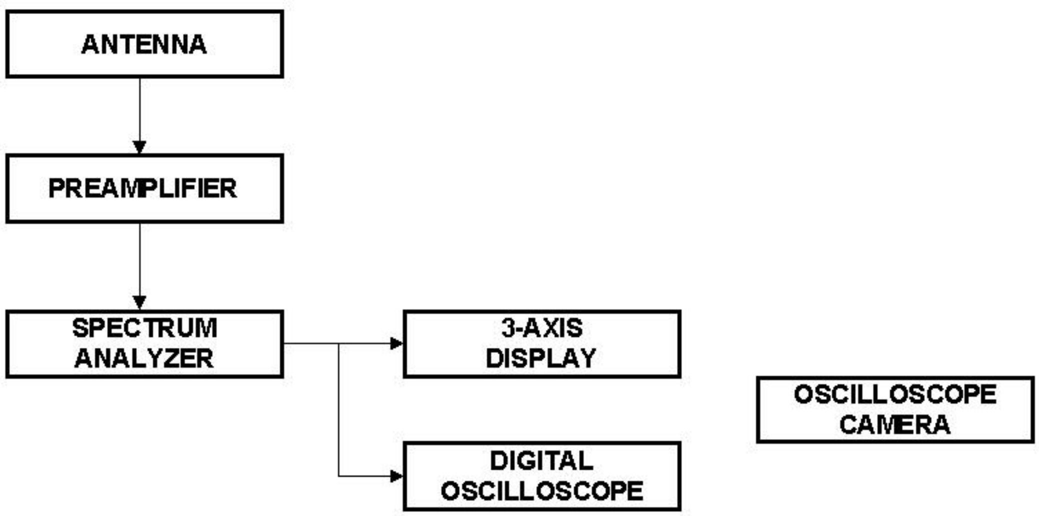


Figure 1
Block Diagram of the Instrumentation

A relatively old spectrum analyzer (HP Model 8565A) was used since its time between scans was lower than for newer models and its manual controls permit the rapid adjustment of the analyzer to cope with frequent changes in the content of emissions. An ELF Engineering Model 7200B 3-Axis Display was used to provide a visual time-history presentation of emissions in the band or in any desired portion of the band. It provides the ability to observe and document the detailed spectral and temporal structure of received emissions.

[18] Wilbur R. Vincent, Richard W. Adler, and George F. Munsch***, An Examination of Man-made Radio Noise at 37 HF Receiving sites***, Document No. NPS-EC-05-003, Signal Enhancement Labpratory, Department of Electrical and Computer Engineering, Naval Postgraduate School, November 2004

A small table containing pertinent measurement parameters accompanies each item of data. The parameters are listed in Table 1.

Table 1
Measurement Parameters

Line 1	Date in yymmdd format, local time in 24 hr. format
Line 2	Site identification,
Line 3	Center frequency, scan width, IF bandwidth, scan time*
Line 4	Antenna i.d., filter, preamplifier gain, RF attenuation, IF gain
Line 5	Additional information

* (LS) is appended when line synchronization is used

Figure 2 is a photograph of the instrumentation used to collect the band use and occupancy data provided in this memorandum.

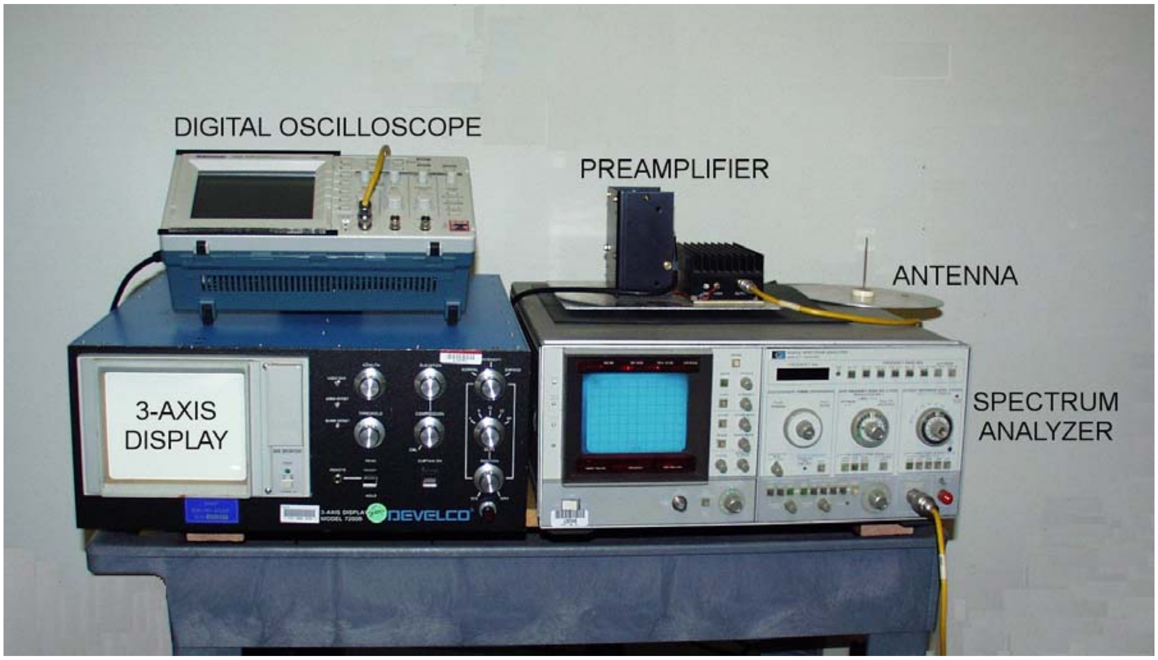


Figure 2

Photograph of Instrumentation

COMMENTS ABOUT THE DATA

The instrumentation was located and operated in a small storage area at the rear of the classroom. One wall separated the instrumentation from the classroom. The nearest laptop was about 15 feet from the instrumentation while the furthest was about 30 feet from the instrumentation. The Access Point was about 25 feet from the instrumentation. This arrangement allowed data to be collected without interruption to normal class activities. Examples of data collected are provided to illustrate conditions encountered by the classroom network.

Example 1 (030326 0822) shows two views of the same data. The upper view shows an amplitude-vs.-frequency presentation. The vertical scale provides signal power delivered from the antenna to the 50-Ohm input of the preamplifier. The lower view shows a time-history view of data collected for 60 successive scans of the spectrum analyzer. In the bottom view the amplitude has been severely, but not completely, compressed. The horizontal axis is slightly rotated to best portray the temporal structure contained in the view.

The upper view shows the spectral shape of the combined emissions of all laptops and the Access Point integrated over the 61.1-second duration of the data. The 22-MHz width of the primary spectral component of the 802.11b emissions is shown along with lower amplitude spectral side bands on each side of the primary emission. These side bands are about 35-dB below the main spectral component. A small bump at a lower frequency is the emission from a portable telephone with a spread-spectrum (SS) emission that is much narrower in frequency than the 802.11b emission.

The lower view is a time-history presentation of the same data as that in the upper view. At the top and the bottom of the time-history view, the 802.11b net was lightly used. The slanting lines across the view are synchronization pulses from the Access Point emitter. These pulses are spaced at approximately 100-ms intervals. The more random pulses associated with the 802.11b emissions are a collection of data pulses from all of the classroom computers. The dense area at the middle part of the time-axis shows a time of heavy use of the classroom network by most of the laptops. The bright line at a lower frequency and parallel to the time-axis is the spread spectrum emission from a nearby wireless device. The weak signal suggests this was a low-power device located some distance from the classroom. It and other such emissions appeared at intermittent times during all of the class sessions.

The slanting lines are caused by the reception of the broadband synchronization pulses (with a constant period) from the Access Point interacting with the slow scan rate of the analyzer. Multiple pulses are received during each scan. Since the pulse rate and the scan rate are not in synchronization, the synchronization pulses are received at a slightly different time for each scan of the analyzer. The accumulation of repetitive pulses over time (60 scan lines) results in the slanting lines. The use of scan-time information, in addition to the conventional spectral information produced by a spectrum analyzer, provides a potent means to examine and document the temporal and spectral details of many types of emissions as well as any time-varying aspects of portrayed emissions.

Example 2 (030326 0930) shows the activity in the band slightly over an hour later in the day. The classroom 802.11b emission is slightly below the center of the frequency axis of the upper view. A SS signal from a portable telephone was injected into the band near the center of the frequency range. The amplitude of this emission is about the same as that of the 802.11b emission. In addition a second 802.11b net was operated just outside the classroom on a higher-frequency channel. This signal did not interfere with the classroom net due to a sufficient frequency separation of the two nets.

The lower side band of the classroom 802.11b emission appears to be higher than shown in Example 1. This is because still another 802.11b net was operating at a more distant location whose primary spectral component was centered at the frequency of the lower side band of the classroom 802.11b signal. Several such nets operate within Spanagel Hall and other nearby buildings, and this particular net was present during most of the class periods. This net caused some interference to the operation of the classroom net.

One additional signal was present at the time of this data. It was a frequency-hopping, spread-spectrum (FHSS) emission from another model of a portable telephone. The signal hopped over the entire 83.5 MHz width of the wireless-radio band. This signal is quite dim in the amplitude-vs.-frequency view, but it can be identified by a careful inspection of the data.

The lower view of Example 2 shows additional information about the collection of emissions present at the time of the data collection. The classroom 802.11b emission and the SS telephone emissions are shown near the center of the frequency axis. A series of slanting lines starts at the bottom of the time-history view and progress from the lower left upward across the entire view. These slanting lines are obscured in the center of the frequency axis by the classroom 802.11b and SS telephone signals. These slanting lines are synchronization pulses from the 83.5-MHz wide emission from the FHSS telephone.

Another set of slanting lines appears at the right of the SS telephone signal. These lines start at the right side of the SS signal and run downward to the right as the time scale approaches lower values. These lines are from the synchronizing pulses of the second 802.11b net.

Example 3 (030325 1024) provides another view of the occupancy and use of the band during the mid morning. The emission from the classroom net is similar to that in the prior examples. In addition, a new spread-spectrum telephone signal (labeled SS-2) appeared at the lower edge of the classroom network emissions, and it is only 9-dB lower in amplitude than the classroom 802.11b signal. Another SS telephone emission (labeled SS-1) is somewhat higher in frequency than the classroom net and did not interfere with the operation and performance of the net. In addition, the FHSS telephone was turned on about ¼ of the way down the time axis of the time-history view, and it remained on for the rest of the observation period.

Example 4 (030325 1124) was obtained during the class lunch period (1100 to 1200 LT), and it shows a different kind of interference. Synchronizing signals from the Access Point continued to be noted since it was not turned off during the lunch period. About ¼ of the way down the time axis of the time-history view, noise from a microwave oven appeared and remained on during the remainder of the observation period. A careful scaling of the time between the microwave oven noise impulses shows their spacing is 16.6 ms, the period of the local power frequency. The spacing is an indicator that the source of the emission was powered by an unfiltered half-wave power supply. In addition, the shape of the spectral component of the noise is typical of that from a microwave oven. Someone in the building, or a nearby building, used a microwave oven to heat their lunch.

Bursts of noise from another source appeared within the bandwidth of the classroom 802.11b net. The duration of these pulses was much longer than the synchronizing pulses, and the time of occurrence was highly erratic. The source of this highly objectionable noise was not located during the class.

Emissions from the other net slightly lower in frequency also appeared in this example. An inspection of the synchronizing signals in the time-history view shows a second set of such signals just below each slanting line from the class net.

Example 5 (030325 1142) provides yet another view of the microwave oven noise. In this case the microwave oven was operating at the top of the time-history view, turned off about 1/3 of the way down the time axis, was off for about 20 seconds, turned back on and remained on at the end of the observation period. The upper view shows the typical shape of the primary spectral component of a microwave oven. This view shows the erratic and time-changing nature of interference from microwave ovens.

The slanting lines from the synchronization pulses of the classroom 802.11b net are shown in the time-history view along with a second set of slanting lines from the other nearby 802.11b net. The heavy blobs in the center of the signal from the classroom net are from an unknown source of interference.

Example 6 (030325 1146) shows still another example of interference from a microwave oven and the wide-pulse interference. In this case the microwave oven started operating about ¾ of the way up the time-history scale and it remained on for the remainder of the observation period. The slanting lines from the classroom 802.11b synchronization pulses are shown as well as those from the second 802.11b net in the lower ¾ of the time-history view.

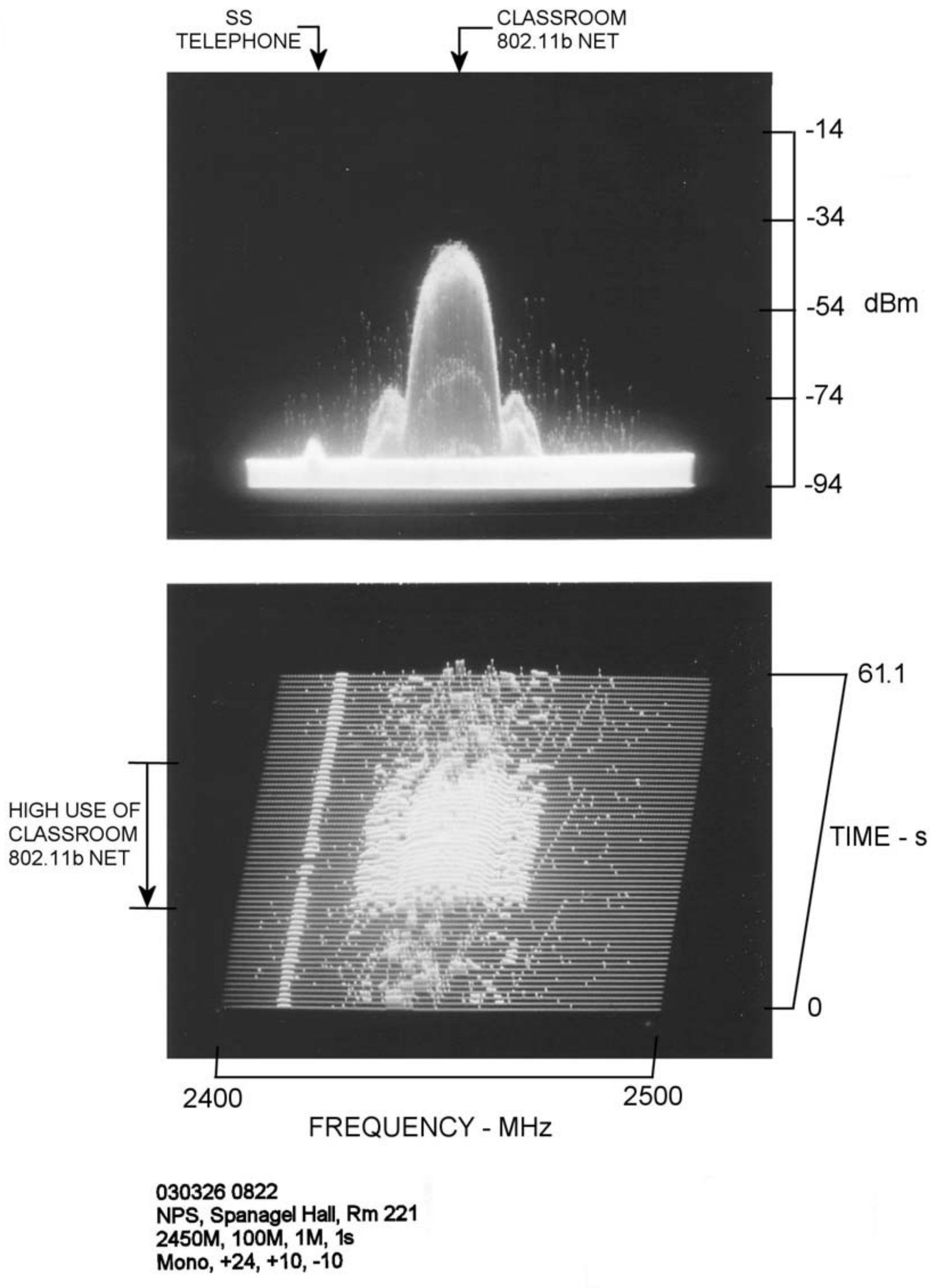
Example 7 (030326 0834) was obtained using a frequency span of 50 MHz in place of the 100-MHz span of the prior examples. This provides an expanded view of the spectral components of all emissions within the span. The spectral shape of the primary component of the classroom 802.11b emissions is shown along with its upper side band. The center of the primary spectral component of the second 802.11b emission is on top of the lower side band of the classroom signal. The synchronization pulses of the two emissions are separated in the time-history view.

A spread-spectrum signal from a portable telephone appeared at the upper end of the frequency scale slightly more than 1/3 of the way down the time axis. Random pulses from other sources exist across the band and for the entire observation period.

Example 8 (030326 0944) shows an example of the time-varying temporal structure of emissions within a 1-MHz bandwidth centered at 2400 MHz. The frequency-scan process of the spectrum analyzer was set at zero to obtain this example; therefore, it shows a succession of oscilloscope type of views of emissions over the 61.1-second measurement period where the sweep time of the oscilloscope was 1 second. The synchronization pulses of the classroom 802.11b net are shown as the short pulses spaced at 100-ms intervals.

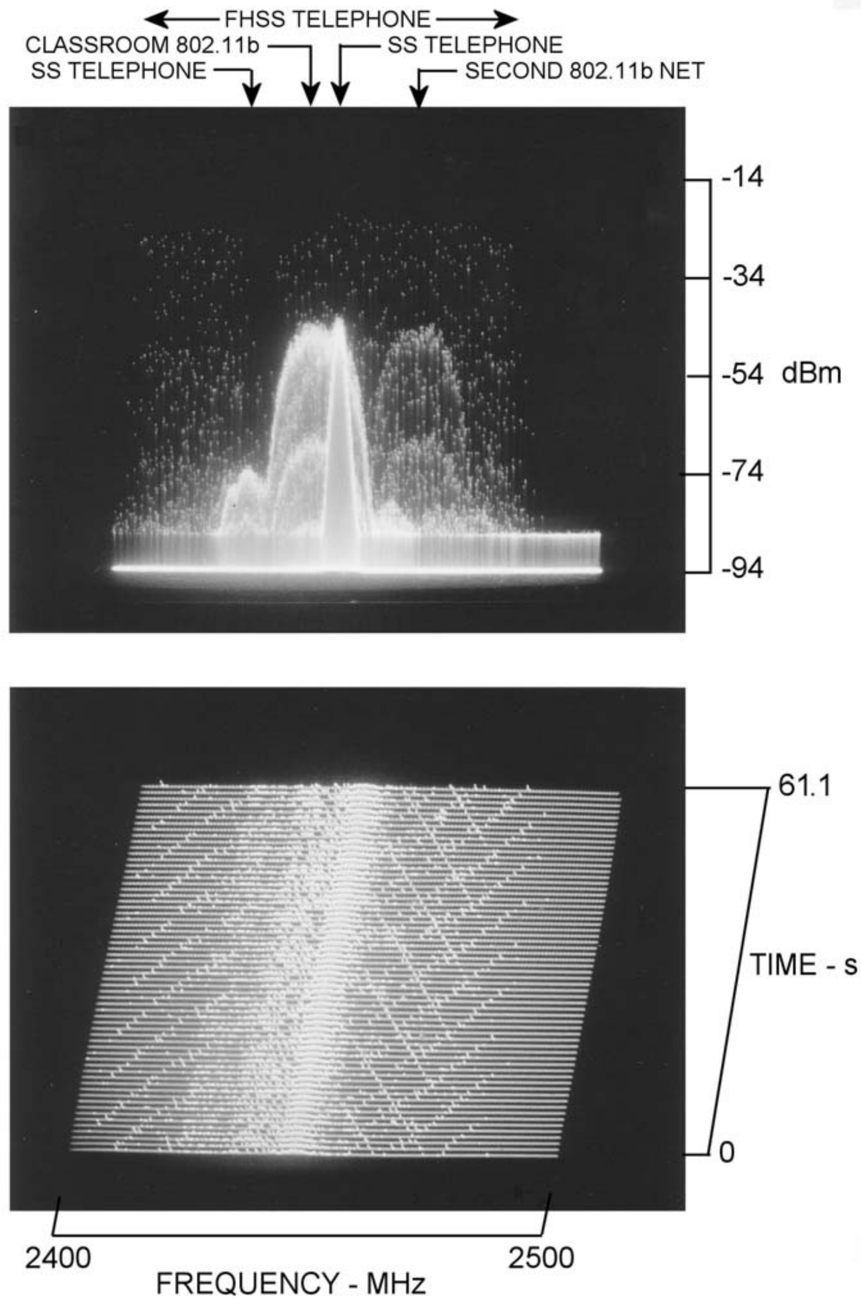
Bursts of noise spaced at about 8.3 ms-intervals appear about 1/3 of the way down the time axis and again about 2/3 of the way down the time axis. The time interval of these pulses suggests the source is synchronized to both the negative and positive portions of the wave shape of the power-line voltage. Since most microwave ovens operate from half-wave power supplies with a noise burst spacing of 16.6 ms, the noise is not from a recent model of a microwave oven although it may be from a very old model built with a full-wave power supply. The source of this particular noise was not tracked down.

Example 9 (030326 0938) was obtained when the frequency-scan process of the spectrum analyzer was set at zero and the center frequency was set at 2450 MHz. The vertical output of the spectrum analyzer was observed with a Tektronix Model 220 Digital Oscilloscope. A single data pulse from one of the laptops in the classroom was received and held in the memory of the oscilloscope. In this example a synchronization pulse from another 802.11b net occurred during the data pulse, and it appears on top of the data pulse. While most data pulses were free of such contamination, an occasional synchronization pulse from another net or a noise pulse would appear simultaneously with a data pulse. This produces in an error in the reception of the information contained in the data pulse and requires the retransmission of the affected data. When a sufficient number of data pulses are affected by such interference, the throughput of the network is significantly reduced.



Example 1

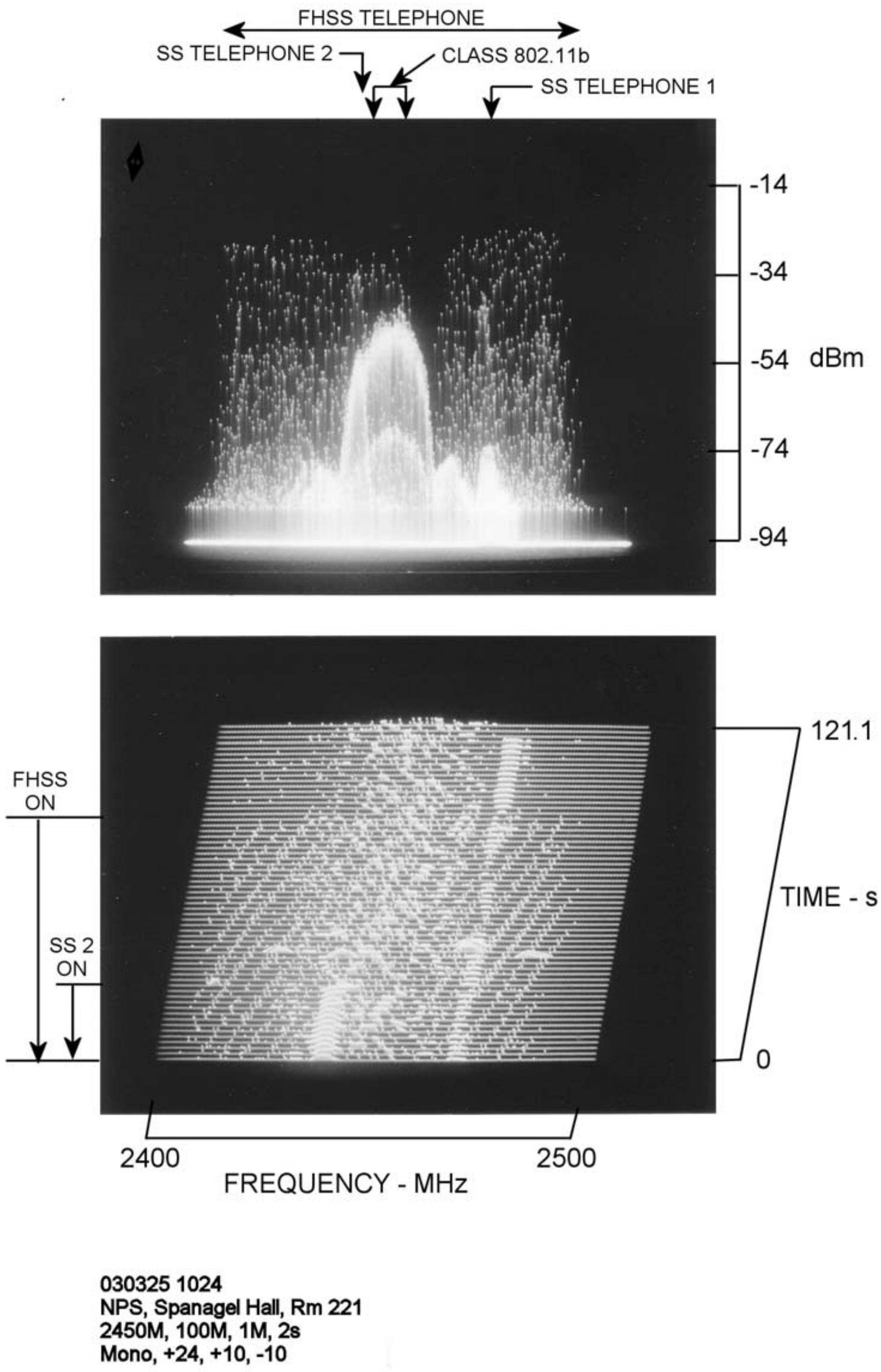
March Wireless Communications Class



030326 0930
NPS, Spanagel Hall, Rm 221
2450M, 100M, 1M, 1s
Mono, +24, +10, -10
Class Net, Second 802.11b, FHSS Phone,
SS Phone, 2 NPS Nets, Intermittent Pulses

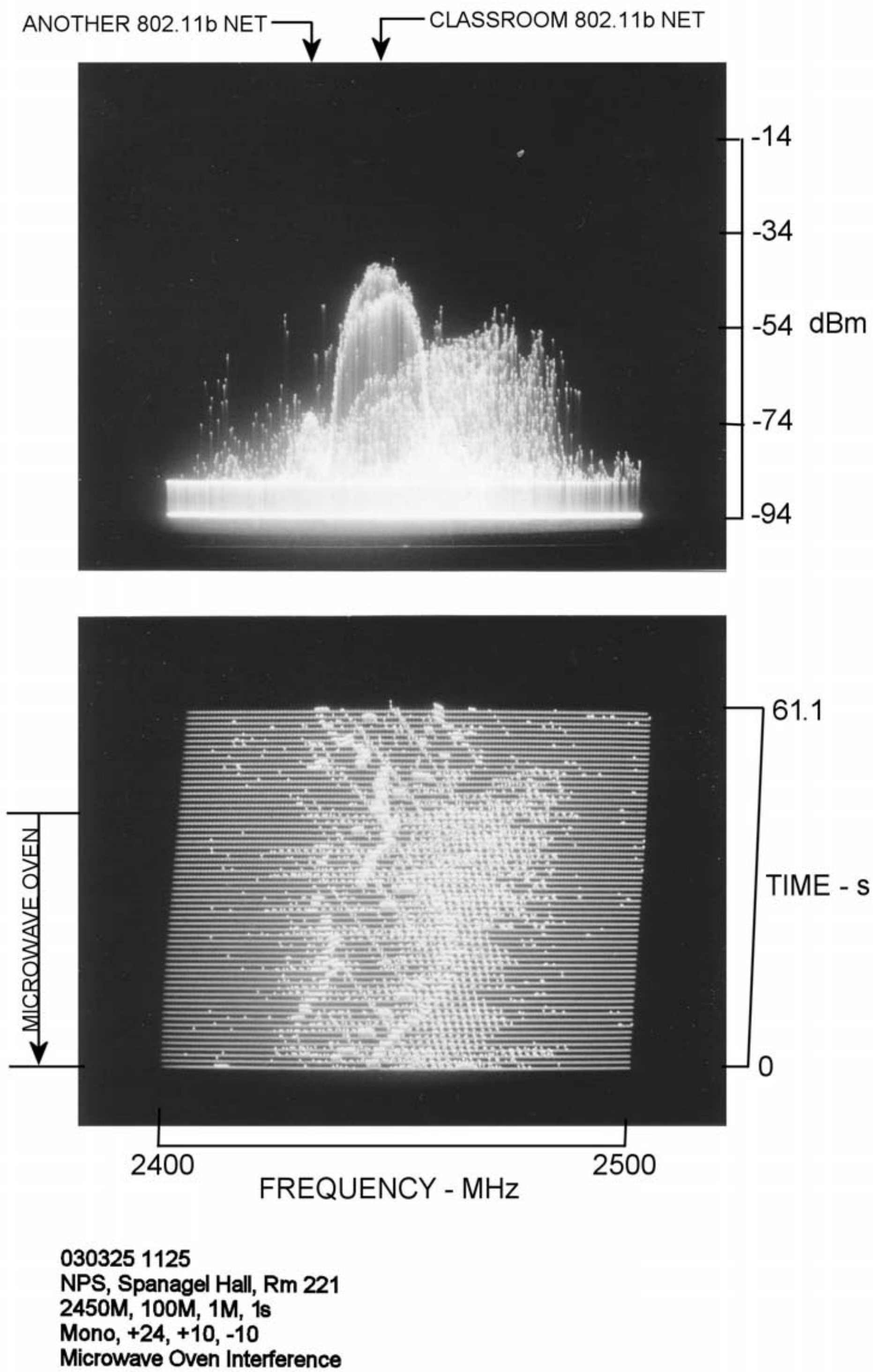
Example 2

March Wireless Communications Class



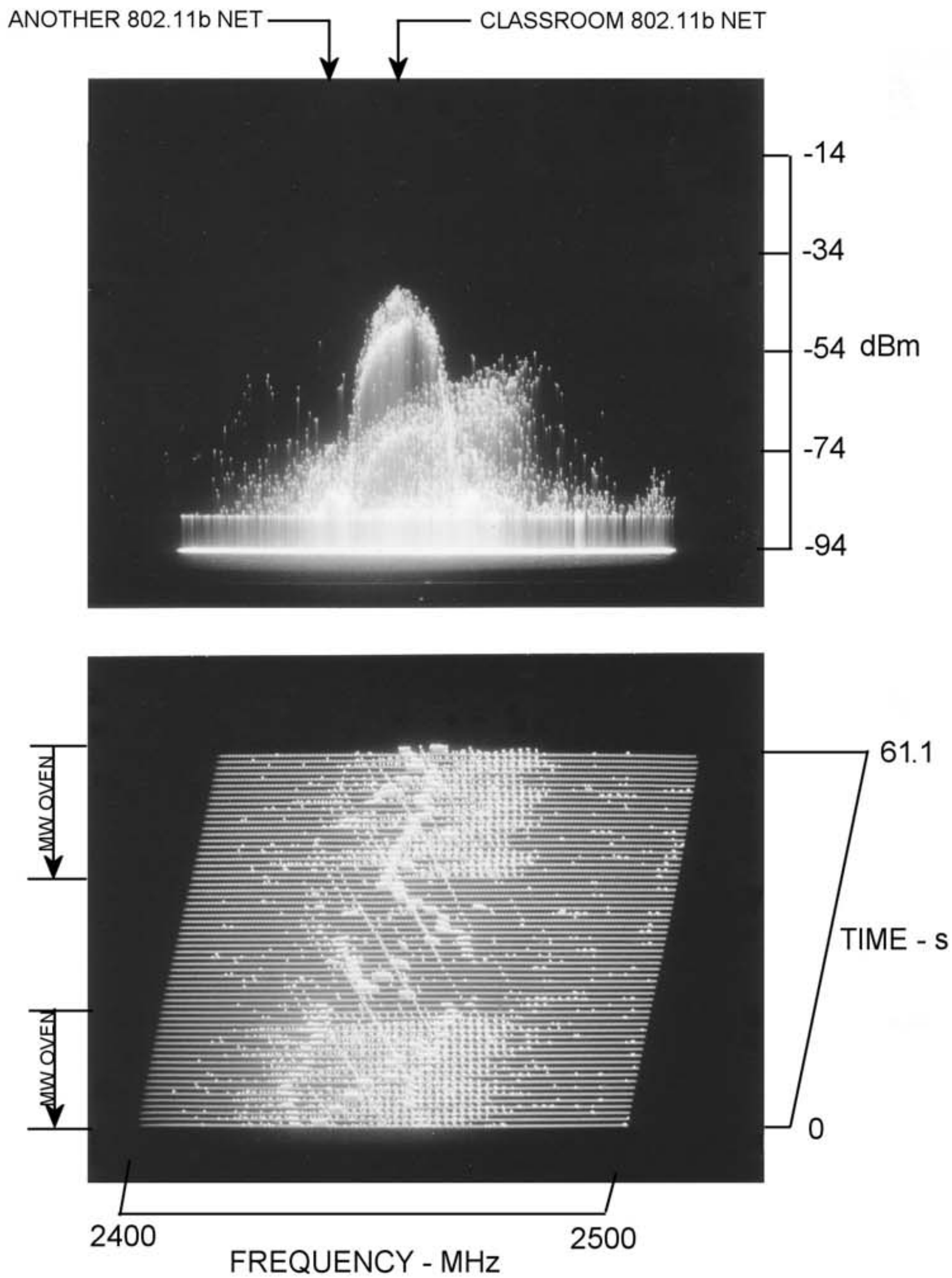
Example 3

March Wireless Communications Class



Example 4

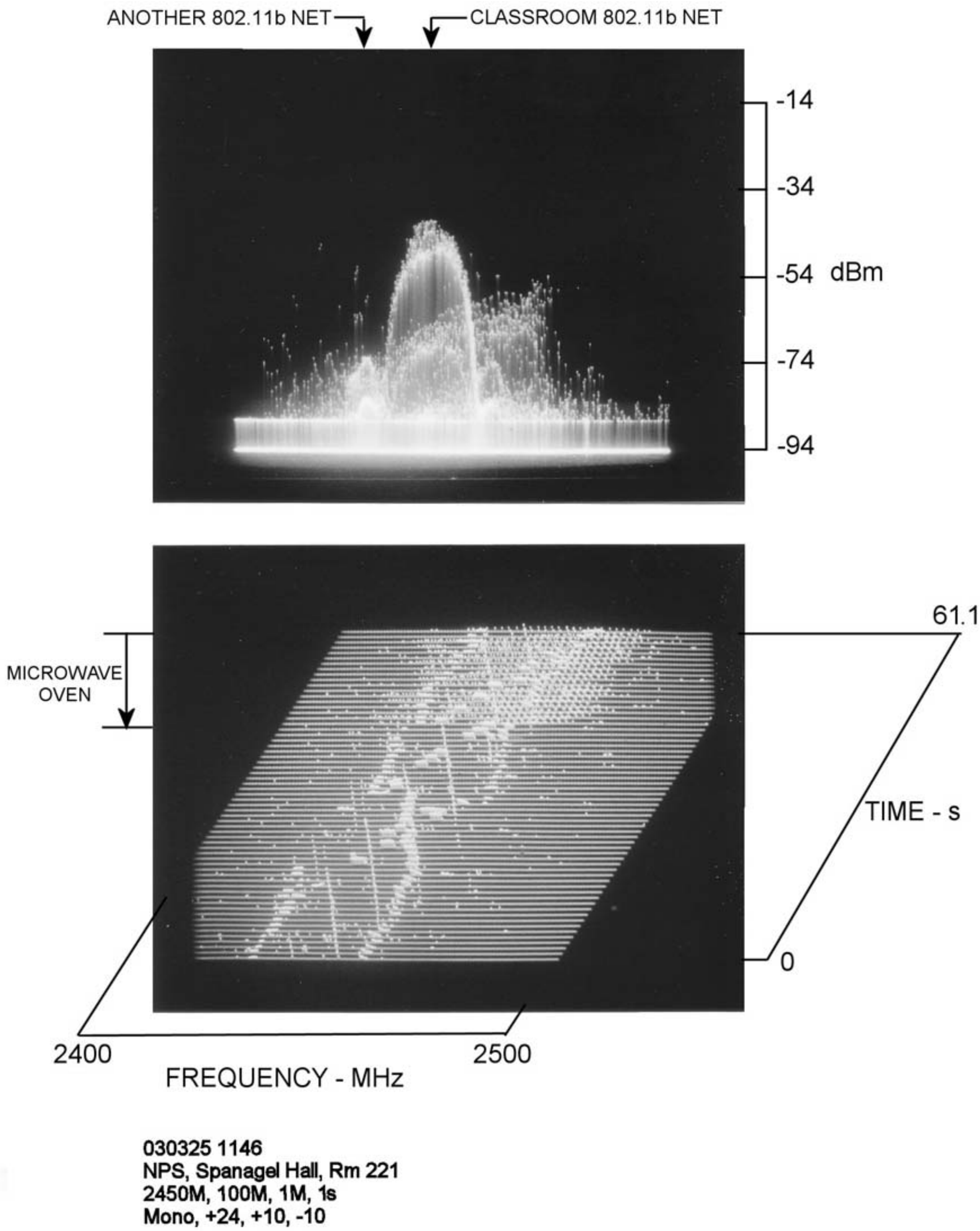
March Wireless Communications Class



030325 1142
NPS, Spanagel Hall, Rm 221
2450M, 100M, 1M, 1s
Mono, +24, +10, -10

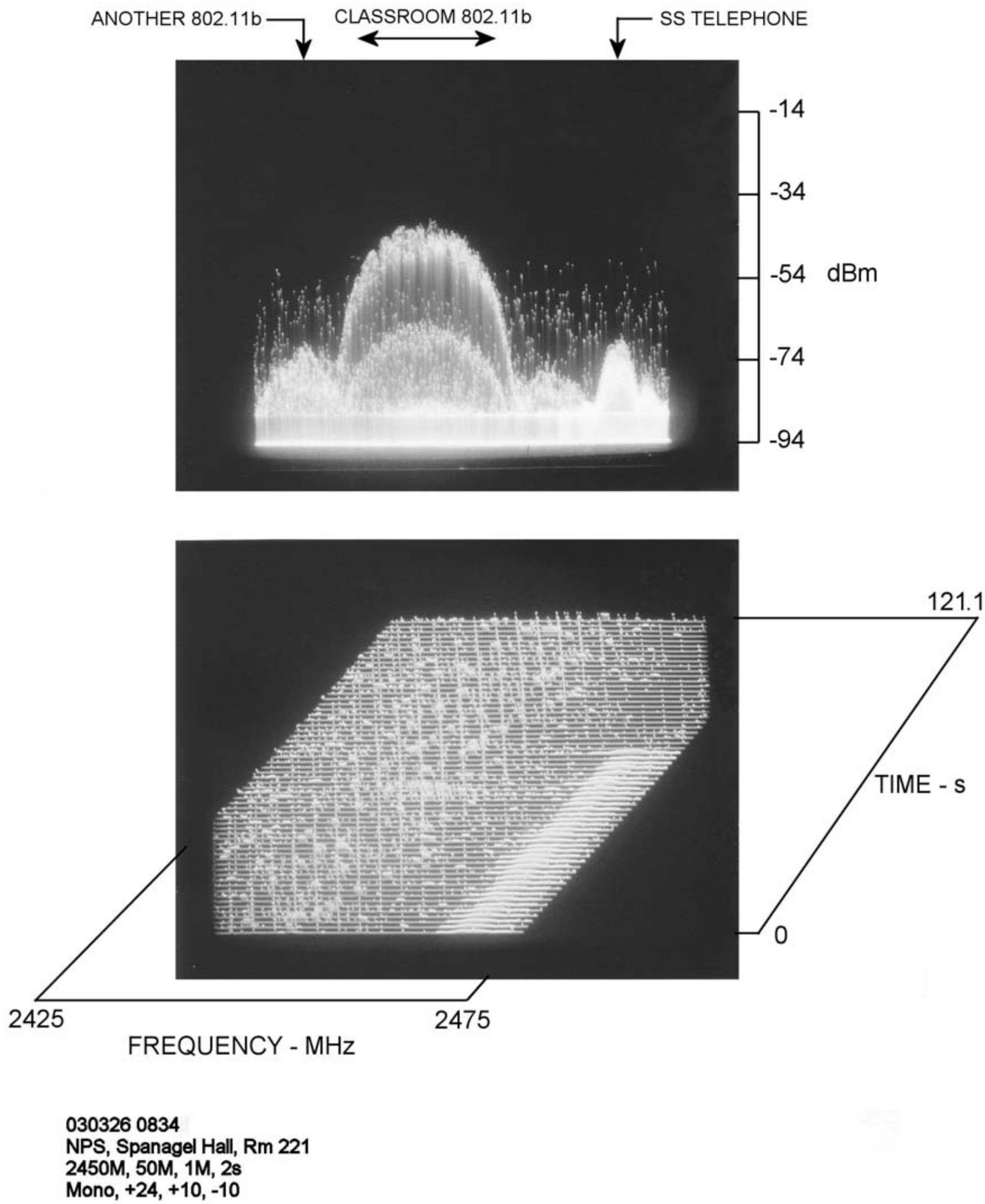
Example 5

March Wireless Communications Class



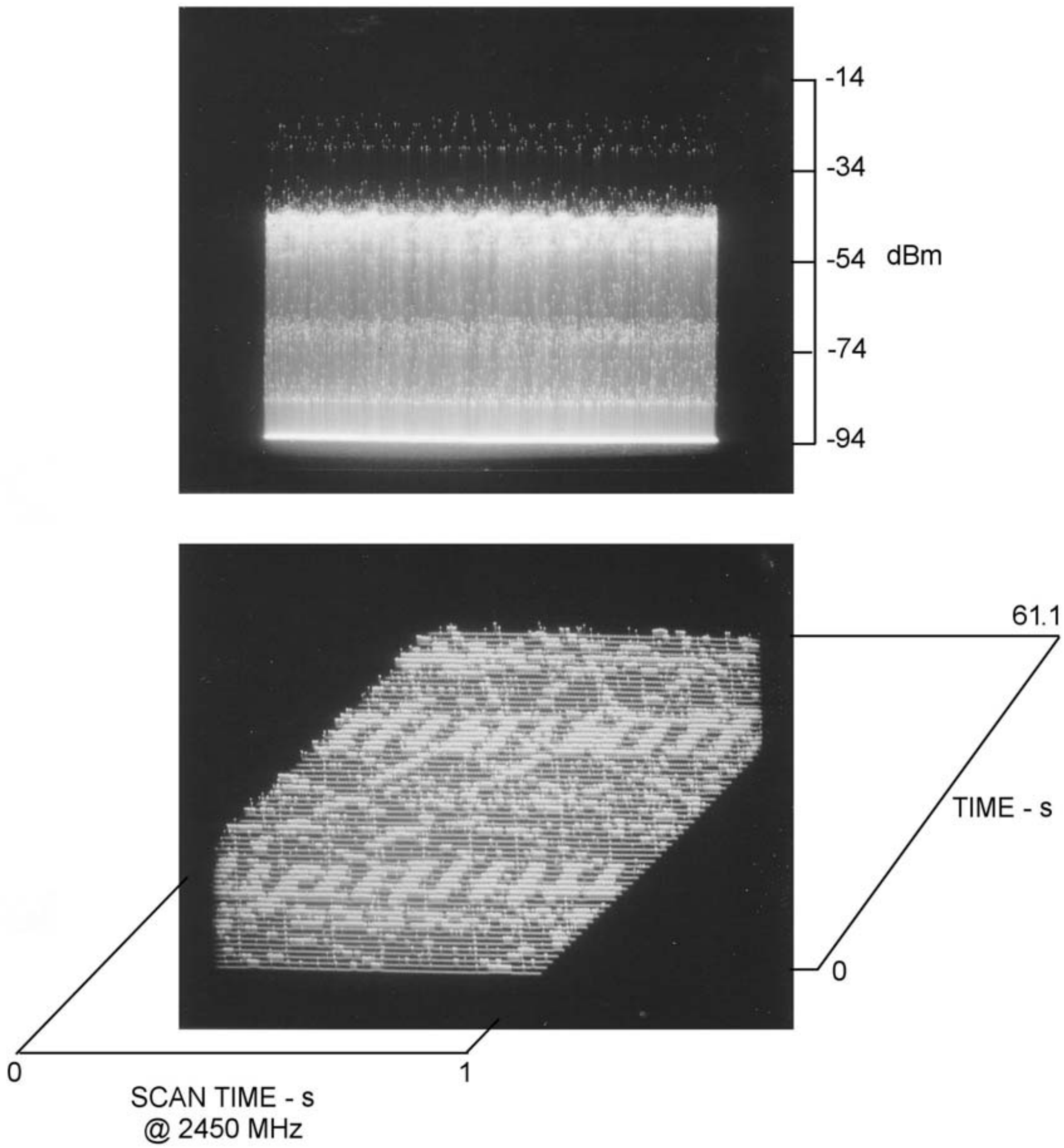
Example 6

March Wireless Communications Class



Example 7

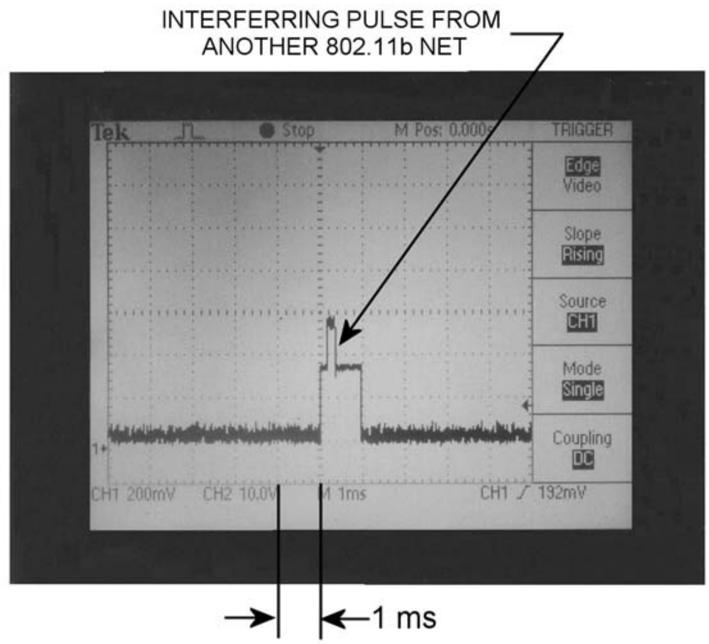
March Wireless Communications Class



030326 0944
NPS, Spanagel Hall, Rm 221
2450M, 0M, 1M, 1s
Mono, +24, +10, -10

Example 8

March Wireless Communications Class



030326 0938
NPS, Spanagel Hall, Rm 221
2450M, 0M,
Mono, +24, +10, -10
Hit from another Net

Example 9

March Wireless Communications Class

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Technical Memorandum 0305
Signal Enhancement Laboratory
Electrical and Computer Engineering Department
Naval Postgraduate School
Monterey, CA

October 2003

Occupancy and Use of the 2.4-GHz License-Exempt Band during the Wireless Communications Class of September 2003

by:
Wilbur R. Vincent
and
Richard W. Adler

INTRODUCTION

Emissions in the 2.4-GHz license-exempt band were monitored during the wireless communication class held at the Naval Postgraduate School during the week of 22 September 2003. This memorandum provides examples of the occupancy and use of the band during the class.

A single 802.11b Access Point was installed on the wall of Room 221 of Spanagel Hall for the class. Each student was provided with a 802.11b wireless-equipped laptop at their desk (a maximum of 27 positions). Instruction material appeared on his laptop and each student could add class notes to his personal file located on a NPS server. In addition, conventional verbal interchange and discussion between the instructors and students was encouraged.

Monitoring of the occupancy and use of the 2.4-GHz band was accomplished during class periods from a small storage room located at the rear of the classroom. Monitoring equipment consisted of a moveable cart containing a receiving antenna, preamplifier, spectrum analyzer, and a time-history display. Data from a time-history display was recorded with an engineering model of a digital oscilloscope camera and saved on the hard drive of a laptop. The digital oscilloscope camera replaced a conventional film-type oscilloscope camera previously used to record data. The recorded data was processed and formatted with same laptop using conventional software (Paint Shop Pro).

Data obtained during the class was similar to that obtained from previous classes.[19] Of importance is the variety of time-variable emissions found during the daytime hours including 802.11b classroom signals, signals from other 802.11b nets, signals from various kinds of wireless portable telephones, random noise impulses, and noise from microwave ovens.

A data-log file from the classroom measurements is provided at the end of the memorandum along with an explanation of the contents of the file. Pertinent information from this file is added to the bottom of each example of data presented in this memorandum.

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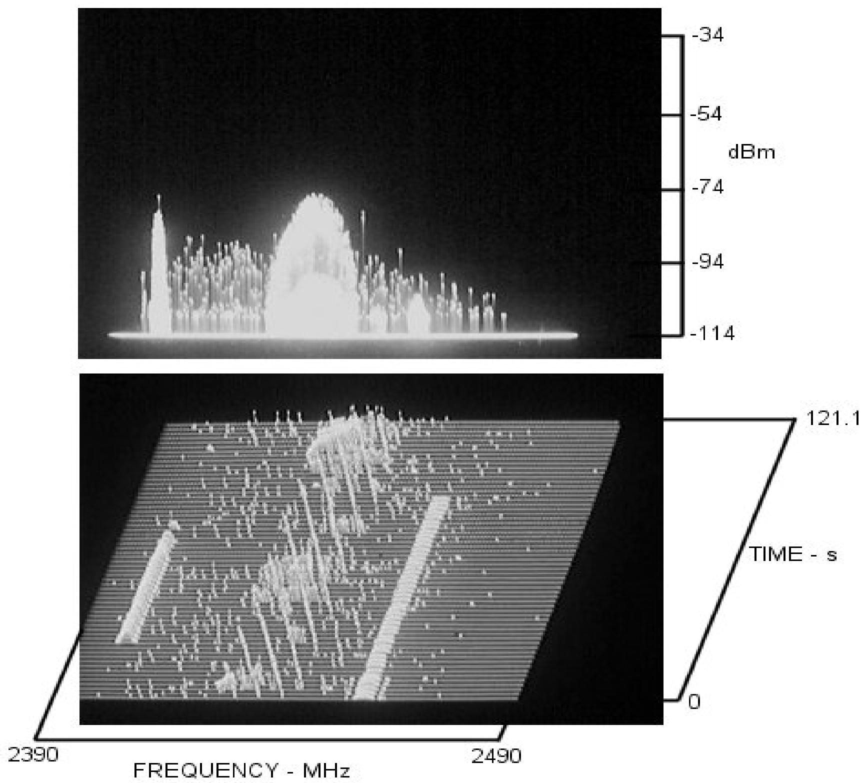
[19] Wilbur R. Vincent, Richard W. Adler, and Andrew A. Parker, ***Occupancy and Use of the 2.4-GHz License-Exempt Band during the Wireless Communications class of March 2003***, Technical Report NPS-EC-03-00, October 2003, Signal Enhancement Laboratory, Department of Electrical and Computer Engineering, Naval Postgraduate School, Monterey, CA

EXAMPLES OF DATA

Figure 1 shows an example of emissions in the 2.4-GHz license-exempt wireless-radio band shortly after the start of the first session of the class. The upper view is similar to the amplitude-vs-frequency view provided by a spectrum analyzer. This view shows the spectral shape of the 802.11b signals emitted by the Access Point and the classroom laptops along with other emissions. The amplitude scale at the right edge of this view provides signal strength at the input terminals of the preamplifier (or the output of the receiving antenna, a small monopole over a ground plane).



10/11, 230905, 0912, 2440, 100, 300, 2000, Mono, 24, 0, -10

Figure 1 Signals and Noise, Example 1

The bottom view shows a time-history presentation of emissions in the 2390 to 2490-MHz frequency range over a period of 121.1 seconds. The amplitude of all emissions is severely, but not completely, compressed in this view. The slanting lines in the center of the frequency range of the time-history view are synchronization pulses emanating from the Access Point. The dense white area near the center top of the time-history view represents data pulses emanating from both the Access Point and the laptops. Data pulses are added between the Access Point synchronizing pulses. Additional data pulses occurred near the middle of the time axis and again near the bottom of the time axis. The 802.11b emissions occupy about 22 MHz of the 83.5-MHz wide 2.4-GHz wireless band.

The two prominent near-vertical and straight lines in the time-history view that are parallel to the right and left edges of the view are signals from portable telephones operating with spread-spectrum (SS) modulation. The amplitudes of these signals are shown in the upper view. The SS signal near the left edge of the frequency range is from a 2.4-GHz portable telephone located in the classroom for demonstration purposes. The SS signal on the right side of the 802.11b signal is from another unidentified 2.4-GHz portable telephone operating at a location outside the classroom.

Still one additional feature is shown in the two views of Figure 1. The time-history view shows numerous white dots throughout the wireless band extending from 2400 up to 2483.5 MHz. These dots are caused by random impulses from an unidentified source. The upper view shows the amplitude of these dots. The strong amplitude of the impulses indicate the source is either close to the classroom or from a very high-powered source located some distance from the classroom.

Figure 2 shows another view of the signal and noise population in the 2.4-GHz wireless band.

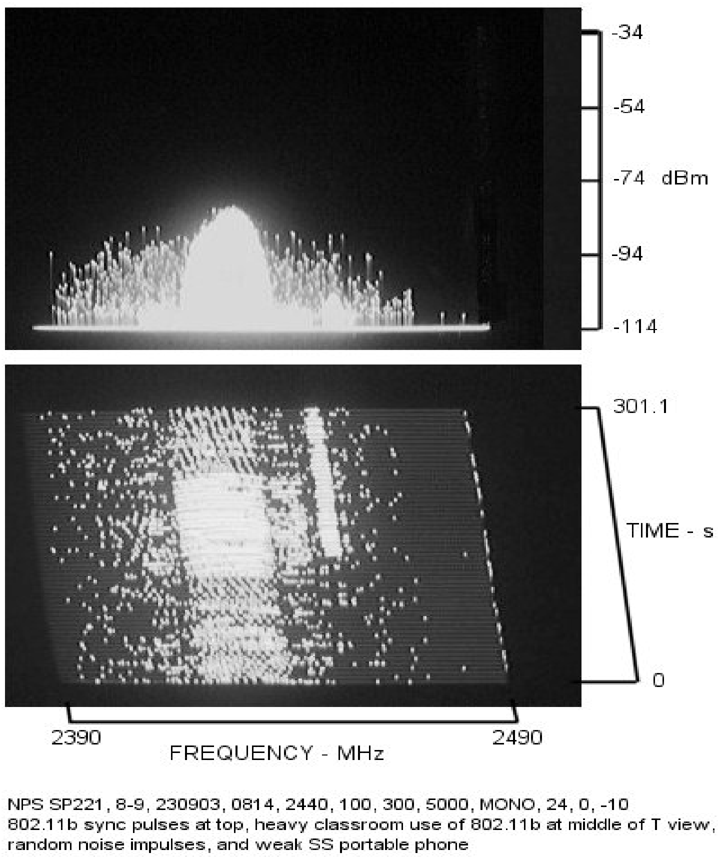


Figure 2 Signals and Noise, Example 2

This example shows the 802.11b signal near the center of the frequency range. Synchronizing signals appear at the top of the time-history view followed by a period of heavy use of the network. A short period of no use occurred after the heavy use followed by short periods of moderate-to-low use. A signal from a portable SS telephone appears at a frequency higher than the 802.11b signal, and it turns off about half way down the time axis. The random pulses appear throughout the 2.4-GHz wireless band. The upper view shows the amplitude of the various signals and the random impulses.

Figure 3 shows another view of the occupancy of the 2.4-GHz band. In this example a microwave oven was brought into the classroom and operated for one minute. The bright area in the center of the time-history view is the microwave oven emission. A second spectral spur occurs at the upper edge of the frequency span, but the full extent of the spur is not defined due to the limited frequency span. The amplitude of all emissions within the frequency span, including the microwave oven noise, is shown in the upper view. Two primary spectral components of microwave oven noise are shown. In this case the microwave oven noise covered only a portion of the frequency range occupied by the 802.11b signal, and only minimal interference to network operation was noted. The random impulses also appear in this example.

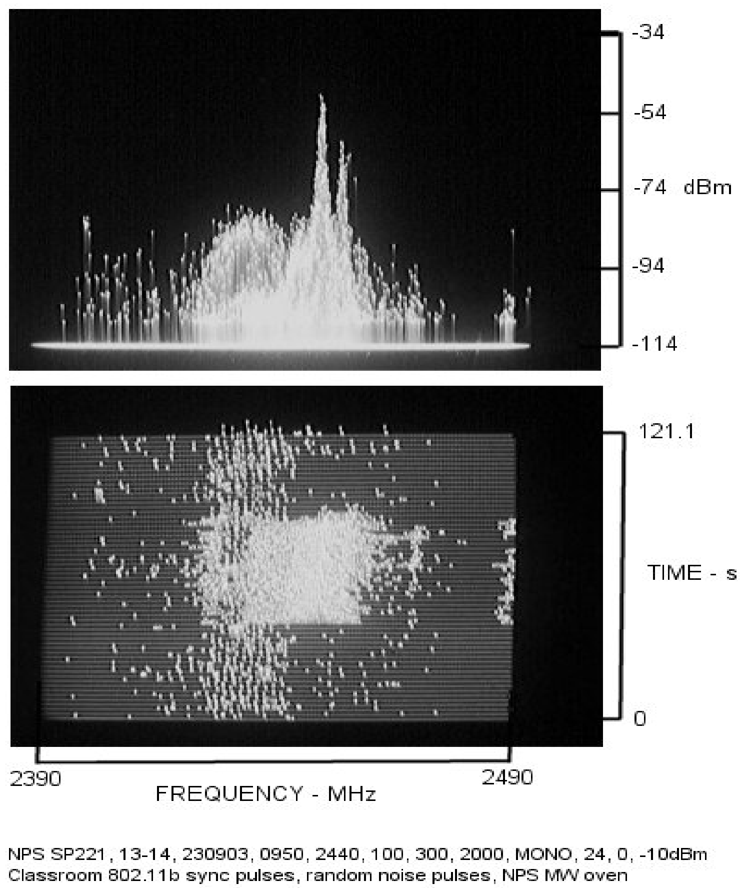


Figure 3   Signals and Noise, Example 3

Figure 4 shows yet another view of signals and noise in the 2.4-GHz wireless band. In the upper 3/4 of the time-history view, a frequency-hopping spread-spectrum (FHSS) portable telephone was operated in the classroom. The base unit of this telephone emanated synchronization signals at all times, and these signals hopped over the entire width of the band with the exception of narrow blank range near the upper edge of the 802.11b signal. The very strong amplitude of the synchronization pulses from the FHSS telephone, about –56 dBm in a 300-kHz bandwidth, can be obtained from the scale on the right side of the top view. The FHSS signal covered the lower-amplitude random-noise impulses in the upper part of the time-history view, but they are visible in the lower part of the time-history view. The 802.11b signal can be observed throughout the entire measurement period. A fine-scale view of the 802.11b and the FHSS signals showed frequent collisions between the two signals which results in a lower throughput for the classroom network.

The signal from a SS portable telephone appears near the right edge of the wireless band. This very strong signal turned off a few seconds prior to the termination of the FHSS signal. Since the SS signal was outside the spectral range of the 802.11b network, it did not cause harmful interference to the classroom network.

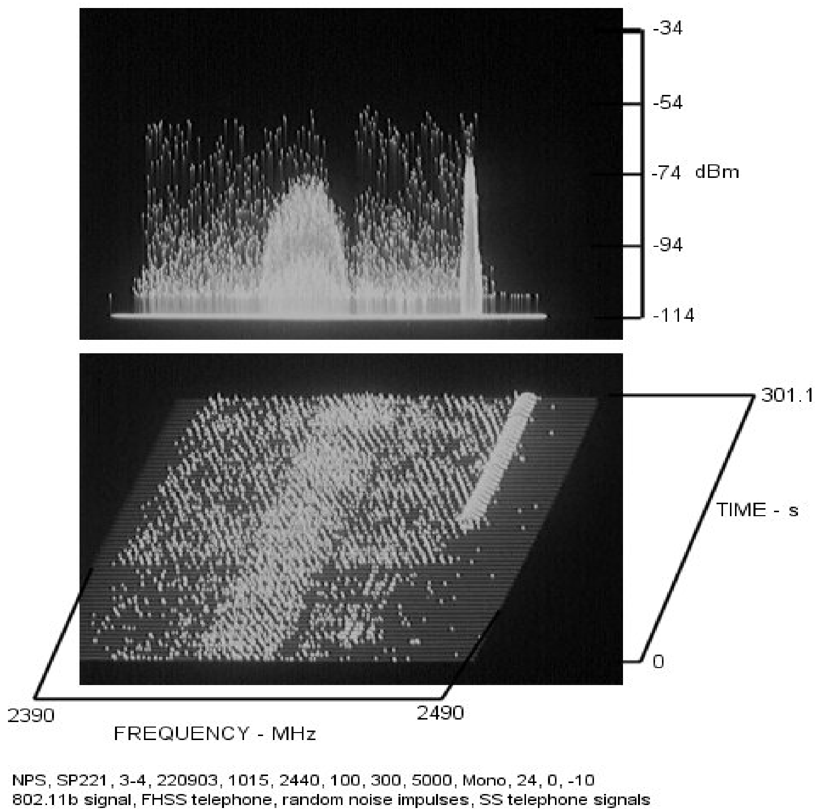


Figure 4 Signals and Noise, Example 4

Figure 5 shows two views of the fine-scale spectral structure of the SS signal emitted from the portable telephone. The upper view shows the full 5-MHz width of the signal's spectral structure including its upper and lower side bands. The bottom view shows the fine-scale structure of the primary spectral component. Of special interest is the sharp null at the center of the spectral structure. This null does not occur on most SS signals, and its purpose is not understood at this time. Additional fine-scale spectral detail related to the SS modulation process is shown in the form of nulls and peaks. This additional detail is related to the modulation technique employed, and it is not present in well-designed SS signals.

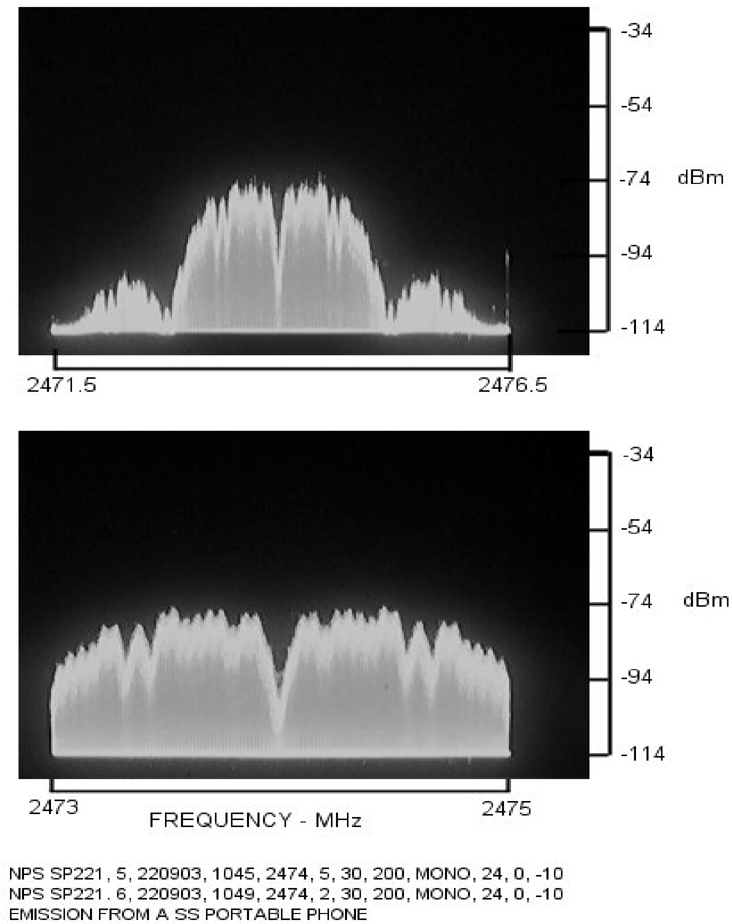


Figure 5 Spectral Detail of Spread-Spectrum Emission from a Portable Telephone

COMMENTS

This memorandum provides examples of the occupancy and use of the 2.4-GHz wireless band at Room 221 of Spanagel Hall at the Naval Postgraduate School during the wireless communications class held during the week of September 22, 2003. The examples are similar to those obtained during several previous classes, and they are provided to illustrate the occupancy and use of the band. The examples show the wide variety of signal formats, interference and noise encountered in the 2.4-GHz band and the crowded conditions that exist in this band at the classroom location.

Of interest is the continued finding of high levels of random-occurring impulsive noise across the 2.4-GHz license-exempt band. These impulses are confined within the frequency limits of the wireless-radio band. The data suggests the impulses are from a nonstandard device using the band, and it probably is located in the near vicinity of the classroom. These impulses are an unidentified and ongoing source of interference to the classroom 802.11b network, and their source should be tracked down.

The data presented in this memorandum was obtained with an engineering model of a digital oscilloscope camera developed for use by the Signal Enhancement Laboratory of the Naval Postgraduate School. Since this was the first use of the camera, the brightness and contrast of some of the views is not ideal. This will be improved as practice is obtained in the use of the new camera. The change from film-to-digital recording significantly reduced the time required to prepare examples of data for incorporation into documents as well as the improving the accuracy of the data presentations. In addition, it eliminated the substantial cost of film and the cost associated with many of the manual steps formerly used in the preparation of data for use in documents and presentations.

Table A.1

Data Identification Table for 7200B Digital Photographs

Column No.	Information in Column
1	Site Identification
2	Picture Number and Type*
3	Date in yy/mm/dd format
4	Local Time of Measurement
5	Center Frequency in MHz
6	Frequency Span in MHz
7	Bandwidth in kHz
8	Total Scan Time in ms
9	Source of Data (Antenna Type, Current Probe, Voltage Probe, etc)
10	Preamplifier Gain in dB
11	RF Attenuation in dB
12	Gain Reference in dBm
13	Comments

* A is an amplitude-vs-frequency view
* C is a calibration view
* T is a time-history view

Information identified in Table A.1 and listed in Table A.2 is added to the bottom of each data example to ensure that the proper information is associated with each item of information.

Table A.2

Data Log, NPS Class 22/23 Sept 03

Location		Date dd/mm/yy	Time Local	Freq. MHz	Span MHz	BW kHz	Scan T ms	Source	Preamp dB	RFAttn dB	RF Ref. dBm
NPS, SP221		03/09/22	9:29	2433	50	300	1000	Mono	24	0	-10
NPS, SP221		03/09/22	9:29	2433	50	300	1000	Mono	24	0	-10
NPS, SP221		03/09/22	10:15	2440	100	300	5000	Mono	24	0	-10
NPS, SP221		03/09/22	10:15	2440	100	300	5000	Mono	24	0	-10
NPS, SP221		03/09/22	10:45	2474	5	30	200	Mono	24	0	-10
NPS, SP221		03/09/22	10:49	2474	2	30	200	Mono	24	0	-10
NPS, SP221		03/09/22	10:57								
NPS, SP221		03/09/22	8:14	2440	100	300	5000	Mono	24	0	-10
NPS, SP221		03/09/22	8:14	2440	100	300	5000	Mono	24	0	-10
NPS, SP221		03/09/22	9:12	2440	100	300	2000	Mono	24	0	-10
NPS, SP221	1-A	03/09/22	9:12	2440	100	300	2000	Mono	24	0	-10
NPS, SP221	2-T	03/09/22	9:22	2434	0	300	2000	Mono	24	0	-10
NPS, SP221	3-T	03/09/22	9:50	2440	100	300	2000	Mono	24	0	-10
NPS, SP221	4-A	03/09/22	9:50	2440	100	300	2000	Mono	24	0	-10

Technical Memorandum 0402
Signal Enhancement Laboratory
Electrical and Computer Engineering Department
Naval Postgraduate School
Monterey, CA

April 2004

Occupancy and Use of the 2.4-GHz License-Exempt Band during the Wireless Communications Class of March 2004

by

Wilbur R. Vincent
and
Richard W. Adler

INTRODUCTION

Emissions in the 2.4-GHz license-exempt band were monitored during a series of wireless communication class held at the Naval Postgraduate School. Technical reports describing the occupancy and use of the 2.4-GHz band were prepared for those classes when preparation time was available[20, 21]. This memorandum provides examples of the occupancy and use of the band during the class held during March of 2004.

A single 802.11b Access Point was installed on the wall of Room 433 of Spanagel Hall. Each student was provided with a 802.11b wireless-equipped laptop at their desk (a maximum of 27 positions). Instruction material appeared on his laptop and each student could add class notes to his personal file located on a NPS server. In addition, the conventional verbal interchange and discussion between the instructors and students was encouraged.

Monitoring of the occupancy and use of the 2.4-GHz band was accomplished during class periods from an adjacent room. Monitoring equipment consisted of a moveable cart containing a receiving antenna, preamplifier, spectrum analyzer, and a time-history display. Data from the time-history display was recorded with an engineering model of digital oscilloscope camera and saved on the hard drive of a laptop. The digital oscilloscope camera replaced a conventional film-type oscilloscope camera previously used to record data. The recorded data was processed and formatted with same laptop using conventional software (Paint Shop Pro).

Data obtained during the class was similar to that obtained from previous classes with the exception that the occupancy of the band was higher than for the previous classes. The increased occupancy resulted in higher levels of interference than encountered by prior classes along with the lower of throughputs. Of importance is the ever-changing variety of emissions found during the daytime hours including the 802.11b classroom signals, signals from other 802.11b nets, signals from various kinds of wireless portable telephones, random noise impulses, and noise from microwave ovens.

The data-log file from the March measurements along with an explanation of the contents of the file at the end of the memorandum. Information from this file is added to the bottom of each example of data presented.

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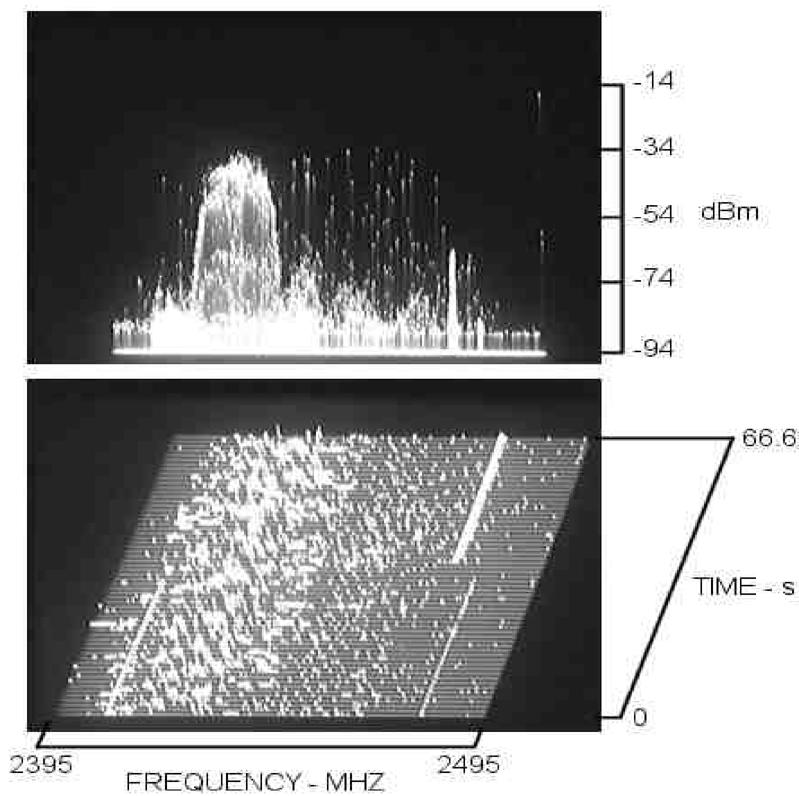
[20] Wilbur R. Vincent and Richard W. Adler, ***Occupancy and Use of the 2.4-GHz License-Exempt Band during the Wireless Communications Class of March 2004***, Report No. NPS-EC-0305, Electrical and Computer Engineering Department, Naval Postgraduate School, Monterey, CA, October 2003

[21] Wilbur R. Vincent and Richard W. Adler, ***Occupancy and Use of the 2.4-GHz License-Exempt Band during the Wireless Communications Class of September 2004***, Report No. NPS-EC-0305, Electrical and Computer Engineering Department, Naval Postgraduate School, Monterey, CA, October 2003

EXAMPLES OF DATA

The occupancy and use of the 2.4-GHz band was monitored on 17 and 18 of March 2004. All data was obtained from an adjacent room including one wall, except for the last example at 1100 hours on 18 March. This example was obtained in the classroom during a demonstration of the monitoring process to the class.

Figure 1 shows a typical example of the occupancy and use of the band at a time of minimal interference. Two views of the same data are provided. The upper view is similar to the amplitude-vs.-frequency view of a spectrum analyzer. The bottom view shows 60 successive scans of the same data where the amplitude is severely compressed. New data enters at the bottom of the view and old data disappears from the top of the time-history view. The frequency span of the spectrum analyzer was adjusted to cover the entire license-exempt wireless band for this example.



NPS, 4/5, 040317, 1030, 2445, 100, 300, 1000, M, N, +24, 10, +10

Figure 1

Occupancy and Use, Example 1

A number features of interest are shown in the two views of Figure 1. Three spread spectrum signals from portable telephones are present in this view. One is near the low-frequency end of the band. This emission started at the bottom of the time-history view and it turned off about half way along the data-acquisition period. Two additional spread spectrum emissions are shown near the upper-frequency end of the band. The brighter appearing emission turned on half way up the time-history view and remained on during the remainder of the data-acquisition period. The other slightly higher frequency signal from a different portable telephone started at the bottom of the time-history view and turned off half way up the view. The amplitude of each of these signals is shown in the upper view.

The spectral width and shape of the 802.11b emission from the access point and the laptops used by the students is the large bright-appearing emission shown in the upper view. Synchronizing pulses from the access point appear as slanting lines in the time-history view. Data pulses occur at intermittent times between the synchronizing pulses as the laptops are used. This results in an erratic appearing collection of wide and narrow data transmissions.

Three additional low-level 802.11b emissions are shown in the upper view. These three emissions are the low amplitude bright areas at channels higher in frequency than the classroom 802.11b emission. Synchronizing pulses from these additional access points can be discerned from a careful examination of the time-history view. These access points are located elsewhere in Spanagel Hall or in another nearby building.

One additional feature appears in the view. Short bursts of high-level emissions appear at random times throughout the entire band at amplitudes approaching -35 dBm in amplitude. They caused intermittent interference to the reception of 802.11b signals by the access point and also by the laptops during the entire class period. The source of these erratic-occurring pulses is certainly nearby, but it has not been located. The temporal and spectral pattern does not fit any known communications system although devices with special and nonstandard emission formats are allowed to use the band. This randomly occurring source of impulses has been noted during measurements at all class sessions.

Figure 2 shows an expanded view of the spectral shape of emissions from the classroom 802.11b Access Point and the laptops during a period of high usage. In this example the combination of the high use of the classroom wireless system along with the long scan time of the spectrum analyzer used to collect the data prevented observing the slanting lines of the synchronizing pulses.

Another emission consisting of closely-spaced pulses at a amplitude of –74 dBm appears slightly higher in frequency than the 802.11b emission. The source of this high repetition rate signal was not identified.

The erratic-occurring pulses shown in the previous example were also found in the portion of the license-exempt band shown in this example.

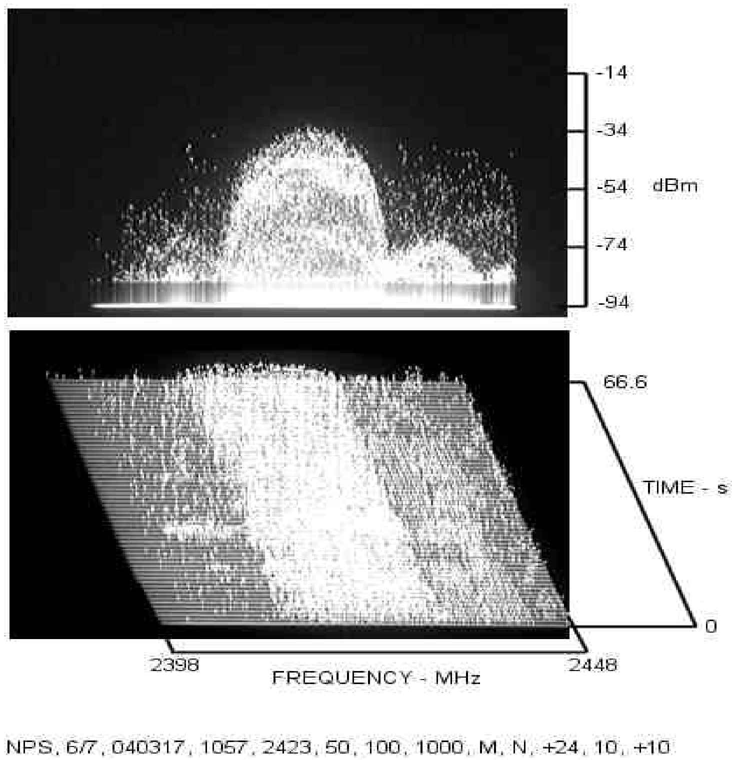


Figure 2

Occupancy and Use, Example 2

Figure 3 shows another example of the occupancy and use of the 2.4-GHz band during a class period. The spectral shape of emissions from the classroom 802.11b access point is shown in the upper view. The lower view shows the use of the access point was high near the top of the time-history view, became minimal for about one minute, and returned to a high use near the bottom of the time-history view.

Synchronizing pulses from two additional access points are shown at a higher frequency. The spectral shape of the two emissions shows that one was on a channel a few MHz lower in frequency than the other. These two signals will interfere with each other, but they did not interfere with the classroom wireless system.

The random high amplitude pulses shown in earlier examples also appear across the entire wireless communications band.

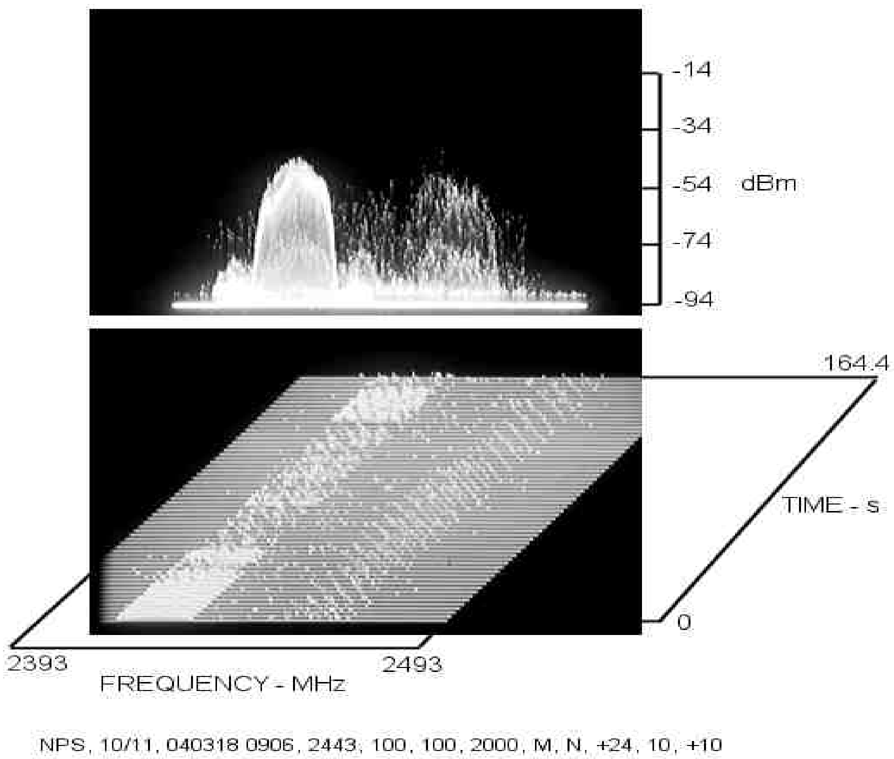


Figure 3

Occupancy and Use, Example 3

Figure 4 shows another example of the occupancy and use of the band. In this case the classroom access point emission is relatively clear of interference with the exception of the high amplitude random occurring pulses.

Another odd-appearing emission started at the bottom of the time-history view and turned off about ¾ of the way up the time axis. The source of this additional emission was not identified. While it did not interfere with the classroom 802.11b wireless system, it did prevent the effective use of the higher-frequency portion of the license-exempt band for 802.11b use in the vicinity of the classroom.

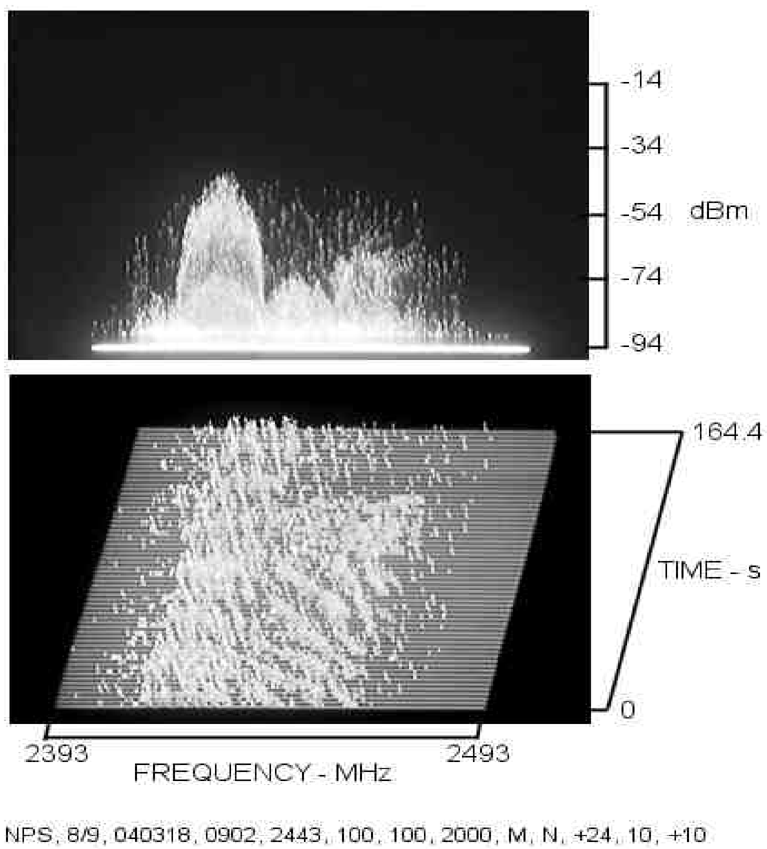


Figure 4

Occupancy and Use, Example 4

Figure 5 shows a time when another 802.11b emission appeared at a channel slightly lower in frequency than the frequency of the classroom Access Point. The synchronizing pulses from these two emissions are shown in the time-history view. Because the spectral shapes of the two Access Point emissions overlapp, they interfered with each other.

A third 902.11b emission is at a higher frequency. Its spectral content is separated from the classroom emission thus it did not interfere with the classroom system.

An unknown emission at low level appears slightly above the center of the frequency range of the two views. The source of this emission is not known.

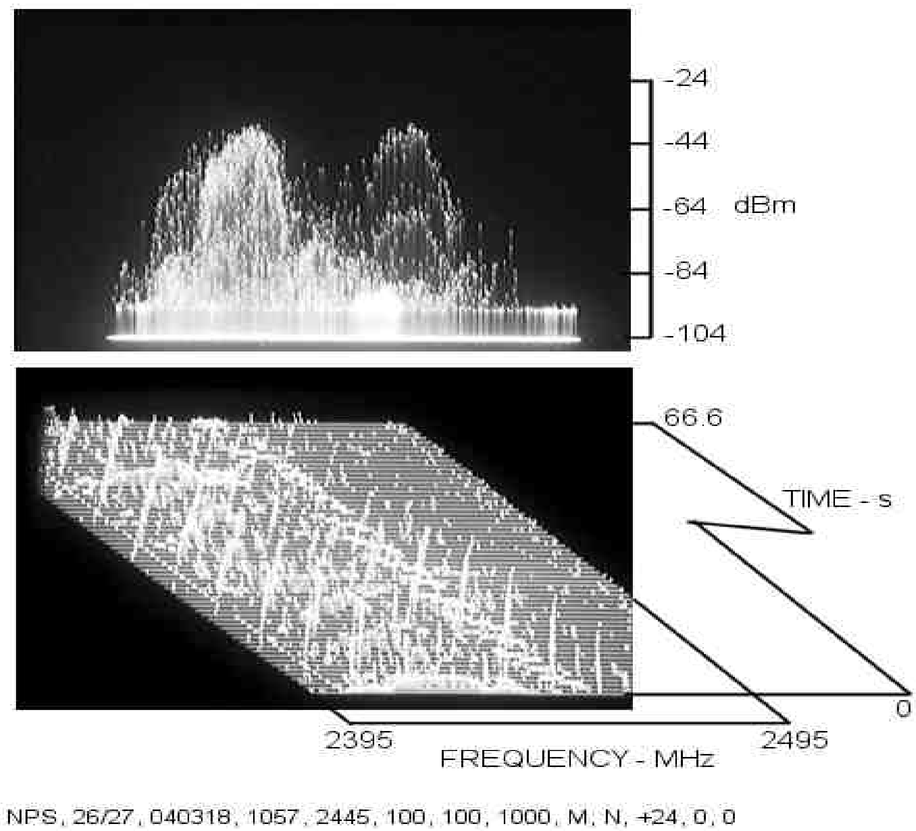


Figure 5

Occupancy and Use, Example 5

Figure 6 shows a time when additional emissions appeared in the 2.4-GHz band. Annotations at the top of the spectral view identify each major emission. A portable telephone with a frequency-hopping spread-spectrum emission was operated during the accumulation of data for the example. The amplitude of the frequency-hopping pulses from the telephone approached –15 dBm as shown in the upper view. A spectral gap in its emission appears slightly above the center frequency of the example.

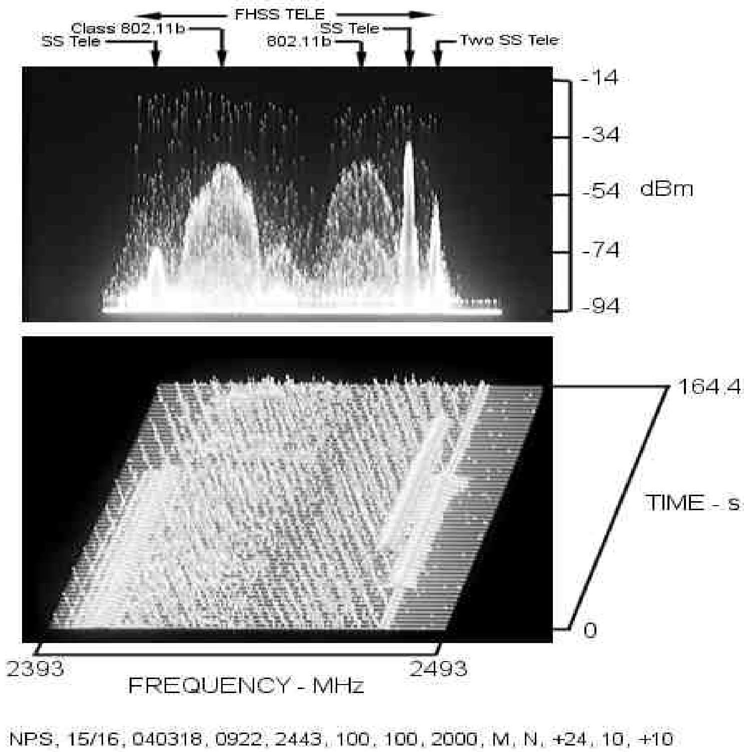


Figure 6

Occupancy and Use, Example 6

Two additional overlapping 802.11b emissions are present in Figure 6 at a higher frequency. While they will interfere with each other, their spectral content is sufficiently separated from the classroom system to ensure noninterference.

A spread-spectrum emission appears near the low end of the band about one-third of the way down the time-history view. The amplitude of this emission is about –73 dBm. The time-history view suggests that this emission contained multiple side bands on the low-frequency edge of the primary spectral component but only a single side band on the upper frequency edge of the primary emission. This emission will be examined in greater detail in subsequent examples.

Emissions from three portable telephones using spread spectrum modulation are shown near the upper end of the frequency scale of Figure 6. A strong emission near the upper-frequency edge of the second 802.11b emission is from a telephone located in the classroom. The other two spread-spectrum signals are from telephones at other locations. Of interest is that signal from one portable telephones fell on top of a similar but lower-level emission.

Figure 7 shows still another example of the occupancy and use of the 2.4-GHz band during the March Wireless Communications Class. The unbalanced spread spectrum emission at the lower end of the frequency scale is more clearly shown than in the previous example.

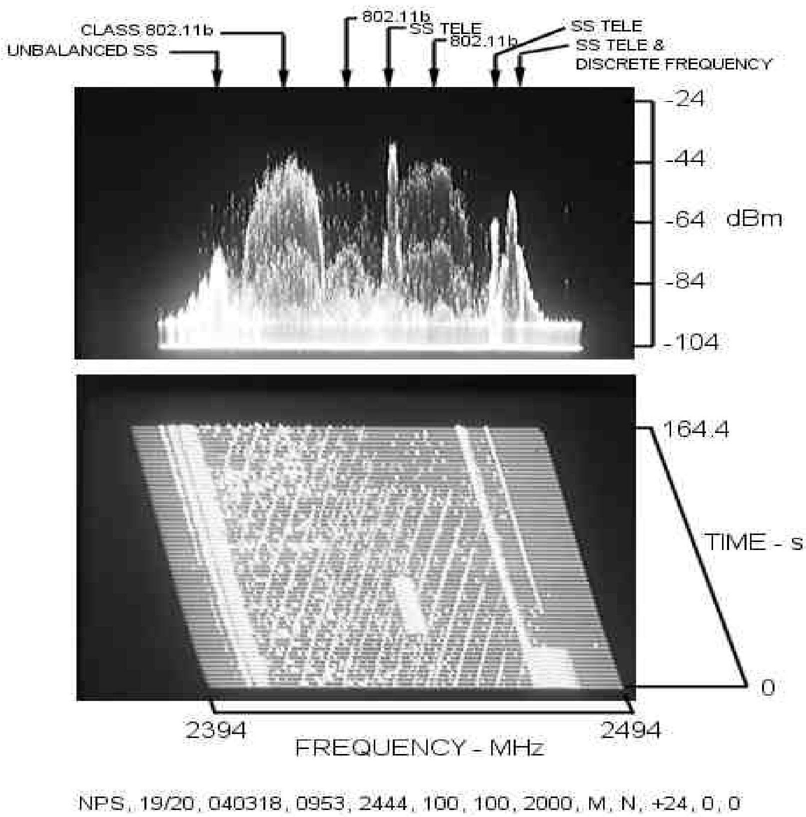


Figure 7

Occupancy and Use, Example 7

The classroom 802.11b emission shown in Figure 7 is present along with one additional high-level 802.11b emission that turned on about one quarter of the way down the time-history view. A low-amplitude 802.11b emission is present slightly higher in frequency than the classroom signal. Three spread spectrum signals from portable telephones are shown along with one signal that appears to be a discrete-frequency signal without modulation.

Figure 8 was obtained at the end of a class period while demonstrating the operation of the measurement system to the class. A very strong spread spectrum signal suddenly appeared on the same frequency as the signal from the classroom 802.11b Access Point. Interference from this signal was sufficient to reduce the throughput of the classroom wireless system to zero. The signal turned off near the bottom of the time-history view and the throughput returned to a useful level.

The source of the high-level spread spectrum interference was not located. No unusual activity in the vicinity of the classroom was noted at the time the signal was observed. The high power level of the signal indicates it was probably from a nearby location or from a very high power source with a directional antenna at a more distant location.

The intermittent and randomly occurring impulses noted in other examples are present in this view along with other low-level emissions at higher frequencies. The low-level emissions at the higher frequencies appear to be associated with the strong spread spectrum interference.

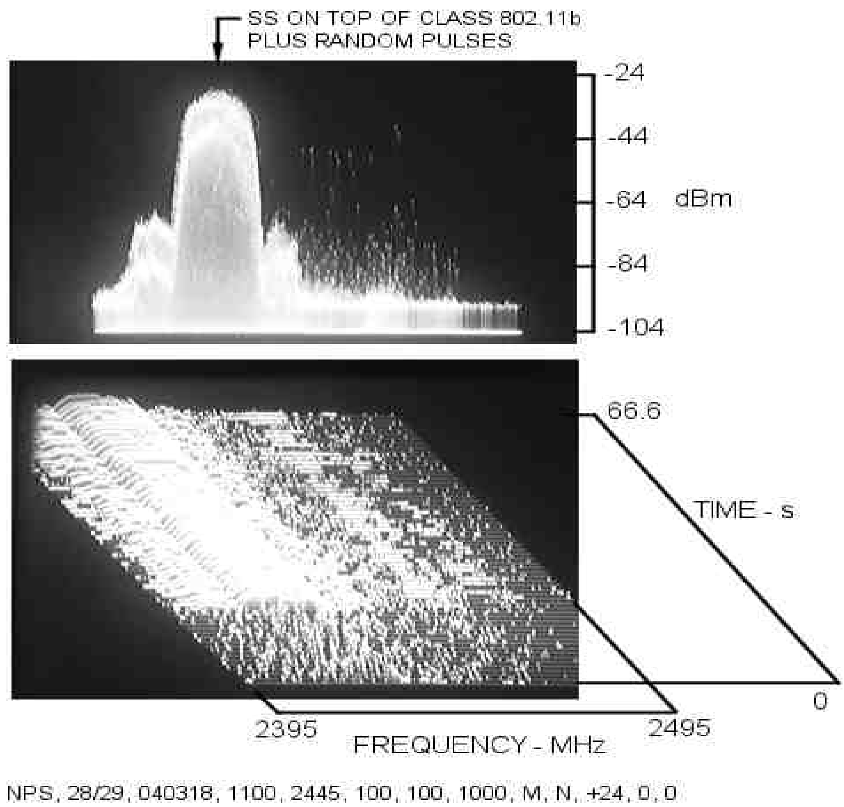


Figure 8

Occupancy and Use, Example 8

DISCUSSION

Eight examples of the occupancy and use of the 2.4-GHz license-exempt band are provided in this report. These examples were obtained during the March 2004 Wireless Communications Course at the Naval Postgraduate School. They are typical examples and not unusual in any respect, and they supplement additional examples obtained during previous classes that are contained in the referenced documents.

Several major aspects of the occupancy and use of the 2.4-GHz band are shown by the examples. These are summarized as follows:

- Large changes in the occupancy and use of the band occurred during each class period, from class period to class period, and from day to day.
- While daytime occupancy and use of the band was high, nighttime occupancy and use was very low.
- A large variety of emission types were found in addition to the classroom 802.11b signal format.
- Interference to the classroom 802.11b system changed with time, and it varied from low to massive. Consistent and reliable use of the license-exempt band was not possible during daytime hours.
- Instructors and students had no control over the interference. It disrupted the operation of the classroom wireless communications system in a highly erratic manner, and they had to contend with time-changing interference conditions.
- No practical means to control or limit the interference could be devised other than conducting a comprehensive and costly survey of all 2.4-GHz emitters in and around the classroom building. Any effective management of the interference would require strict control over the operation of all emitters on and near the spectral width of the classroom 802.11b system that are located in the vicinity of the classroom.
- A comparison of the examples presented in this memorandum with examples provided in referenced memoranda indicates that the use of the 2.4-GHz License-Exempt band at the classroom location has significantly increased with time.
- The general view of 802.11b users that they have unfettered use of the license-exempt band is not supported. Many other sources with other emission formats also share the band.
- The users of the classroom system did not have a means to identify times of high interference or the intermittent cause of low throughput.

DATA RECORDS

Each example of the occupancy and use of the 2.4-GHz band in this report contains a data-identification line located below the example. The information in this line is obtained from the field-log table provided on a subsequent page. Measurement and instrumentation parameters needed to identify the source of each example and add amplitude, frequency, and time scales to each example are separated by commas in this line. The parameters in this line in order of occurrence are:

1. Location of the measurement.
2. Photograph file numbers.
3. Date in yymmdd format.
4. Local time of the measurement.
5. Center frequency in MHz.
6. Frequency span in MHz.
7. IF bandwidth in kHz.
8. Scan time in ms.
9. Antenna identification (M is a monople over a ground plane).
10. RF filter identification (N means no filter).
11. Preamplifier gain in dB.
12. RF attenuation in dB.
13. Analyzer gain in dB.

Data Log, NPS Class 040317/18

Location	Pic No.	Date yymmdd	Time Local	Freq. MHz	Span MHz	BW KHz	Scan T ms	Source	Filter ID.	Preamp dB	RF Attn dB	Ref. dBm	Comments
SP433	1T	040317	0201	2446	100	300	2000	M	N	+24	10	+10	
SP433	2A		1020										
SP433	3T	040317	1030	2445	100	300	1000	M	N	+24	10	+10	
SP433	4A		1030										
SP433	5A		1030										
SP433	6T	040317	1057	2423	50	100	1000	M	N	+24	10	+10	
SP433	7A		1057										
SP433	8T	040318	0902	2443	100	100	2000	M	N	+24	10	+10	
SP433	9A		0902										
SP433	10T	040318	0906	2443	100	100	2000	M	N	+24	10	+10	
SP433	11A		0906										
SP433	12	040318	0916	2443	100	100	2000	M	N	+24	10	+10	Top NPS Class & SS Phone, another access Pt added. FHSS Phone added, SS Phone added
SP433	13		0916										
SP433	14	040318	0922	2443	100	100	2000	M	N	+24	10	+10	
SP433	15A		0922										
SP433	16T		0922										
SP433	17	040318	0934	2444	100	100	2000	M	N	+24	0	0	
SP433	18		0934										
SP433	19	040318	0953	2444	100	100	2000	M	N	+24	0	0	Distorted SS at low end, 80211b added, 2 SS phones plus 1 discrete, ss phone in short burst
SP433	20		0953										
SP433	21A	040318	1000	2405	20	100	200	M	N	+24	0	0	SS expanded
SP433	22T												
SP433	23A	040318	1008	2407	5	300	500	M	N	+24	0	0	
SP433	24T		1008										
SP433	25T		1008										
SP433	26A	040318	1057	2445	100	100	1000	M	N	+24	0	0	Multiple 80211b sync sigs plus RFI near 2445
SP433	27T		1057										
SP433	28	040318	1100	2445	100	100	1000	M	N	+24	0	0	
SP433	19		1100										

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Technical Memorandum 0406
Signal Enhancement Laboratory
Electrical and Computer Engineering Department
Naval Postgraduate School
Monterey, CA

June 2004

Occupancy and Use of the 2.4-GHz License-Exempt Band during the Wireless Communications Class of June 2004

by:

Wilbur R. Vincent
and
Richard W. Adler

INTRODUCTION

Emissions in the 2.4-GHz license-exempt band were examined during a series of wireless communication classes held at the Naval Postgraduate School. Technical Memoranda describing the occupancy and use of the 2.4-GHz band were prepared for those classes when preparation time was available[22, 23, 24]. This memorandum provides examples of the occupancy and use of the band during the class held during June of 2004.

A single 802.11b Access Point was installed on the wall of Room 221 of Spanagel Hall. Each student was provided with an 802.11b wireless-equipped laptop (a maximum of 27 classroom positions). Instruction material appeared on the laptops, and each student could add class notes to his personal file located on a NPS server. In addition, the conventional verbal interchange and discussion between the instructors and students was encouraged.

Monitoring of the occupancy and use of the 2.4-GHz band was accomplished during class periods from an adjacent room. The monitoring equipment consisted of a moveable cart containing a receiving antenna, preamplifier, spectrum analyzer, and time-history display. Data from the time-history display was recorded with a digital oscilloscope camera and saved on the hard drive of a laptop. The digital oscilloscope camera replaced a conventional film-type oscilloscope camera used previously to record data. The recorded data was processed and formatted with another laptop using conventional software (Paint Shop Pro).

Data obtained during the class was similar to that obtained from previous classes. Of importance is the ever-changing variety of emissions found during the daytime hours including the 802.11b classroom signals, signals from other 802.11b nets, signals from various kinds of wireless portable telephones, random noise impulses, and noise from microwave ovens. All past classes experienced erratic impulsive interference in the lower half of the band. The characteristics of this interference were examined in some detail during this class.

A copy of the data-log for the June 2004 measurements is provided at the end of the memorandum along with an explanation of the contents of the file. Information from this file is added to the bottom of each example of data presented in this memorandum.

---

[22] Wilbur R. Vincent and Richard W. Adler, ***Occupancy and Use of the 2.4-GHz License-Exempt Band during the Wireless Communications Class of March 2004***, Report No. NPS-EC-0305, Electrical and Computer Engineering Department, Naval Postgraduate School, Monterey, CA, October 2003

[23] Wilbur R. Vincent and Richard W. Adler, ***Occupancy and Use of the 2.4-GHz License-Exempt Band during the Wireless Communications Class of September 2003***, Report No. NPS-EC-03-05, Electrical and Computer Engineering Department, Naval Postgraduate School, Monterey, CA, October 2003

[24] Wilbur R. Vincent and Richard W. Adler, ***Occupancy and Use of the 2.4-GHz Band during the Wireless Communications Class of March 2003***, Report No. NPS-EC-03-04, Electrical and Computer Engineering Department, Naval Postgraduate School, Monterey, CA, June 2004

EXAMPLES OF DATA

The occupancy and use of the 2.4-GHz band was monitored during class sessions held on 14 through 16 of June 2004. Monitoring was done from an adjacent room to prevent interference with normal classroom activities. A demonstration of the operation of the monitoring system was provided to the students at the end of the monitoring period.

Figure 1 shows a typical example of the occupancy and use of the band at a time of minimal interference. Two views of the same data are provided. The upper view is similar to the amplitude-vs.-frequency view obtained from a spectrum analyzer. The bottom view shows 60 successive scans of the same data where the amplitude is severely compressed. New data enters at the bottom of the view and old data disappears from the top of the time-history view. The spectrum analyzer was adjusted to cover the entire license-exempt wireless band for this example.

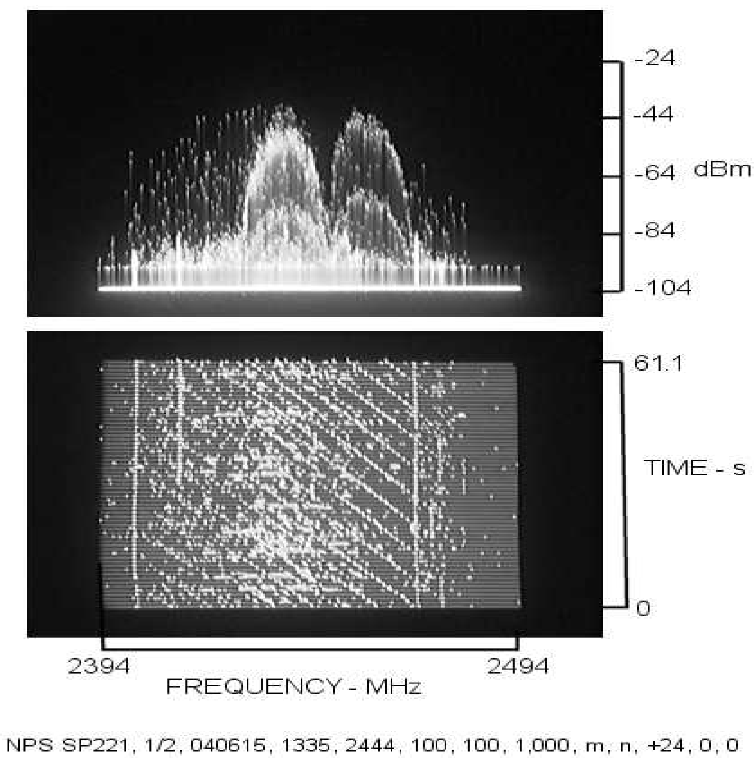

Figure 1

Occupancy and Use, Example 1

A number of features of interest are shown in the two views of Figure 1. The classroom 802.11b emission is shown at the center of the frequency range. Its amplitude (-46 dBm at the center of the emission), and its spectral shape are shown in the upper view. Synchronizing pulses emitted from the access point appear as slanting lines in the lower time-history view. Data pulses appear between the synchronizing pulses as the laptops are used by the students, resulting in a somewhat confusing picture of emissions from both the access point and the laptops.

A second 802.11b emission from another nearby access point appears at a higher frequency. Synchronization pulses from this emission are more clearly shown in the time-history view because data transmission to and from other computers associated with this access point was not underway at the time of the example. The time displacement of the slanting lines from the two access points indicates that each operates from its own time base.

Emissions from two spread-spectrum portable telephones appear in both views at frequencies lower than the classroom 802.11b signal. The width and spectral shape of the spread-spectrum emissions is not shown because of the rather wide band of frequencies being observed. Expanded views of the spectral and temporal properties of such emissions are provided in the referenced documents. A third spread-spectrum emission from a portable telephone appears at the upper edge of the higher-frequency 802.11b emission, and three additional low-level spread-spectrum emissions appear at higher frequencies.

One other item of special interest is shown in this view. Additional pulses at erratic times and at erratic amplitudes are shown below and above the two 802.11b emissions. Those at lower frequencies are very high in amplitude while those above the emission from the nearby 802.11b access point are considerably lower in amplitude. These erratic pulses have been noted during all previous classes, and they cause intermittent interference to the classroom wireless system.

One additional feature appears in the view. Short bursts of high-level emissions appear at random times throughout the entire band at amplitudes approaching -35 dBm in amplitude. They caused intermittent interference to the reception of 802.11b signals by the classroom access point and by the laptops during the entire class period. The source of these erratic-occurring pulses is nearby, but it has not been located. The characteristics of these emissions are presented in more detail later in this report.

Figure 1 represents a typical case of the occupancy and use of the 2.4-GHz band during a classroom session at a time of relatively low use. It indicates that a maximum of three 802.11b emissions can operate in the band at one location without mutual interference. Any 802.11b system must expect intermittent interference from other emissions such as portable telephones, microwave ovens and other sources. The references show examples of interference from microwave ovens.

Figure 2 shows another example of the occupancy and use of the 2.4-GHz band during a class session. In this case the scan time of the spectrum analyzer was increased from the 1000 ms values of Figure 1 to 5,000 ms. The longer scan time resulted in a longer duration of the time-history axis. The emission from a frequency-hopping portable telephone was introduced into the band. Signals from this particular telephone hopped across the entire band, resulting in occasional collisions with the synchronizing and data pulses of the classroom 802.11b system and with the second 802.11b system. This reduced the throughput of both systems. Since the telephone was designed to emit synchronizing signals spaced at 100-ms intervals at all times throughout the entire license-exempt band, it was considered an undesirable type of emission. The portable telephone synchronizing pulses were locked to the power-line frequency so that its data-transmission pulses occurred during the off times of noise pulses from microwave ovens.

An emission from a nearby spread-spectrum portable telephone was introduced into the band for a short time at a frequency below the classroom 802.11b signal. This signal appears in both the upper and lower views. Its amplitude is about –40 dBm. Erratic interference of undetermined origin appears in the upper-right portion of the time-history view.

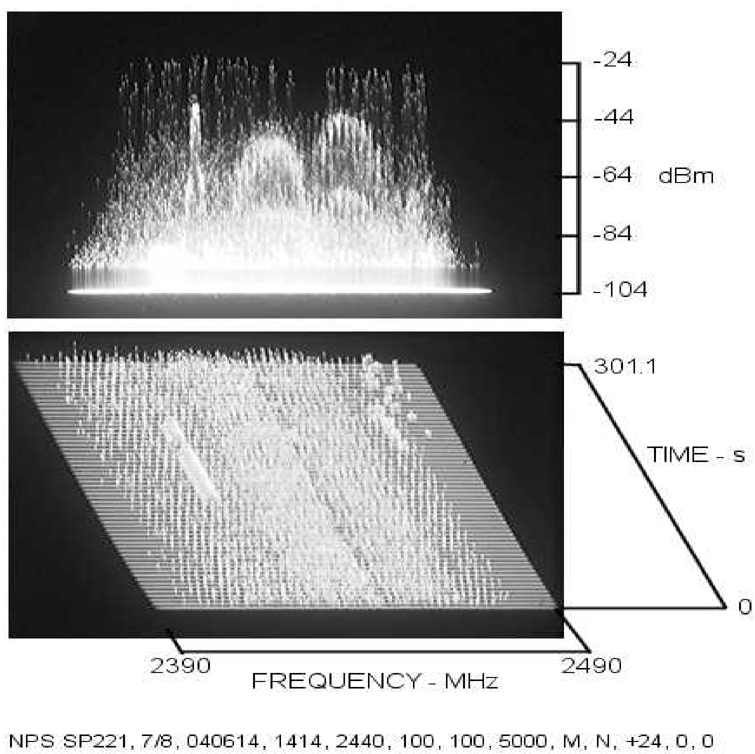

Figure 2

Occupancy and Use, Example 2

Figure 3 shows another example of the occupancy and use of the 2.4-GHz band during a class period. The two 802.11b signals remain, but another emission stronger in amplitude appeared in the band appeared about 1/3 of the way up the time-history axis. Its amplitude is about –44 dBm, and the emission remained on for the remainder of the observation time. An examination of the spacing of its synchronizing pulses indicates it operates at a rate about three times that of 802.11b systems. The emission occupied about 80 percent of the 2.4-GHz band, leaving only a small portion of the band at the high end for other uses. This emission was a serious source of interference to the classroom 802.11b system since its high synchronization pulse rate resulted in numerous collisions with 802.11b synchronizing and data pulses.

A close examination of the time-history view indicates that a second such signal also exists at low levels. This lower-level signal can be seen in the lower part of the time-history axis, and it also appears in the upper view at about –72 dBm in amplitude.

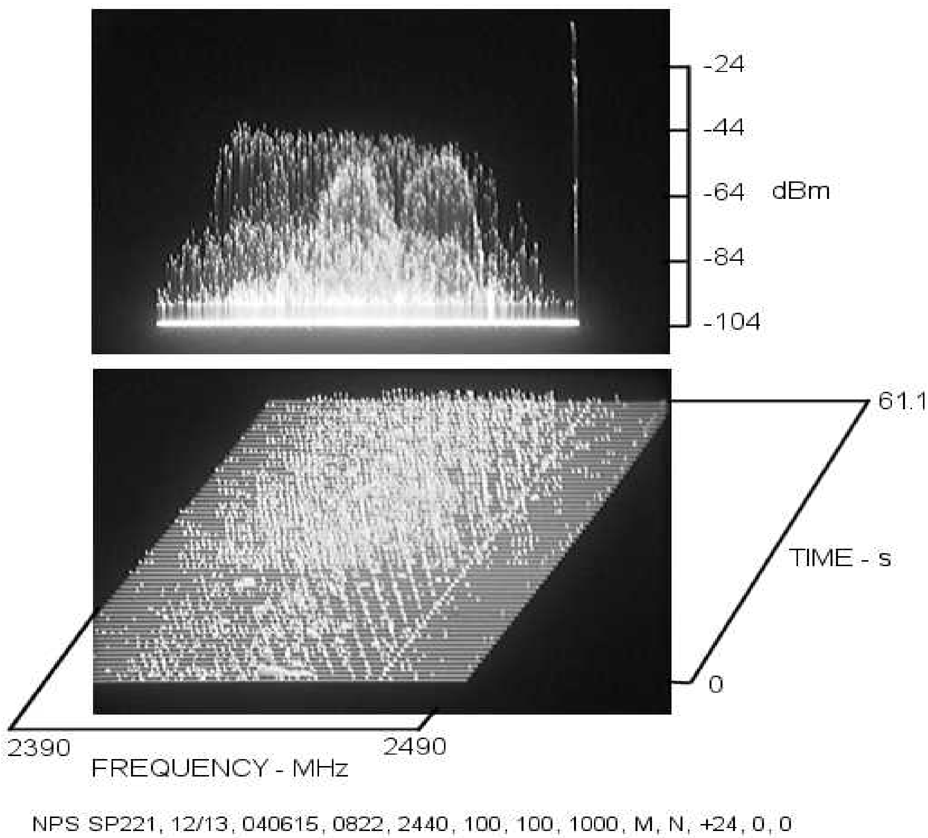

Figure 3

Occupancy and Use, Example 3

Figure 4 shows another example of the pulse interference found in the 2.4-GHz band. The reduced frequency span of the example shows only a portion of the spectral shape of the interference along with the classroom 802.11b signal. The lower view shows the slanting lines caused by the repetitive rate of the interference pulses. An examination of these lines show they change in slope with time. This is caused by a change in the repetition rate of the pulses. The pulse rate of the interference can be crudely scanned from the data, it is on the order of 2 to 4 pulses per second. Similar radio interference is often found in the HF, VHF, and low UHF portions of the spectrum from digitally-controller power-conversion devices, but the origin of these pulses was not identified during the short classroom monitoring periods.

A burst of higher repetition rate pulses occurred at the top of the time-history view. These pulses were from a different source. Another brief burst of interference occurred about two-thirds of the way down the time-history view. The sources of these additional bursts of interference were not identified.

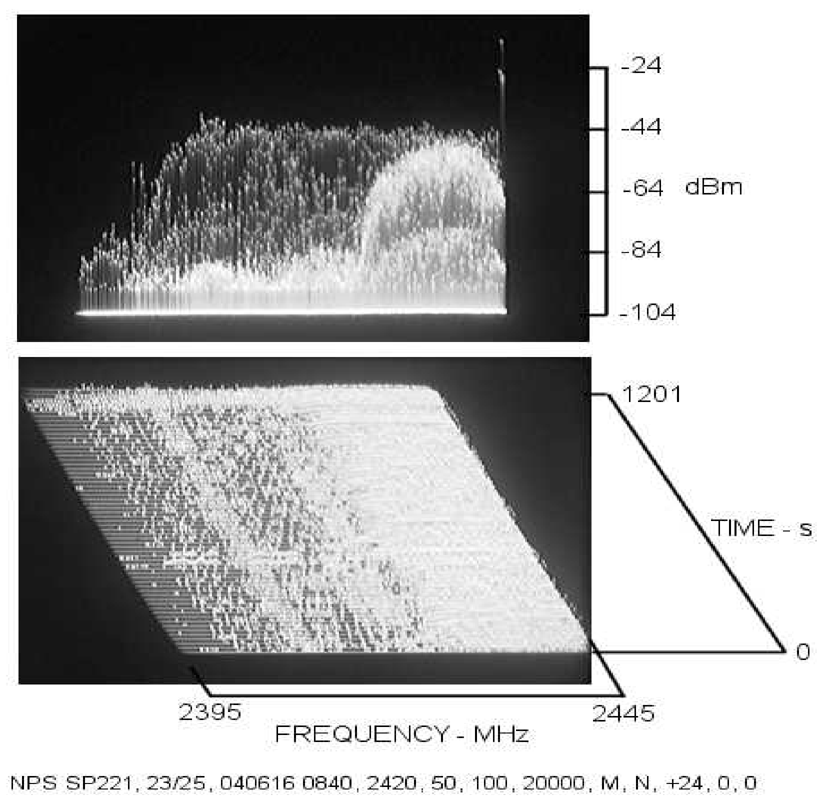

Figure 4

Occupancy and Use, Example 4

Figure 5 examines the random impulsive noise that often appears in the 2.4-GHz band. The frequency span of the data was reduced to 50 MHz, and the scan time was increased to 10,000 ms. for this example. Pulses at random times are shown across most of the band, and another high-amplitude emission is shown on top of the classroom 802.11b signal. These two emissions can be distinguished from each other in the upper view. The characteristics and sources of these emissions were of concern since they were present during all previous classes.

Additional lower-level emissions appear as the bright area in the upper view at frequencies below the 802.11b signal. The threshold control was adjusted to remove these low-level signals from the time-history view.

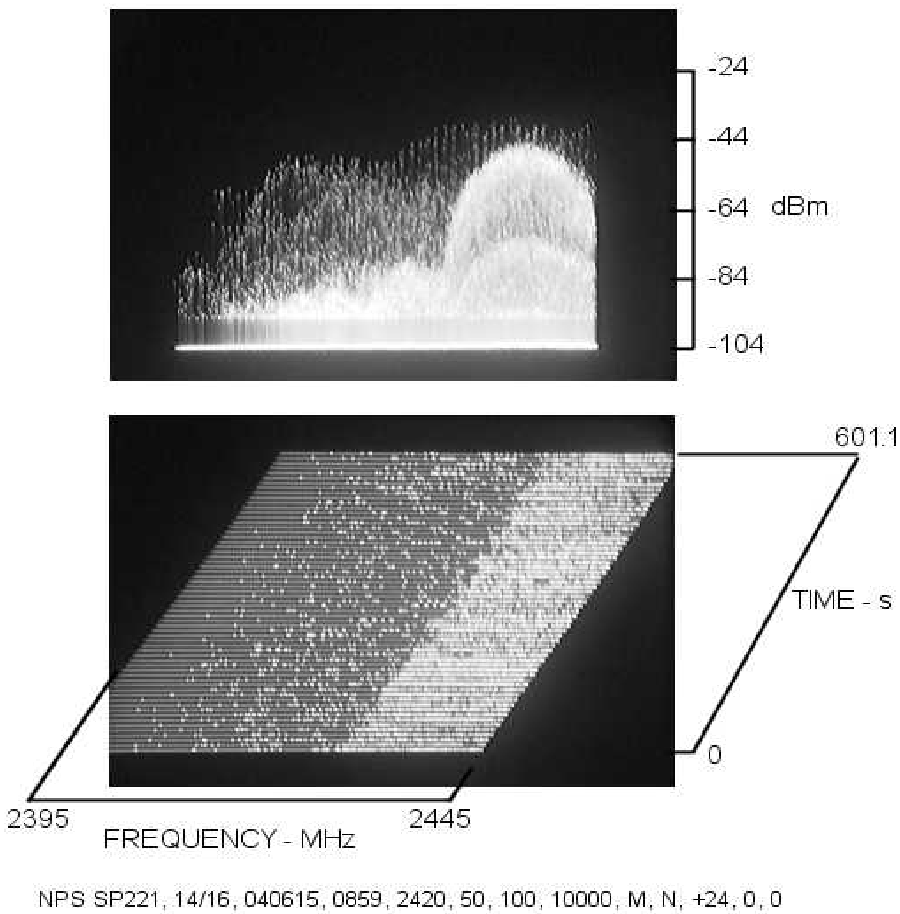

Figure 5

Occupancy and Use, Example 5

Figure 6 shows another view of the data in Figure 5. The threshold level of the time-history view was increased to eliminate all except the high-amplitude pulses at and near the frequency of the classroom 802.11b signal. The time-history view shows that this emission consisted of groups of four or five close-spaced pulses that occurred at a low rate, they then turned off and reappeared at the same low rate. The source of this unusual signal format or its purpose is not known at this time. It is another example of the erratic emissions that are found in the 2.4-GHz band. The strong signal level of this emission implies that the source is nearby or from a more distant location using high transmitter power and a high-gain antenna.

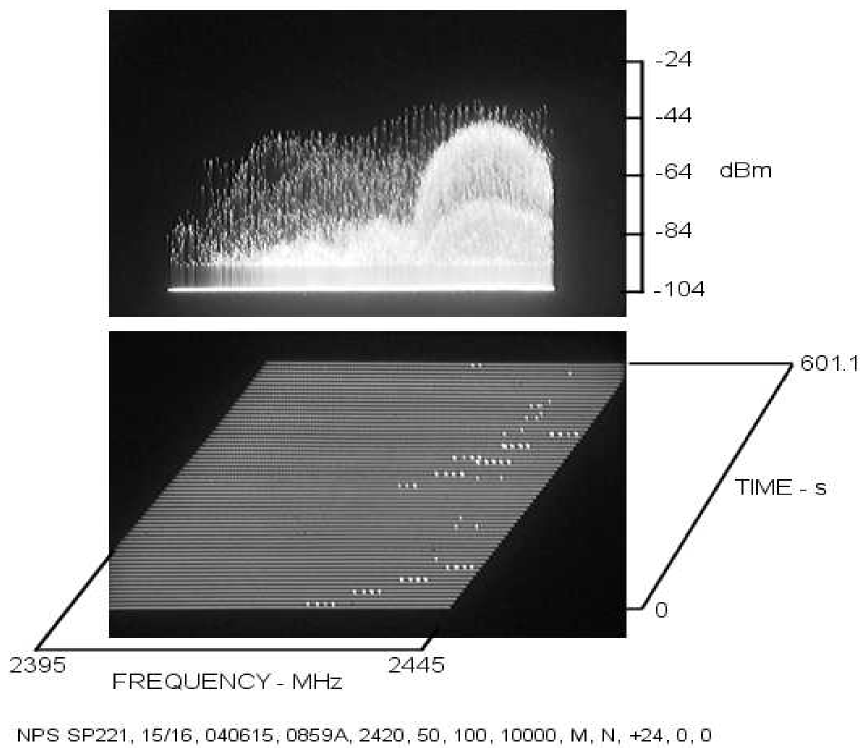

Figure 6

Occupancy and Use, Example 6

The random-appearing pulses at the low end of the 2.4-GHz band were further investigated by changing the measurement system operating parameters to optimize the presentation of these signals. Also a time was chosen when the high-level signal shown in Figure 6 was not present and when the classroom laptops were not sending data to, or receiving data from, the access point.

The upper view of Figure 7 shows the usual spectral shape of the classroom 802.11b signal and the impulsive emissions at lower frequencies. The time-history view shows the synchronizing pulses of the classroom access point as well as synchronization pulses from two nearby 802.11b systems operating on the same frequency. The two additional 802.11b systems operating on the same frequency as the classroom system reduced the throughput of the classroom system.

An examination of the impulses at frequencies below the classroom 802.11b system indicate that these pulses are from other 802.11b systems operating outside the classroom. The spectral shape of these emissions is not defined as expected because of random variations in pulse amplitudes. Some aspect of the sources, or the propagation path from the sources to the measurement system, caused the amplitude to significantly change from pulse to pulse.

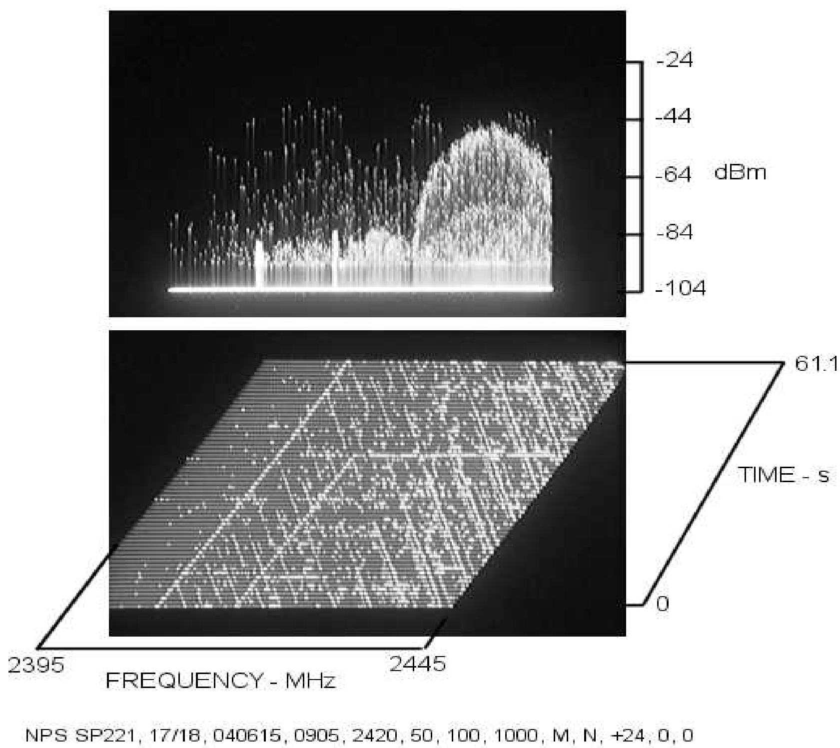

Figure 7

Occupancy and Use, Example 7

Figure 8 shows another example of interference at the low end of the 2.4-GHz band. The frequency span was reduced to 20 MHz for this example, thus this narrow band did not include the classroom 802.11b signal.

The slanting lines from the synchronizing signals of several 802-11b signals can be found in the time-history view. Bursts of impulsive signals also appear at four times along the time axis. These bursts occur at about the same rate of the interference shown in Figure 4. The increased resolution of the scan time indicates the pulse-to-pulse spacing is not consistent. The amplitude of these bursts is about –45 dBm. The amplitude of the 802.11b synchronizing signals is lower and much more erratic.

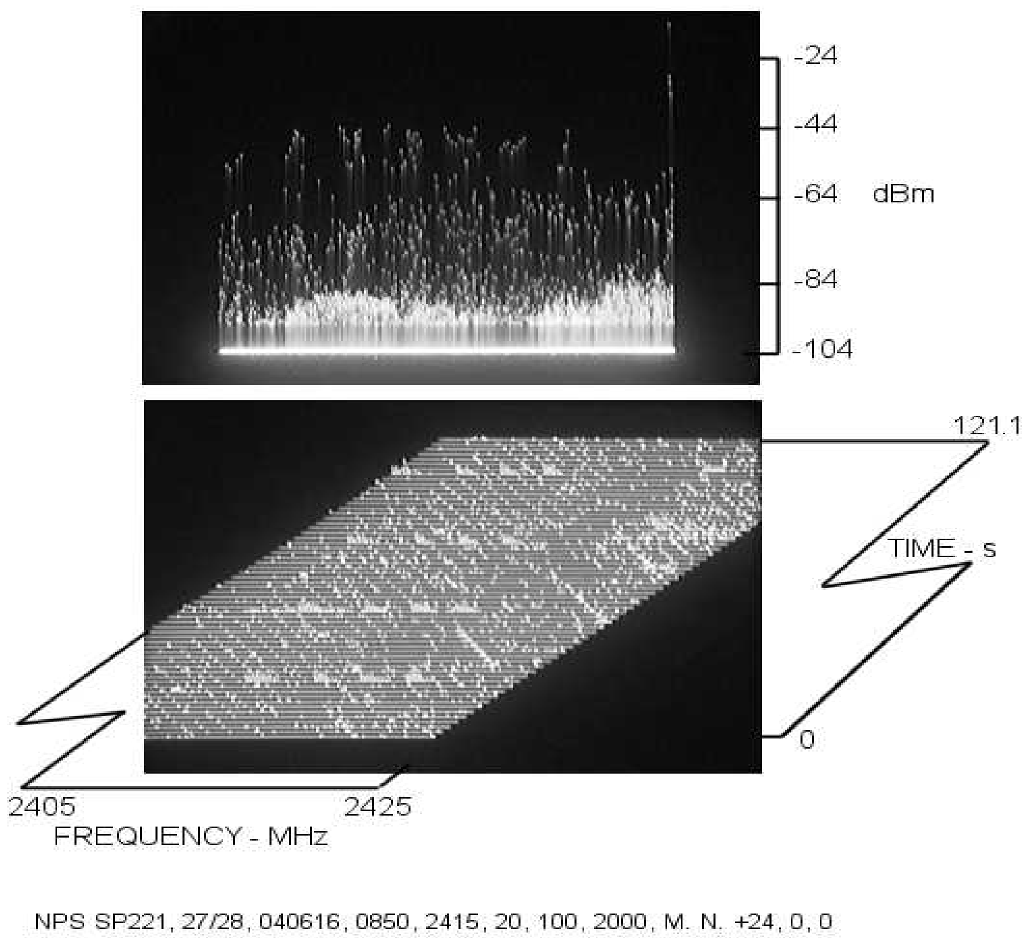

Figure 8

Occupancy and Use, Example 8

Figure 9 shows still another example of the occupancy and use of a portion of the 2.4-GHz band during the June 2004 wireless communications class. The bursts of noise described in Figure 8 are present in this view, and they cause the impulses appearing in the upper view at about –44 dBm. In addition, a single large burst of signal appeared about half way down the time axis of the lower view. The amplitude of this burst is also about –45 dBm and it cannot be distinguished from the amplitude of the other bursts in this example. Additional signal bursts appear at other times in the time-history view.

The slanting lines of several 802.11b signals are shown in the time-history view. Their amplitude is more random and peaks at about –65 dBm. As in previous examples the spectral shapes of the 802.11b emissions cannot be distinguished because of the random amplitude of the pulses.

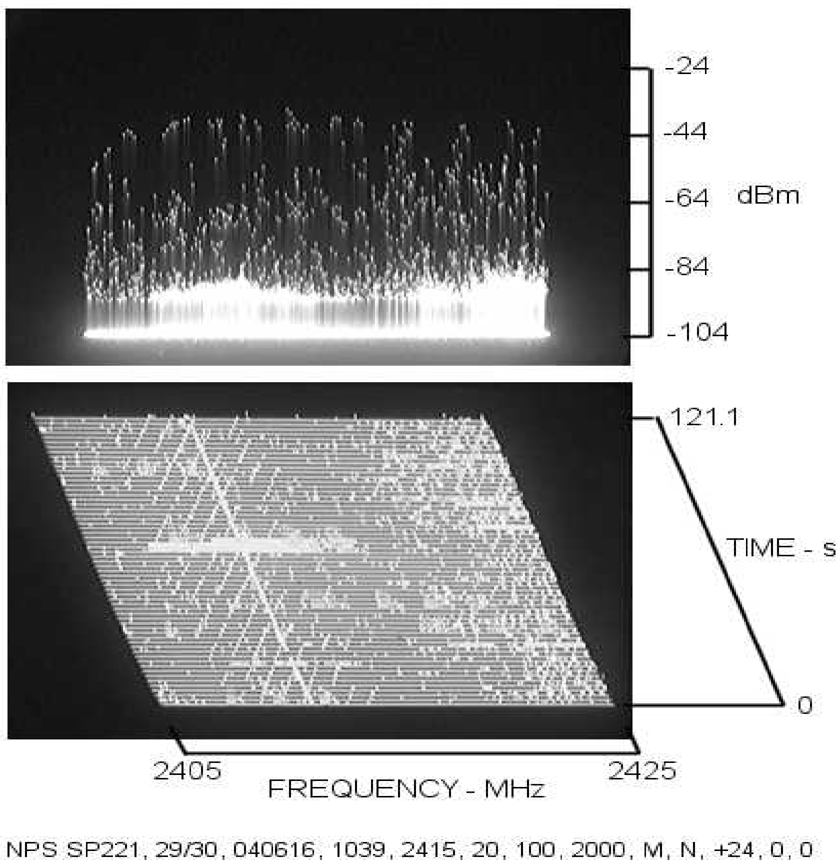

Figure 9

Occupancy and Use, Example 9

The large burst shown in the previous view was explored in more detail by examining the four scan lines containing the burst. The upper view of Figure 10 shows the complex amplitude detail of the burst as well as other random impulses contained on the four scan lines. It also shows an increase in the noise floor starting just before the burst and extending after the burst.

The amplitude of pulses in the four scan lines has been compressed in the time-history view to optimize the visual presentation of the signal structure. The top scan line shows only the random amplitude noise pulses. The second scan line shows four bursts of pulses where the first pulse burst is wider than the next three. The spacing between pulses is about 212 ms. A longer duration emission exists lower in amplitude and under the four pulses. The high amplitude bursts disappeared in the third and fourth scan lines, but the low-level emission remained.

The properties of the interference shown in the two views are highly useful during source-identification tasks.

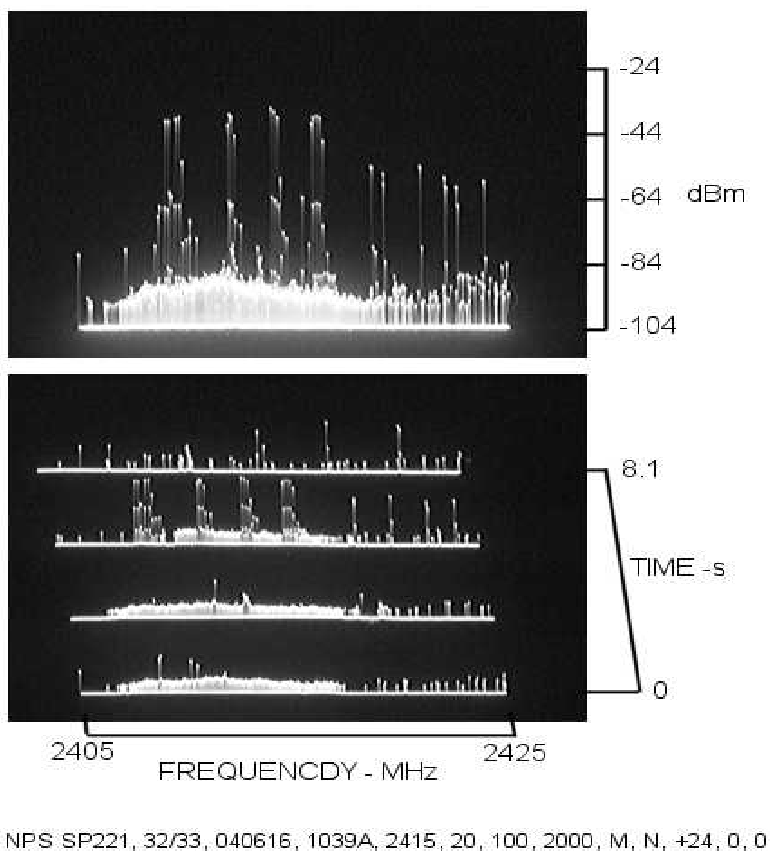

Figure 10

Fine-Scale View of Temporal Structure of a Noise Burst

DISCUSSION

Ten examples of the occupancy and use of the 2.4-GHz license-exempt band are provided in this report. These examples were obtained during the June 2004 Wireless Communications Class at the Naval Postgraduate School. They are typical examples, and they supplement similar data and information obtained during previous classes.

Erratic pulses have been observed in the lower half of the 2.4-GHz license-exempt band during all measurements sessions at the Naval Postgraduate School at Monterey CA and to a lesser extent in the upper half of the band. Special attention was given to the temporal and spectral characteristics of these pulses during this measurement session. The type of source has been identified as synchronizing pulses emitted from several 802.11b Access Points located outside and probably some distance from the two classrooms in Spanagel Hall used for the wireless communications classes. The large variation in amplitude from pulse to pulse (often more than 40 dB and at times more than 60 dB) obscured observing the orderly temporal structure of these emissions during prior measurement sessions.

Early measurements at the home office in Davis CA did not produce similar results although very recent measurements indicate that erratic amplitude pulses now appear in portions of the 2.4-GHz band at that location. This suggests the reception of impulses ranging in amplitude from the receiver noise floor up to the very high levels (60 dB or even more) might be a common problem at other locations.

The reason for the very large variation in amplitude from pulse to pulse is not understood at this time since the actual sources were not located nor is the propagation path from the source to the receiver known. The possibility of impulsive intermodulation noise generated by RF component saturation from high-level pulse emissions has been eliminated by the careful examination of all signals within the bandpass of the measurement system. One possibility is that multipath from reflections off moving objects that are within the propagation path between the source and the measurement location can result in the reception of pulses at varying amplitudes. This possibility will be examined in subsequent measurement sessions.

Other results from this measurement session were similar to those reported in the referenced documents.

DATA RECORD FOR WIRELESS COMMUNICATION

Class of June 2004

Information about each item of data obtained during a measurement session is recorded in a table. The two tables from the June 2004 Wireless Radio Communications class at NPS follow this page. The information in this table is used to add amplitude, frequency, and time scales to each item of data and to add any desired annotation to the data..

Each example of the occupancy and use of the 2.4-GHz band contained in this report has a data-identification line located below the example. The information in this line is obtained from the table on the following pages. Measurement and instrumentation are separated by commas in this line. The parameters in this line in order of occurrence are:

1. Location of the measurement.
2. Photograph file numbers.
3. Date in yymmdd format.
4. Local time of the measurement.
5. Center frequency in MHz.
6. Frequency span in MHz.
7. IF bandwidth in kHz.
8. Scan time in ms.
9. Antenna identification (M is a monople over a ground plane).
10. RF filter identification (N means no filter).
11. Preamplifier gain in dB.
12. RF attenuation in dB.
13. Analyzer gain in dB.

Data Log, NPS 040615/17, Rm SP221, Page 1

Location	Pic No.	Date yymmdd	Time Local	Freq. MHz	Span MHz	BW kHz	Scan T ms	Source	Filter id	Preamp dB	RF Attn dB	Ref. dBm	Comments
SP 221	1T	040614	1335	2444	100	100	1000	M	N	+24	0	0	
SP211	2A	“	“	“	“	“	“	“	“	“	“”	“	
SP221	3T	040614	1404	2444	100	100	2000	M	N	+24	0	0	
SP221	4A	“	“	“	“	“	“	“	“	“	“	“	
SP 221	5A	“	“	“	“	“	“	“	“	“	“	“	
SP211	6A	“	“	“	“	“	“	“	“	“	“	“	
SP221	7T	040614	1414	2440	100	100	5000	M	N	+24	0	0	
SP221	8A	“	“	“	“	“	“	“	“	“	“	“	
SP 221	9A	“	“	“	“	“	“	“	“	“	“	“	
SP211	10T	040615	0822	2440	100	100	1000	M	N	+24	0	0	
SP221	11T	“	“	“	“	“	“	“	“	“	“	“	
SP221	12	“	“	“	“	“:	“	“	“	“	“	“	
SP 221	13T	“	“	“	“	“	“	“	“	“	“	“	
SP211	14T	040615	0859	2420	50	100	10,000	M	N	+24	0	0	
SP221	15T	“	“	“	“	“	“	“	“	“	“	“	
SP221	16	“	“	“	“	“	“	“	“	“	“	“	
SP 221	17T	040615	0905	2420	50	100	1000	M	N	+24	0	0	Multiple 802.11b systems
SP211	18	“	“	“	“	“	“	“	“	“	“	“	“
SP221	19T	040615	0916	2420	50	100	500	M	N	+24	0	0	
SP221	20	“	“	“	“	‘	“	“	“	“	“	“	

Data Log, NPS 040615/17 Rm SP221, Page 2

Location	Pic No.	Date yymmdd	Time Local	Freq. MHz	Span MHz	BW kHz	Scan T ms	Source	Filter id	Preamp dB	RF Attn dB	Ref. dBm	Comments
SP221	21	040615	1332	2420	50	100	10,000	M	N	+24	0	0	
SP221	22	"	"	"	"	"	"	"	"	"	"	"	
SP221	23T	040616	0840	2420	50	100	20,"000	M	N	+24	0	0	
SP221	24	"	"	"	"	"	"	"	"	"	"	"	
SP221	25	"	"	"	"	"	"	"	"	"	"	"	Top 16 scans
SP221	26	"	"	"	"	"	"	"	"	"	"	"	Bottom 16 scans
SP221	27T	040616	0850	2415	20	100	2000	M	N	+24	0	0	Erratic 802.11b sigs on low end
SP221	28	"	"	"	"	"	"	"		"	"	"	
SP221	29	040616	1039	2415	20	100	2000	M	N	+24	0	0	
SP221	30	"	"	"	"	"	"	"	"	"	"	"	
SP221	31	"	"	"	"	"	"	"	"	"	"	"	4 lines at burst, wide pulses
SP221	32	"	"	"	"	"	"	"	"	"	"	"	
SP221	33	"	"	"	"	"	"	"	"	"	"	"	Amplitude of No. 31

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APPENDIX C. HOMELAND SECURITY MEASUREMENTS

Two documents are provided in this appendix. They are:

- Technical Memorandum 0501, ***Signal Population in the License-Exempt Radio Bands at the MOUT Site***, October 2004
- Technical memorandum 0409, ***Ambient Signal Population at Three Locations on Camp Roberts***, September 2004

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Technical Memorandum 050115
Signal Enhancement Laboratory
Department of Electrical and Computer Engineering
Naval Postgraduate School,
Monterey, CA

October 2004

SIGNAL POPULATION IN THE LICENSE-EXEMPT RADIO BANDS AT THE MOUT SITE

by:
Wilbur R Vincent
Richard W. Adler
and
Andrew A Parker

1. INTRODUCTION

Radio-signal population and radio-interference conditions were examined at the Military Operations in Urban Terrain (MOUT) site located on the former Fort Ord, CA on two occasions. Background measurements were made on 18 August 2004, and measurements during a field exercise were made on 30 September 2004. The purpose of the measurements was to identify any signal or noise that might interfere with radio communications and data links during field exercises, and to observe the occupancy of portions of the radio spectrum of interest during a field exercise.

Additional measurements of the occupancy of the bands of interest were made at the CIRPAS Hangar (at the Marina, CA (OAR) airport) at the completion of the MOUT site exercise.

Available instrumentation was installed in a NPS instrumentation van for mobility, and it was used for the measurements. The instrumentation is briefly described in Section 2. Extensive information about the occupancy and use of portions of the radio spectrum is provided in the form of photographs of time-history views of signals and noise in selected portions of the radio spectrum. All examples of data included in this report are calibrated in frequency, time, and amplitude.

Figure 1 shows a photograph of the instrumentation van at the MOUT site.

Figure 1 Photograph of Instrumentation Van at the MOUT Site

2. INSTRUMENTATION

A Naval Postgraduate School instrumentation van was equipped with radio spectrum measurement equipment, and it was used for this effort. Figure 2 shows a photograph of the instrumentation van and its diesel generator trailer at a field measurement location. The van could be rapidly moved from location to location, and it could be operated while in motion.

Figure 2 Photograph of Instrumentation Van

Antennas for each band of interest were installed in the roof of the van. Figure 3 shows the three antennas used for these measurements. Short coaxial cables ran from each antenna through the roof vent and to instrumentation preamplifiers located directly below the roof vent.

Figure 3 Photograph of Antennas on the Instrumentation Van

Two sets of instrumentation were installed in the van. One set covered the band from 0.1 MHz up to 1250 MHz. The second set covered the frequency range of 10 MHz up to 14 GHz. Figure 4 is a photograph of the 10-MHz to 14-GHz instrumentation. A Hewlett Packard Model 3565A Spectrum Analyzer is on the bottom of the photograph, the time-history display in the middle of the photograph, and preamplifiers are on the top of the time-history display.

Figure 4 Instrumentation for the UHF and Microwave Bands

Figure 5 is a photograph of the instrumentation used to cover the 0.1 to 1250 MHz frequency range. A Hewlett Packard Model 141 Spectrum Analyzer is shown on the lower left part of the photograph. The time-history display used to observe signals in the 0.1- to 1250-MHz band is above the spectrum analyzer, and its preamplifier and a filter are located on top of the display.

The oscilloscope camera used to photograph examples of data is in the center of the photograph, and the laptop computer used to store and process data is at the right edge of the photograph. These two items were shared with the first instrumentation suite to minimize equipment and allow all data files to be stored on one computer.

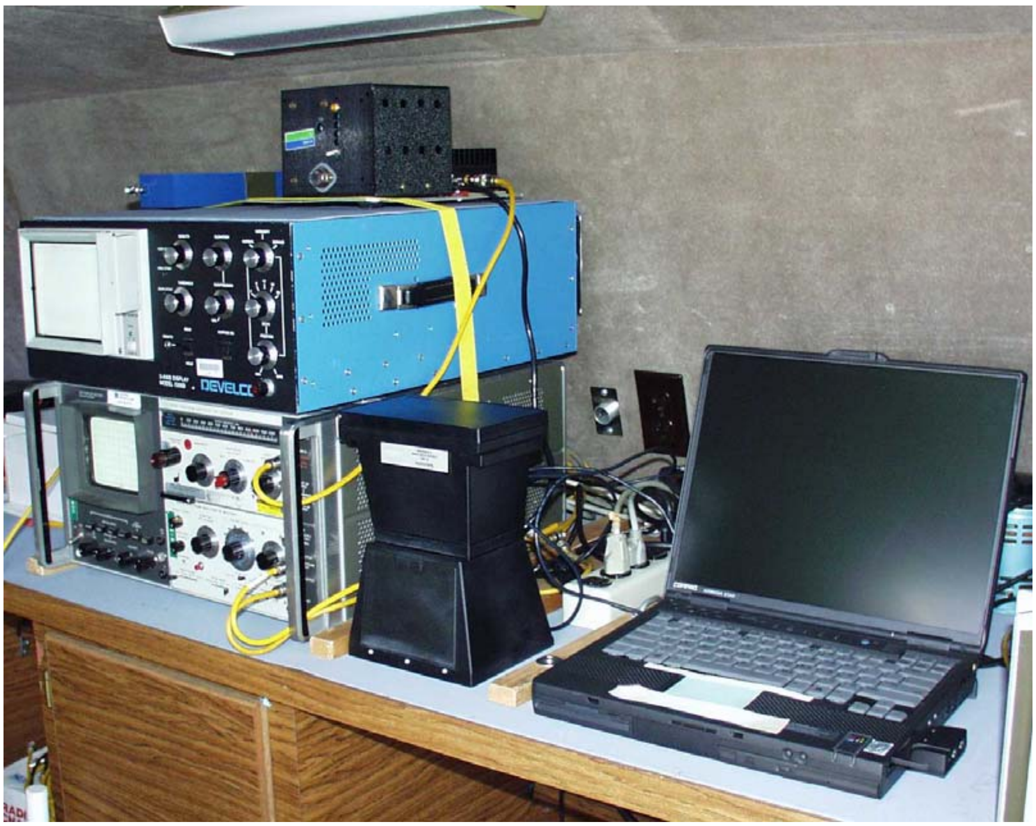


Figure 5 Instrumentation for the 0.1- to 1250-MHz Band

3. AMBIENT MEASUREMENTS

3.1 General Approach

The background electromagnetic environment in the license-exempt wireless-radio bands was explored at the MOUT site prior to the conduct of a field exercise. This was conducted on 18 August 2004. The purpose of the effort was to obtain information about ambient signals at that site that might interfere with the operation of devices in these bands during an extensive field exercise to be conducted at a later date. In addition to the exploration of the ambient environment, an 802.11b access point and one portable communications set was briefly operated to obtain preliminary information about its spectral and temporal properties.

The instrumentation van and its diesel-generator trailer were driven to the MOUT site on the morning of 18 August 2004. The van was parked near the middle of the MOUT facility, and it was operated for several hours collecting data on emissions in the wireless-radio bands.

The MOUT facility is located in a remote part of the former field-exercise range of Fort Ord, California, now under the control of the United States Bureau of Land Management. The facility is located at the bottom of a valley with rather steep hills surrounding the valley. No visible sign of facilities or equipment for the use of the license-exempt wireless-radio bands were visible to the van's operators during the test other than a single test communication device. This device was under the complete control of a NPS student.

Since the location of the van was in a valley surrounded by high hills, the ambient population of signals in the bands of interest was expected to be very low to none. Of interest was that earlier measurements at nearby higher elevation locations had identified two rather strong emissions in the 2.4-GHz license-exempt wireless-radio band. The two emissions originated from a nearby mountaintop communications site that provided wireless communications to clients in nearby urban areas. These two emissions were found at higher elevations in the hills surrounding the MOUT site and on the road to the site, but not at the actual test location. Signal attenuation due to terrain loss reduced the level of these signals well below the noise floor or the instrumentation and below the detection levels of the communications systems used for the tests as long as the communications systems were deployed at the lower elevations of the MOUT site.

3.2 Ambient Results

Figure 6 shows that the band is almost vacant of emissions at the low elevation of the MOUT site. A very low-level signal (or set of signals) was found near the center of the band. It is suspected that this signal is from a source outside the valley, and the signal level is attenuated by terrain loss sufficiently that it will not affect the operation of communications systems in this band that are operated at and near the valley floor.

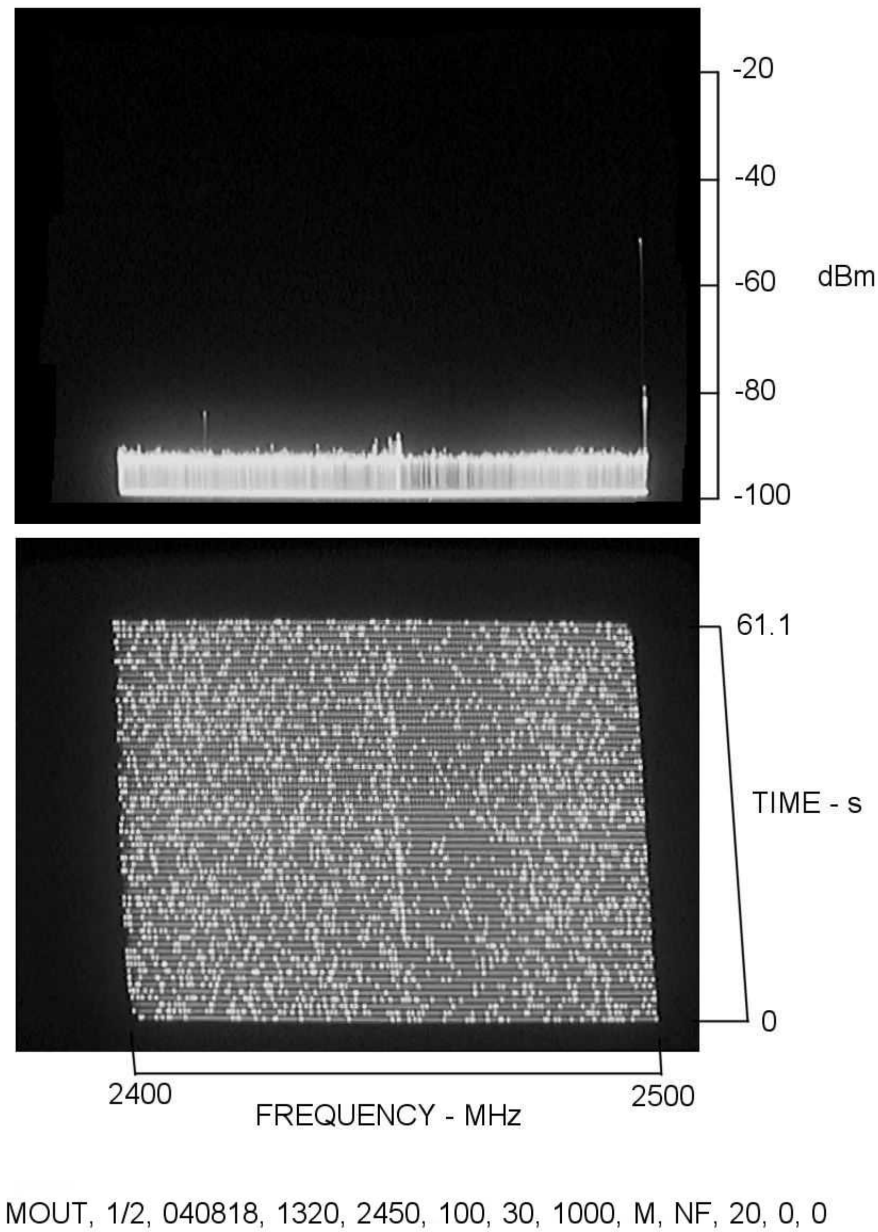


Figure 6 Background Emissions in the 2400- to 2500-MHz Band

The frequency axis was changed from a width of 100 MHz to 10 MHz to obtain a more detailed look at the low-level signals shown in the prior example. Figure 7 shows that pairs of bursts of signals are on three frequency channels. Again, these signals are low in amplitude and should not interfere with the operation of other devices in the lower elevations of the valley.

The source of the signal bursts was not identified during the ambient background measurements. Of interest is that these signals were not found during other measurements at higher elevation locations in the general vicinity of the MOUT site.

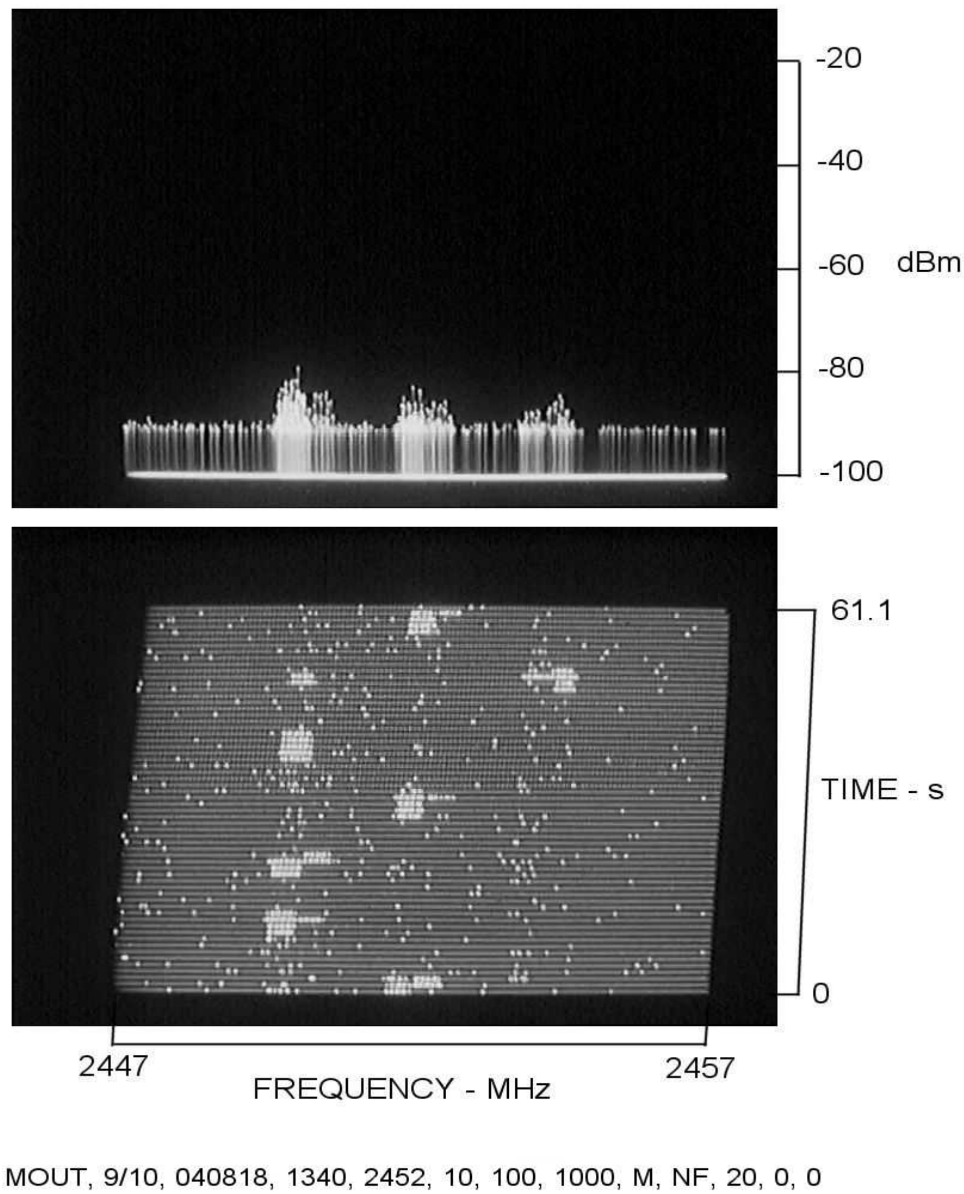


Figure 7 Pairs of Low-Level Burst Signals

During the ambient measurements at the MOUT site, one communications unit of the type to be used in later field exercises at the site was available for test transmissions. It was set up about 100 ft from the NPS instrumentation and operated for a few minutes. Figure 8 shows the emission from the unit at turn-on. At turn on spurious emissions were noted above and below the normal operating frequency of the unit. A normal spectral shape occurred a few seconds later, but a few intermittent pulses higher than the normal emission bandwidth were noted about ¾ the way down the time axis.

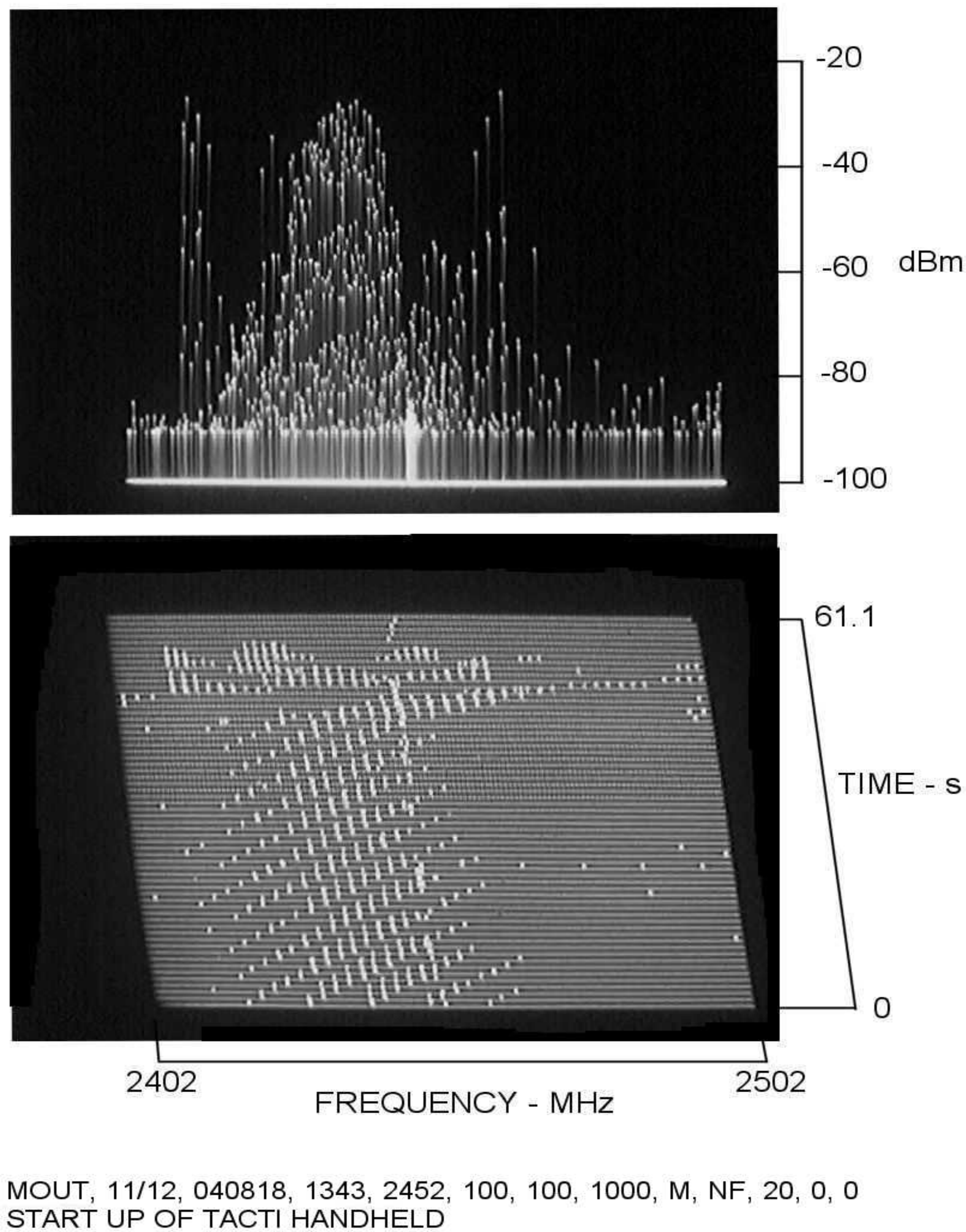


Figure 8 Spectral Content of Test Communications Device, Example 1

The time-history view in Figure 8 is also somewhat confusing since it is not representative of the temporal structure of a signal from an 802.11b device. The temporal structure changed later and became more representative of an emission from an 802.11b device as shown in Figure 9. Of interest is that spurious pulse emissions above and below the normal spectral width of the signal were still present. This suggests the unit needs to be checked for proper operation.

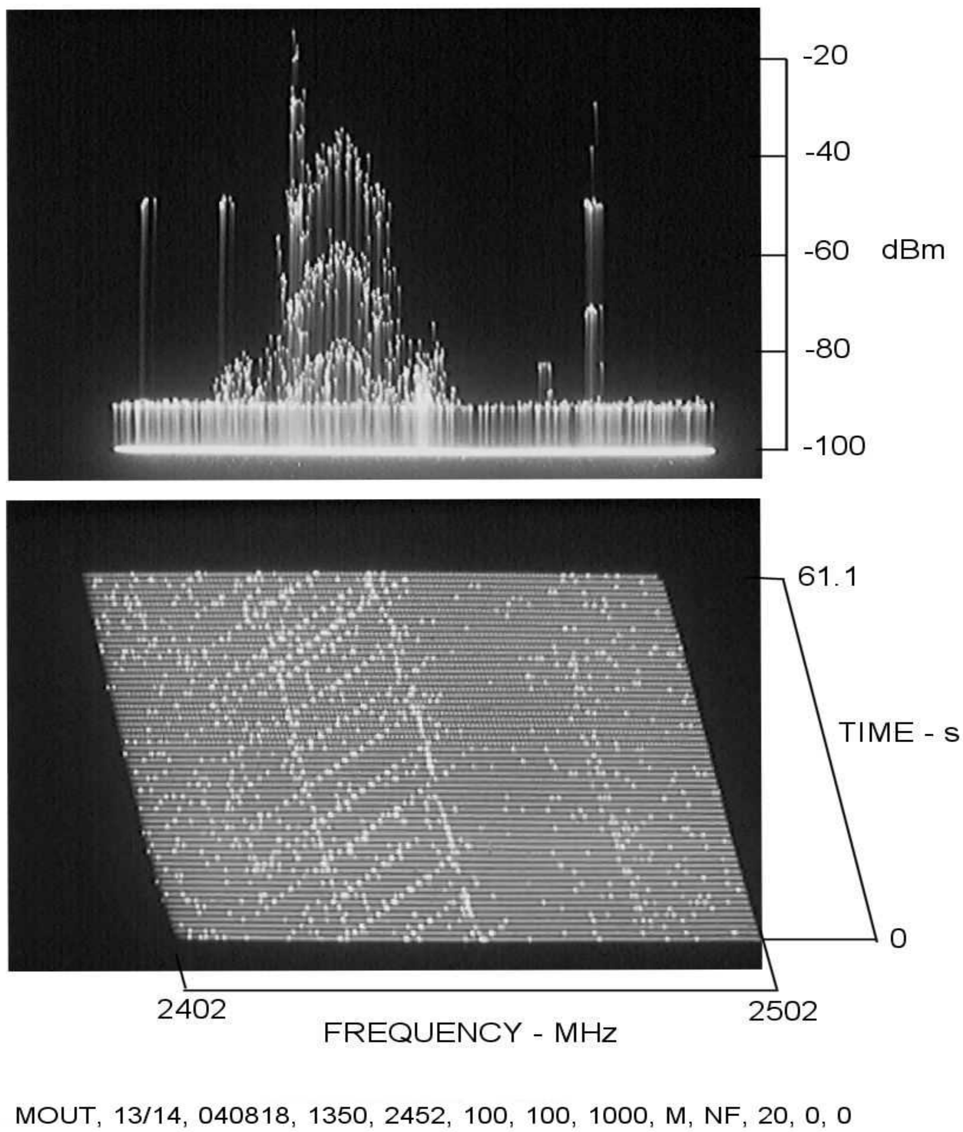


Figure 9 Spectral Content of Test Communications Device, Example 2

The low-level signals shown in Figure 7 from a distant source are present in the above example. These signals were not strong enough to interfere with the operation of the test communications device.

4.0 FIELD-EXERCISE MEASUREMENTS

4.1 General Approach

The instrumentation van was driven to the MOUT site on 30 August 2004 prior to the start of a field exercise at that location. The van was placed at a convenient location near the center of exercise activity. The occupancy and use of four portions of the radio spectrum were examined prior to, during, and after the exercise.

The three bands observed covered the frequency ranges of 600 to 800 MHz, 890 to 940 MHz, 2400 to 2500 MHz, and 5400 to 5800 MHz. One instrument operator controlled the 0.1- to 1250-MHz instrumentation suite and time-shared it for measurements on the two lower-frequency bands. A second operator controlled the 10-MHz to 14-GHz instrumentation suite and time-shared it for measurements on the two upper-frequency bands. In this case it was necessary to change the antennas and preamplifiers for each band change. The sharing of instrumentation limited the simultaneous measurement to any of the two bands.

At the end of the MOUT exercise, the van was driven to the CIRPAS hangar located at the Marina Airport (OAR) for additional measurements of emissions at that location. The hangar contained other communications devices that support field exercises at the MOUT location.

4.2 Occupancy and Use of the 2.4-GHz Band

Figure 10 shows the occupancy and use of the radio spectrum from 2400 to 2500 MHz at the start of the field exercise. Multiple 802.11b-type emissions were noted at this time including emissions from at least seven different access points along with occasional replies from hand-held devices, especially at the highest-frequency access points.

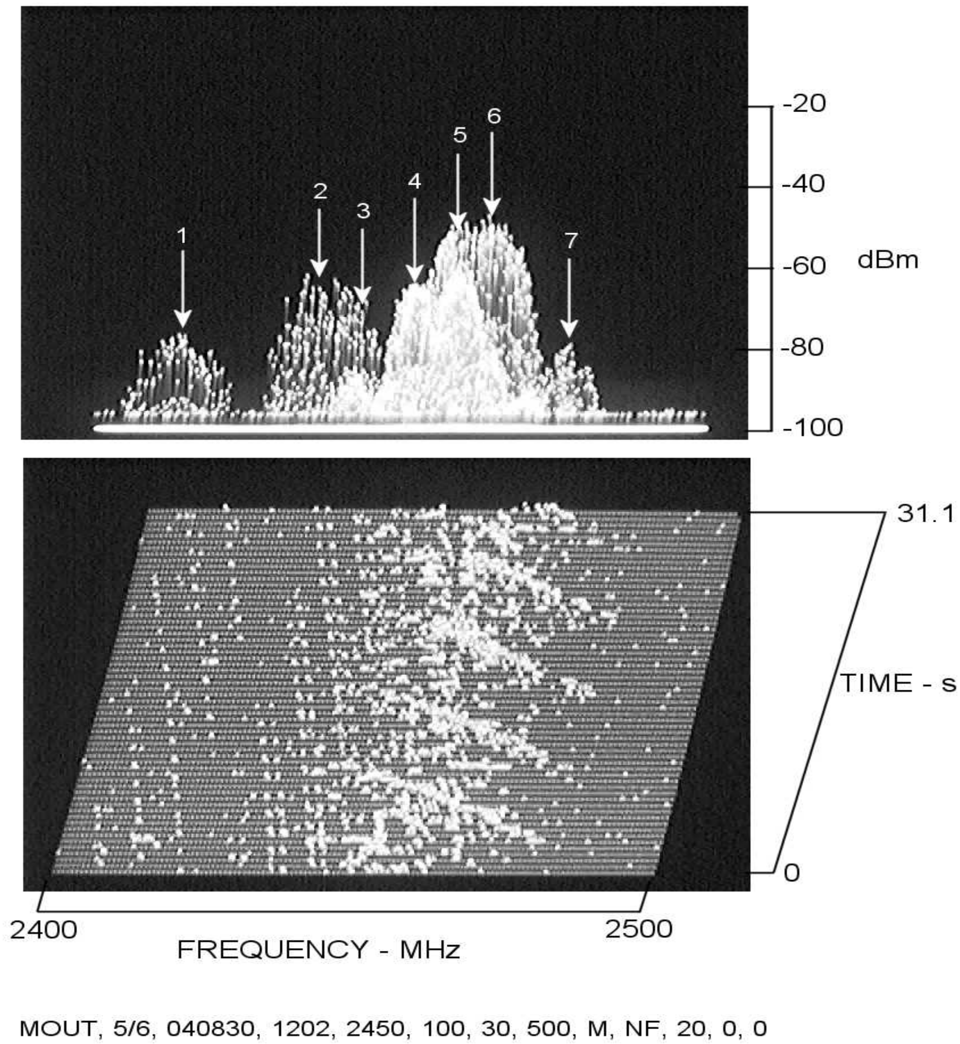


Figure 10 Occupancy of 2400- to 2500-MHz Band, Example 1

The top view shows the amplitude of each signal in dBm at the input terminals of the instrumentation preamplifier (essentially the power received by the intercept antenna and delivered to a 50-Ohm load). The spectral width and shape of each signal is shown in this view. An arrow is placed at the center frequency of each emission and an emission identification number is located above each arrow.

Emission 1 is at the low-frequency end of the 2400- to 2483.5-MHz license-exempt band. This emission is in the clear and does not interfere with any other emission and the other emissions do not interfere with the reception of this signal. Emission 2 is higher in frequency. Emission 3 is the small bright area on the upper-frequency side of Emission 2 at an amplitude of about –83 dBm. These two signals interfere with each other. Emissions 4, 5 and 6 overlap and interfere with each other. Emission 6 appears to be from a non-802.11b device. Emission 7 appears to be partly free from interference, but its spectral width will overlap that of Emission 6 at locations close to the source of Emission 6.

The bottom view is a time history of signals over a 31.1-second period. This view consists of 60 successive scans of the spectrum analyzer where the newest scan is at the bottom and the oldest scan at the top. The data in this view is the same as that used to form the amplitude-vs.-frequency view except that the amplitude is severely compressed. The frequency axis under the time-history view is also used for the upper view.

The slanting lines in the time-history view are the result of interaction between the repetitive, wide-bandwidth, synchronizing-pulses of the access points and the scanning process of the spectrum analyzer. The scan time of the spectrum analyzer must be slower than the repetition rate of the synchronizing pulses to show them as slanting lines. The somewhat different looking slanting bars associated with Emission 6 are not understood at this time. The other blobs of white between these bars are reply pulses from portable communications gear associated with emissions 4 and 5. No reply pulses were associated with the emissions from access points 1 and 2 at the time of this example.

In this example all emissions are within the 2400- to 2483.5-MHz license-exempt wireless-radio band. All emissions were associated with the exercise underway at the MOUT site. No spurious emissions were found at frequencies immediately above or below this band.

To better understand the overlapping emissions from the access points and the portable communications devices, a smaller 50-MHz wide portion of the band from 2432- to 2452-MHz as shown in Figure 11. The signals are identified with the same numbers used in the previous example.

Emissions 2 and 3 remain about the same as for the previous example. The synchronizing lines for Emission 2 are clearly shown in the time history view, but the threshold was raised sufficiently to eliminate the synchronizing lines from the weaker Emission 3. Emissions 4 and 5 are shown in the upper view along with pulses at higher amplitudes. The lower view shows the synchronization pulses from Emissions 4 and 5 along with data pulses from portable communications devices. The lack of a clean spectral shape of the emissions from the portable communications devices is puzzling since the reply pulses should fall on top of, and have the same shape as, the access-point pulses. In addition, the overlapping spectral shapes of Emissions 4 and 5 clearly show they interfere with each other.

Spurious pulses from some other emitter are shown above the emission from Access Point 7.

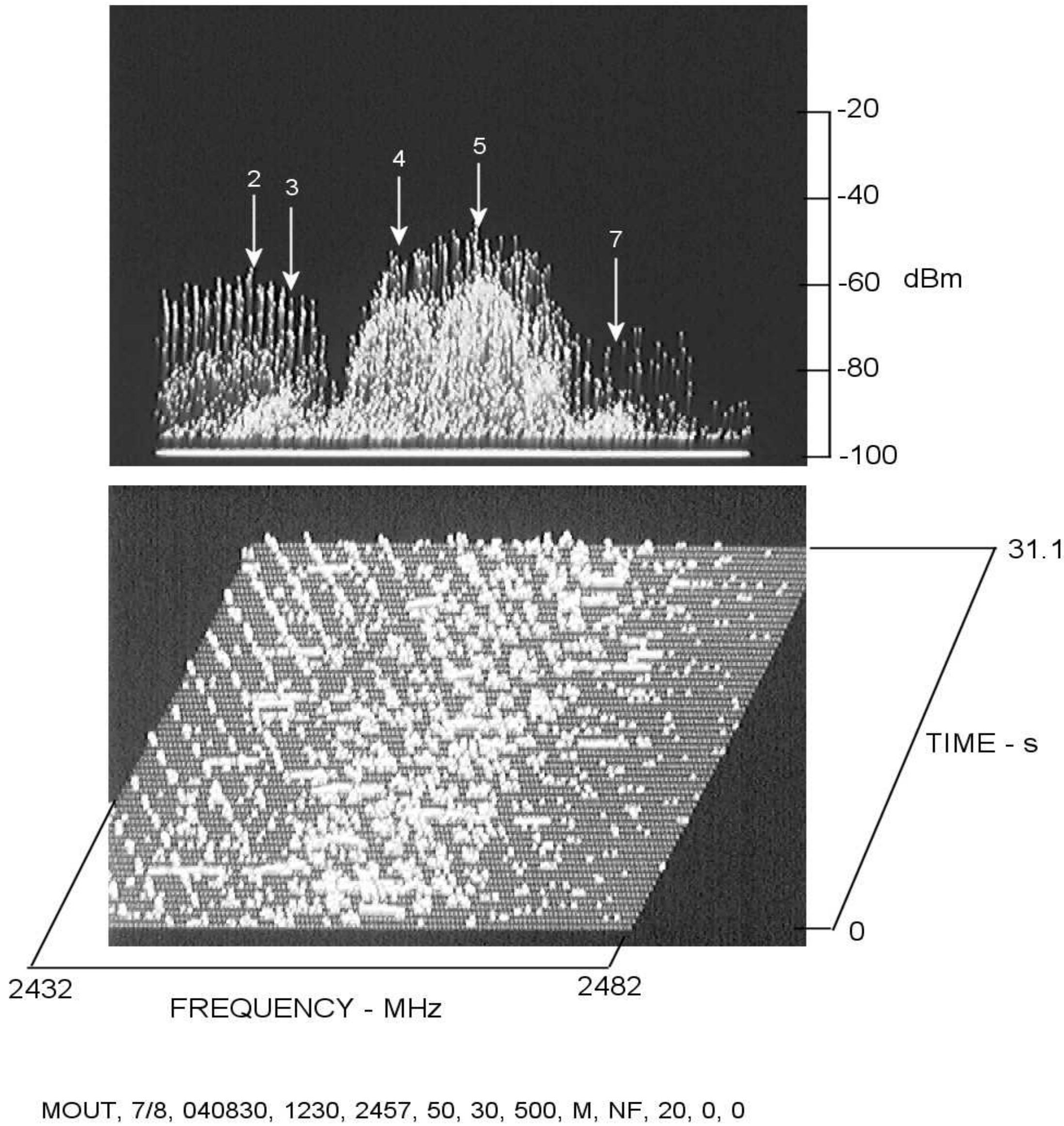
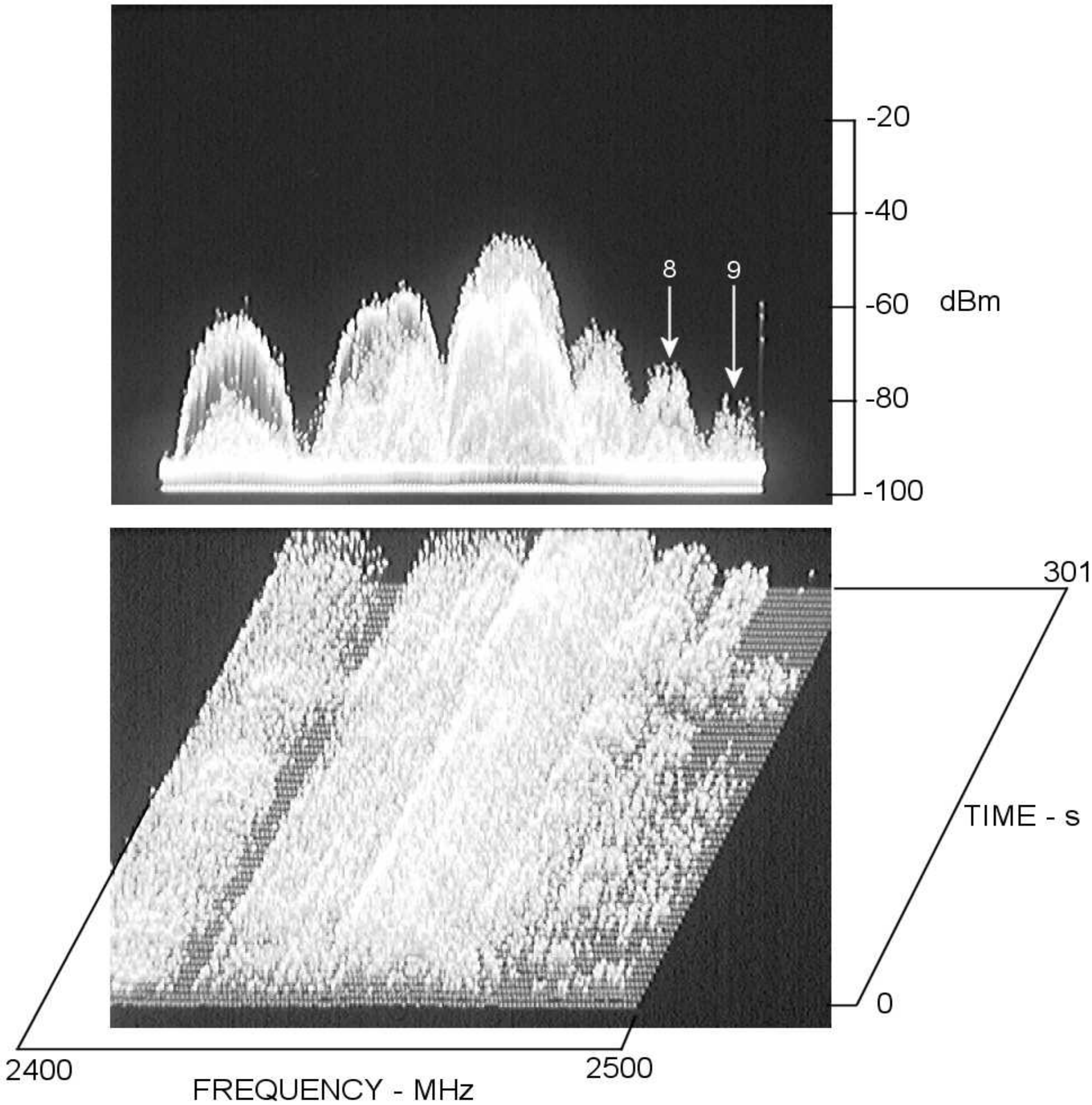


Figure 11 Occupancy of the 2432- to 2452-MHz Band

The occupancy of the 2400- to 2500-MHz band generally increased as the exercise activity continued and fell off at the end of the exercise. Figure 12 shows the occupancy of the band at the height of the activity. It is obvious that all of the access points and the portable communication units moved closer to the instrumentation van. The longer duration of the time axis resulted in more dense amplitude-vs.-frequency spectral information. Source 1 remained free of interference. Sources 2 and 3 appear to be buried under emissions from nearby portable communications units. Sources 4 and 5 now are about equal in amplitude and also are lower in amplitude than signals from portable communications devices. Source 7 is higher in amplitude than in the earlier data.



MOUT, 22/23, 040830, 1317, 2450, 100, 100, 5000, M, NF, 20, 0, 0

Figure 12 Occupancy of the 2400- to 2500-MHz Band, Example 2

Two new sources appear in Figure 12. They are labeled sources 8 and 9. Both are above the limits of the 2400- to 2483.5-MHz license-exempt band, but they are within the limits of the wider Industrial, Scientific, and Medical band of 2400 to 2500 MHz and the same band limits provided to radio amateurs. These two new sources were associated with the exercise.

Shortly after the data in Figure 12 was obtained the entire band became vacant which coincided with the end of the exercise.

4.3 Occupancy and Use of the 600- to 800-MHz Band

Some related activities used portions of the radio spectrum near 700 MHz. This part of the spectrum was monitored during the exercise to determine if other signals might interfere with normal operations of the related activities. Figure 13 shows the occupancy of that portion of the spectrum at the height of the exercise.

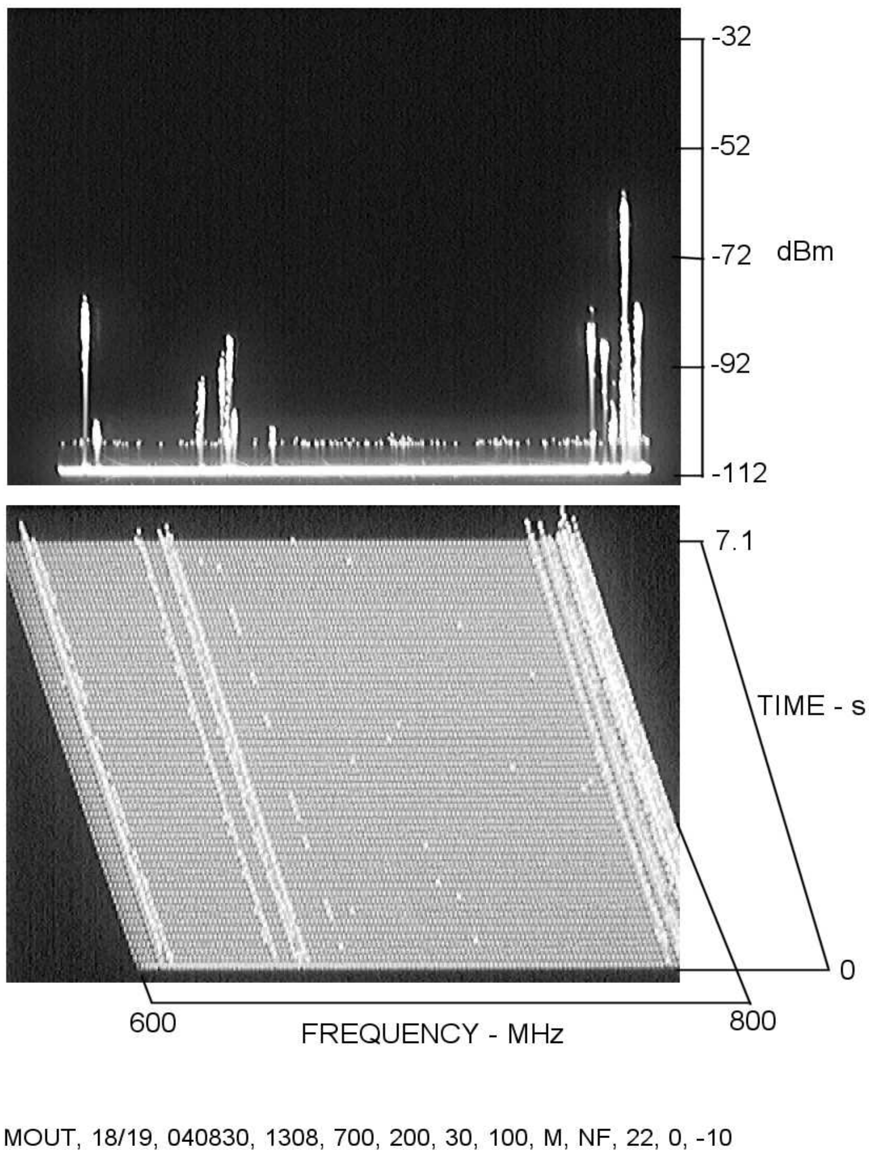
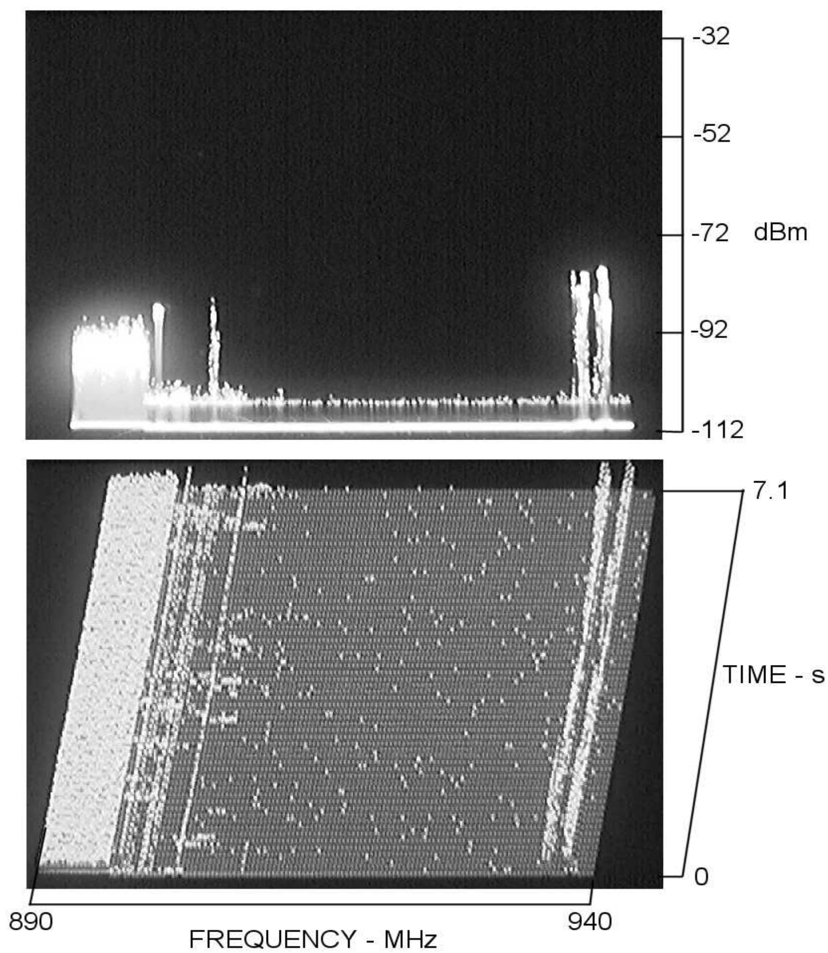


Figure 13 Occupancy and Use of the 600- to 800-MHz Band

No significant or unknown signal appeared in this portion of the spectrum that would interfere with the conduct of the exercise.

4.4 Occupancy of the 902- to 928-MHz Band

The band from 902 to 928 MHz is a license-exempt band available for general use. The occupancy of this band was also examined during the height of the field exercise. Figure 14 shows signals in this band along with small additional bands above and below the license-exempt band.



MOUT, 20/21, 040830, 1313, 915, 50, 30, 100, M, NF, 22, 0, -10

Figure 14 Occupancy of the 890- to 940-MHz Band

No significant signal was found within the limits of the 902- to 928-MHz license-exempt band. Signals shown in Figure 14 above and below this band are from licensed radio services operating on mountain-top or tower sites within or near to line of sight of the MOUT location. These services are protected from interference, and their frequencies are not available for general use.

4.5 Supplementary Measurements at the CIRPAS Hangar

At the completion of the exercise at the MOUT site, the instrumentation van was moved to the CIRPAS hangar located at the Marina Airport. Additional ambient measurements were made in the parking lot at the south end of the CIRPAS hangar.

Figure 15 shows signals in the 2.4-GHz band during the testing of equipment at that location. All signals observed are believed to originate from devices under test at the CIRPAS hangar. Multiple 802.11b type emissions were found as well as non-802.11b emissions. The highest level pulses appear to be from a frequency-hopping emitter that covered the entire band. Pulses from this emitter will occasionally collide with synchronizing and data pulses from 802.11b type emitters, resulting in repeat transmissions and reduced data throughputs.

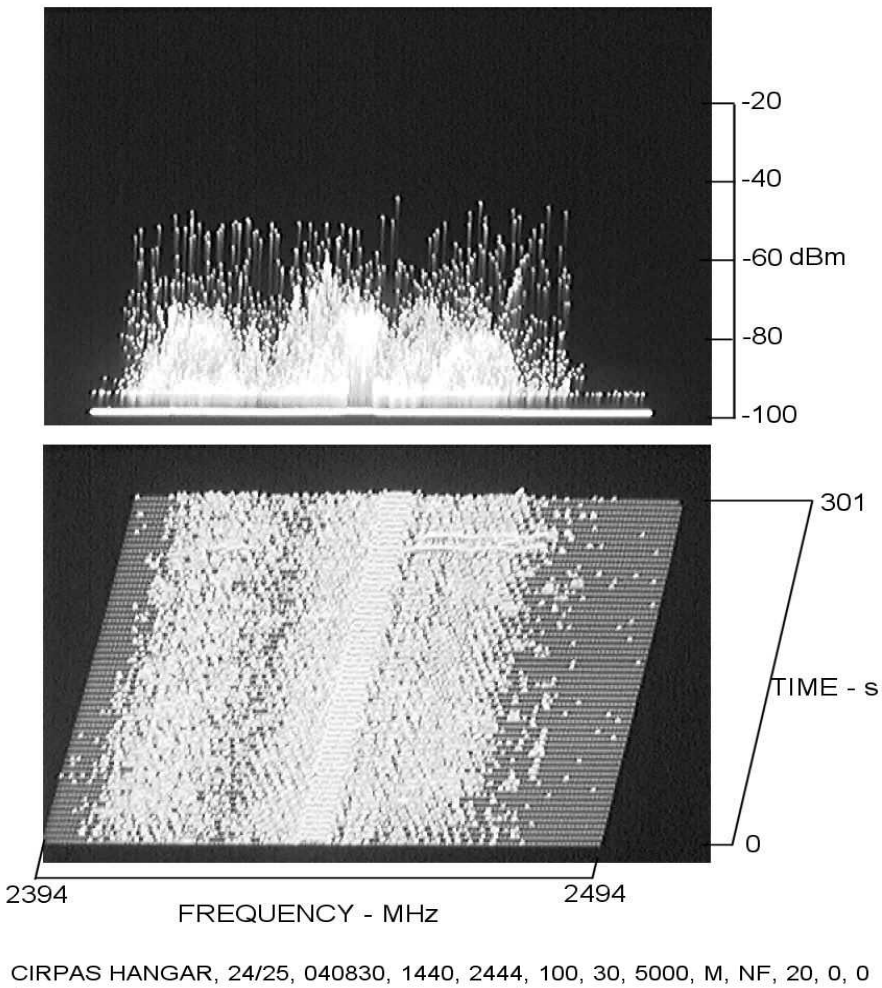


Figure 15 Occupancy of the 2394- to 2494-MHz Band at the CIRPAS Hangar

Initial measurements at the CIRPAS hangar indicated the lack of signals in the 902 to 928-MHz license-exempt band. Multiple wide-bandwidth emitters suddenly turned on while exploring this band. Figure 16 shows two rather complex broadband signals observed while examining that portion of the band from 912.5 to 917.5 MHz.

Two adjacent spread-spectrum emissions appear near the center of the frequency range. These two emissions were present during the entire 64.7 seconds of the measurement time. The complex signal at the upper end of the frequency scale turned on about off half way up the time-history axis. It appears to consist of multiple frequency sub-bands but with a common synchronizing-pulse source.

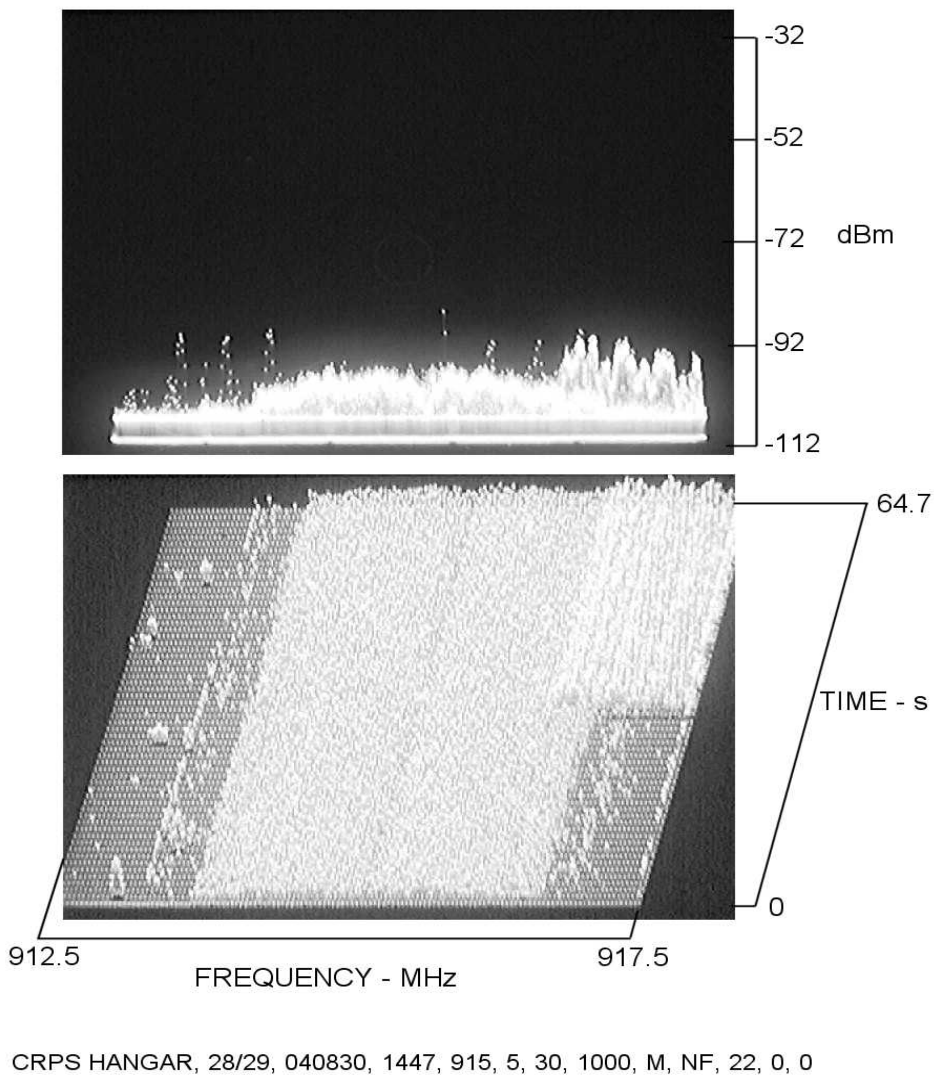


Figure 16 Emissions in the 912.5- to 917.5-MHz Band at the CIRPAS Hangar

Eleven minutes later a second observation of signals in the 902- to 928-MHz license-exempt band was obtained. Figure 17 shows this band as well as portions of the spectrum above and below the license-exempt band. The two signals noted in the previous example are shown near the center of the frequency axis. A brief emission from an unknown source occurred near the bottom of the time axis and at a higher frequency. The low-level and close-spaced spectral components across the entire frequency axis are unwanted emissions that were traced to radiation from the USB cable connecting the digital camera (used to record data) to a laptop computer. This cable was connected to the laptop about ¼ of the way down the time axis.

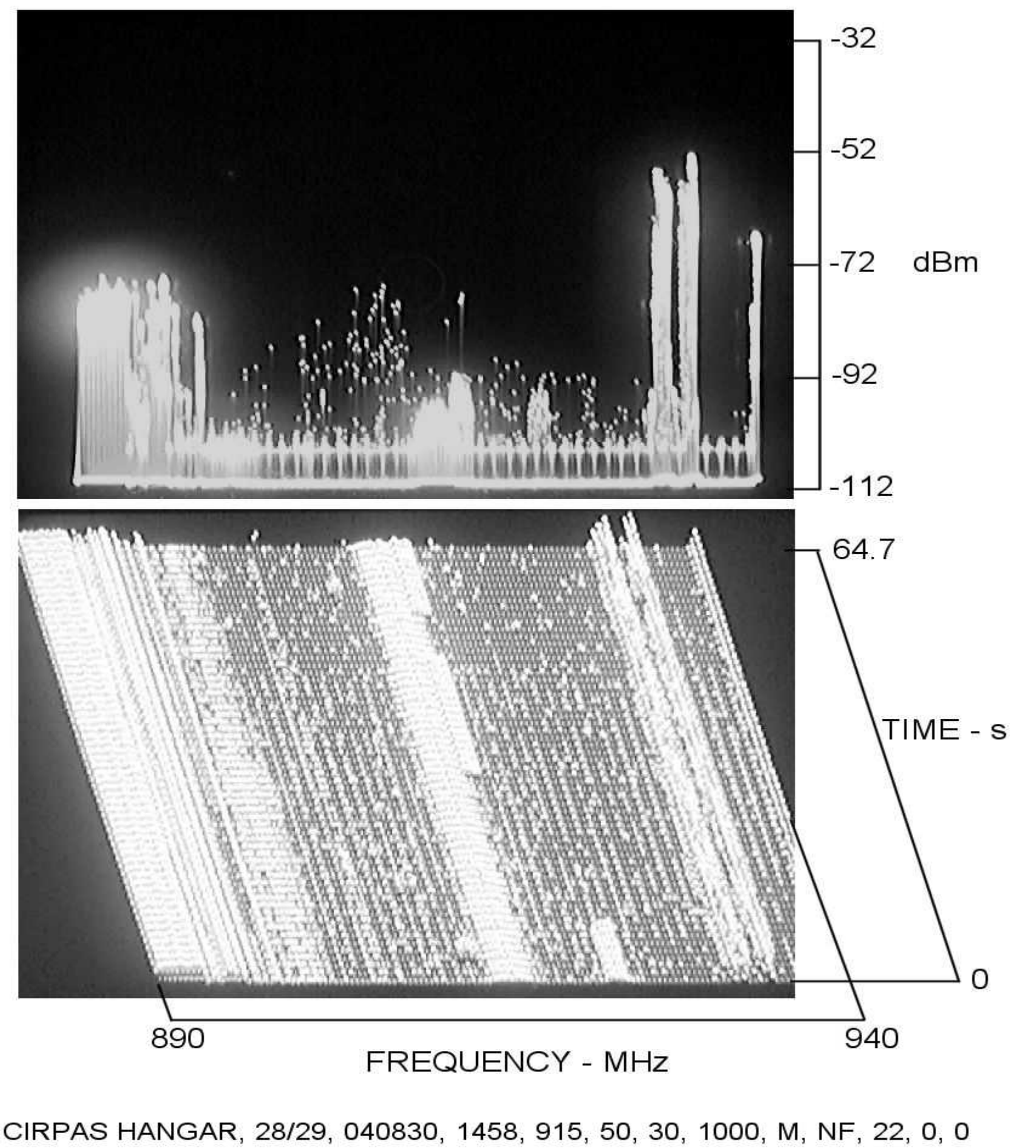


Figure 17 Occupancy of the 880- to 930-MHz Band at the CIRPAS Hangar

4. DISCUSSION

4.1 Ambient Background

Ambient measurement of the wireless-radio bands of interest were made at the MOUT site on 18 August 2004, and they showed only very low-level signals that would not affect the performance of communications systems during a field exercise planned for a later date.

The ambient measurements also included preliminary tests of the spectral and temporal structure of emissions from a test communications device. The test indicated the device emitted spurious pulse signals at start up and at later times. This suggests the communications device and other similar devices should be checked in the laboratory to fully investigate the spurious emission problem.

4.2 Spectrum Use During a Field Exercise

The 2400- to 2483.5-MHz license-exempt band was essentially vacant at the MOUT location prior to the start of the exercise. This condition rapidly changed to a very high occupancy of the band at the start and during the entire exercise along with several instances of overlapping signals. No part of the band was free of signals. Signals also appeared in that portion of the spectrum above the license-exempt band from 2483.5 to 2500 MHz. No signal or spurious emission was noted above or below the 2400- to 2500-MHz band.

The data shows that one 801.11b-type signal was free of interference (see signal 1 in Figures 6 and 7), and the communications devices using the access point probably performed as expected. All other signals from access points and other sources encountered significant radio-interference problems. The synchronizing signals from other 802.11b-type access points and the data signals transmitted between the access points and users indicate these communications systems encountered numerous pulse collisions, resulting in the retransmission of many blocks of data and a reduced throughput.

The access point equipment appeared to be designed to find free channels or the best channel available. Since free channels were not available, the various communications systems simply piled on top of each other. Since the technical characteristics of the channel-seeking portion of the communications systems were not known, there is no good way to fully assess the extent and impact of the interference on performance from the data collected. A frequency manager may prove useful in planning the communications aspects of the future exercises.

No unusual activity was found at or near 700 MHz. Since the measurements in this report were made under blind conditions and without real-time inputs about exercise progress, no conclusion can be reached about use of this portion of the spectrum by devices associated with the exercise.

The 5.6-GHz license-exempt band was monitored from time to time during the survey. Unfortunately, it was necessary use one spectrum analyzer to examine conditions in both the 2.4-GHz and 5.6-GHz bands. Due to the high level of activity in the 2.4-GHz band, it received priority for measurement time. No signals were detected in the 5.6-GHz band even though it was known that this band was intermittently used during the survey. The 5.6-GHz band devices were operated some distance from the instrumentation van and on point-to-point links with antennas pointed away from the van. Since only a single nearby point-to-point link was known to be in intermittent operation and it was operated within the deep valley used for the exercises, no significant interference problem would be expected.

The supplementary measurements at the CIRPAS hangar suggest that similar equipment to that at MOUT was operated at that site. In addition a frequency-hopping signal covered the entire 2400- to 2483.5-MHz wireless-radio band. The signals were lower in amplitude than those encountered at the MOUT site, but a later site inspection showed the large CIRPAS hanger was between the signal sources and the instrumentation van.

Signals were found at the CIRPAS Hangar in the 902- to 928-MHz license-exempt band that may have been associated with the operation of communications or data-transmission devices. These signals are shown in Figures 16 and 17.

Figure 17 also shows low-level radio interference from a portion of the instrumentation system. The USB cable from the digital camera to a laptop computer radiated sufficient noise to be received by the antenna located on the roof of the instrumentation van. The distinctive spectral properties of this low-level interference allowed it to be distinguished from other signals.

No unusual activity was noted at the CIRPAS hangar at and near 700-MHz. The ambient signal population was very low in this portion of the spectrum.

Data Log, NPS, MOUT, 0408030, 1of 2 sheets

Location	Pic No.	Date dd/mm/yy	Time Local	Freq. MHz	Span MHz	BW kHz	Scan T ms	Source	Filter id	*Preamp* dB	RF Attn dB	Ref. dBm	Comments
MOUT	1	040830	1141										Cal-WRV
MOUT	2	040830	1141										Cal- WRV
MOUT	3	040830	1141										Cal-WRV
MOUT	4	040830	1141										Cal-NPS
MOUT	5A	040830	1202	2450	100	30	500	m	nf	20	0	0	Overlapping Signals
MOUT	6T	040830	“	“	“	“	“	“	“	“	“	“	“
MOUT	7A	040830	1230	2457	50	30	500	m	nf	20	0	0	Overlapping Signals
MOUT	8T	040830	“	“	“	“	“	“	“	“	“	“	“
MOUT	9A	040830	1235	2457	20	30	500	m	nf	20	0	0	3 Overlapping Signals
MOUT	10T	040830	“	“	“	“	“	“	“	“	“	“	“
MOUT	11A	040830	1239	2457	20	30	2000	m	nf	20	0	0	3 Overlapping Signals
MOUT	12T	040830	“	“	“	“	“	“	“	“	“	“	“
MOUT	13A	040830	1250	2457	20	100	1000	m	nf	20	0	0	Multiple Overlapping Signals
MOUT	14T	040830	“	“	“	“	“	“	“	“	“	“	“
MOUT	15A	040830	1303	2450	100	100	5000	m	nf	20	0	0	Multiply Overlapping Signals
MOUT	16T	040830	“	“	“	“	“	“	“	“	“	“	
MOUT	17T	040830	“	“	“	“	“	“	“	“	“	“	Display Tweak
MOUT	18T	040830	1308	700	200	30	100	m	nf	22	0	-10	700 Band, No Signals
MOUT	19A	040830	“	“	“	“	“	“	“	“	“	“	“
MOUT	20	040830	1313	915	50	30	100	m	nf	22	0	-10	915 Band, No Signals
MOUT	21	040830	“	“	“	“	“	“	“	“	“	“	“
MOUT	22	040830	1317	2450	100	100	5000	m	nf	20	0	0	Strong Burst, Top of T view
MOUT	23	040830	“	“	“	“	“	“	“	“	“	“	“

Data Log, NPS, MOUT, 040830, 2 of 2 sheets

Location	**Pic** No.	**Date** dd/mm/yy	**Time** Local	**Freq.** MHz	**Span** MHz	**BW** kHz	**Scan T** ms	**Source**	**Filter** id	***Preamp*** dB	**RF Attn** dB	**Ref.** dBm	**Comments**
CIRPAS	24A	040830	1440	2444	100	30	5000	m	nf	20	0	0	
CIRPAS	25T	040830	“	“	“	“	“	“	“	“	“	“	
CIRPAS	26T	040830	1445	2444	100	30	1000	m	nf	20	0	0	
CIRPAS	27A	040830	“	“	“	“	“	“	“	“	“	“	
CIRPAS	28T	040830	1447	915	5	30	200	m	nf	22	0	-10	
CIRPAS	29A	040830	“	“	“	“	“	“	“	“	“	“	
CIRPAS	30	040830	1458	915	50	30	1000	m	nf	22	0	-10	
CIRPAS	31	040830	“	“	“	“	“	“	“	“	“	“	

Technical Memorandum 0409
Signal Enhancement Laboratory
Department of Electrical and Computer Enginering
Naval Postgraduate School
Monterey, CA

September 2004

AMBIENT SIGNAL POPULATION
at
THREE LOCATIONS
on
CAMP ROBERTS

by:

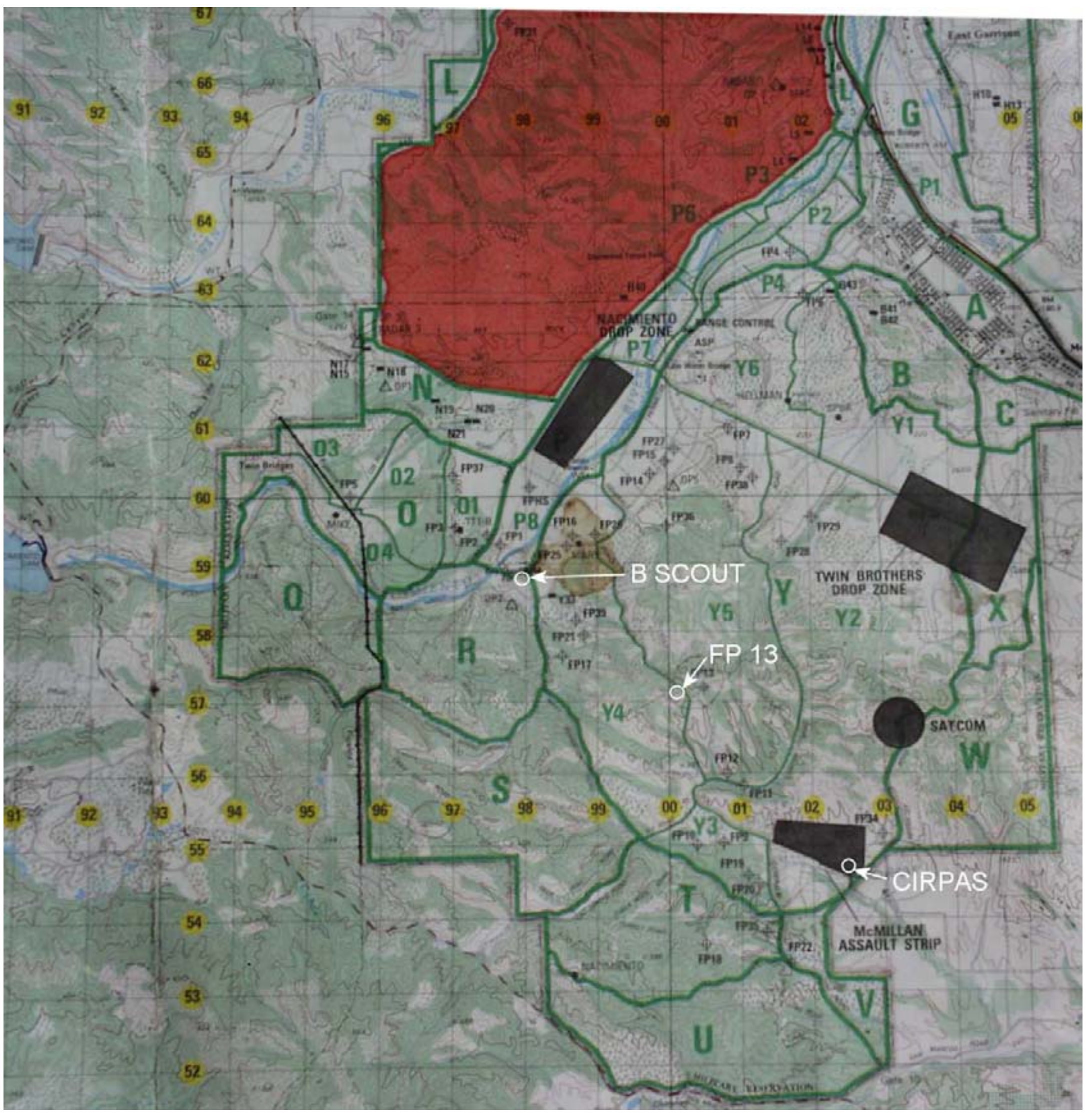
Wilbur R. Vincent
and
Andrew A. Parker

1. INTRODUCTION

The ambient radio-signal and radio-noise population was examined at three locations on Camp Roberts on September 9, 2004. The three locations are identified as CIRPAS, Boy Scout (B Scout), and Firing Point 13 (FP 13). The purpose of the measurements was to identify any signal or noise that might interfere with radio communications and data links during field exercises.

Available instrumentation was used for the measurement. This instrumentation is briefly described in Section 2. Extensive data is provided in the form of photographs of time-history views of signals and noise in selected portions of the radio spectrum. All examples of data included in this report are calibrated in frequency, time, and amplitude.

A map illustrating the locations of the measurement sites is shown below.



2. INSTRUMENTATION

A Naval Postgraduate School instrumentation van was equipped with radio spectrum measurement equipment and was used for this effort. Figure 1 shows a photograph of the instrumentation van and its diesel generator trailer at a field measurement location. The van could be rapidly moved from location to location, and it could be operated while in motion.

Figure 1 Photograph of Instrumentation Van

Antennas for each band of interest were installed in the roof of the van. Figure 2 shows the three antennas used for these measurements. Short coaxial cables ran from each antenna through the roof vent and directly to the instrumentation preamplifiers located directly below the roof vent.

Figure 2 Photograph of Antennas on the Instrumentation Van

Two sets of instrumentation were installed in the van. One set covered the band from 0.1 MHz up to 1250 MHz. The second set covered the frequency range of 10 MHz up to 14 GHz. Figure 3 is a photograph of the 10 MHz to 14 GHz instrumentation. A Hewlett Packard Model 3565A Spectrum Analyzer is on the bottom of the photograph, the time-history display in the middle of the photograph, and preamplifiers are on the top of the time-history display.

Figure 3 Instrumentation for the UHF and Microwave Bands

Figure 4 is a photograph of the instrumentation used to cover the 0.1 to 1250 MHz frequency range as well as the digital oscilloscope camera used to photograph data and the laptop computer used to store data files. A Hewlett Packard Model 141 Spectrum Analyzer is shown on the lower left part of the photograph. The time-history display used to observe signals in the 0.1 to 1250 MHz band is above the spectrum analyzer, and its preamplifier and a filter are located on top of the display.

Figure 4 Instrumentation for the 0.1 to 1250 MHz Band

The oscilloscope camera and the laptop computer shown in Figure 4 were shared with the first instrumentation suite to minimize equipment and allow all files to be stored on one computer.

3. FIELD MEASUREMENTS

3.1 CIRPAS Location

For the CIRPAS measurements the instrumentation van was located where the aircraft taxiway meets runway 28. For safety reasons the van was located on the taxiway and not on the runway should an emergency require the use of the runway during the measurement period. The location of the van, obtained from a GPS, was:

35° 44.420' N and 120° 47.267' W at an elevation of 920 feet.

Figure 5 shows an overall view of signals in the 0.1 to 1250 MHz band. The upper view shows the amplitude of each signal at the output terminals of a monopole antenna or the signal level at the input to the preamplifier. The strong signals at 88 to 108 MHz are from transmitters in the FM broadcast service. The transmitters in this service are generally located on distant hilltops, and several were within line of sight of the CIRPAS location. The signal levels are about as expected and are not unduly high.

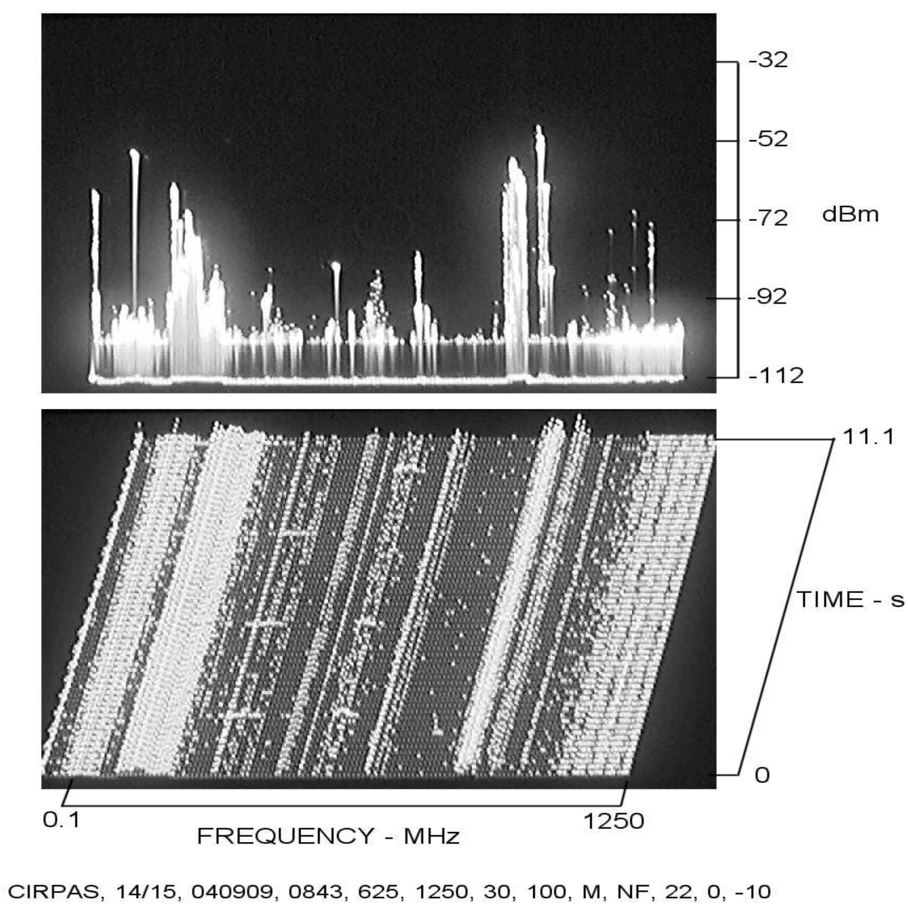


Figure 5 CIRPAS Site, Occupancy of the 0.1 to 1000 MHz Band

Additional strong signals in the upper part of the frequency range are from television stations and base stations for mobile communications that are located on distant hilltops. While the signal strengths of these signals are quite high, they are not abnormal nor are they sufficiently strong to cause saturation or nonlinear operation of the instrumentation or a well designed radio receiver.

The unusual low-level bands of noise at the upper end of the frequency scale are caused by the out-of-band use of the particular preamplifier used for this frequency range. Its upper frequency limit was 1000 MHz. While its gain was normal, it did not provide a good match to the antenna, resulting in low-level noise above 1000 MHz. Since the preamplifier covered the primary range of interest, the noise bands from 1000 to 1250 MHz were not of concern.

Figure 6 shows an expanded view of signals in the 600 to 800 MHz band. Only low-level signals are noted. No unusual activity was noted in this portion of the band at this location.

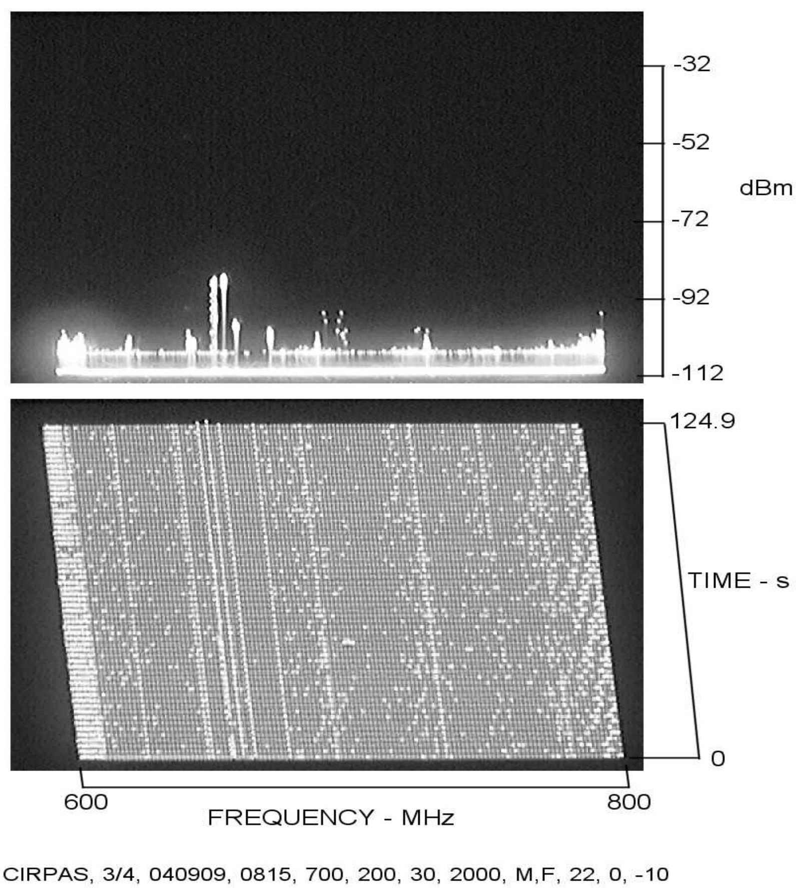


Figure 6 CIRPAS Site, Occupancy of the 600 to 800 MHz Band

Since the center of the band shown in Figure 5 was of primary interest, an expanded view of the portion of the spectrum covering the 650- to 750-MHz range was obtained. Figure 7 shows signals in this portion of the spectrum.

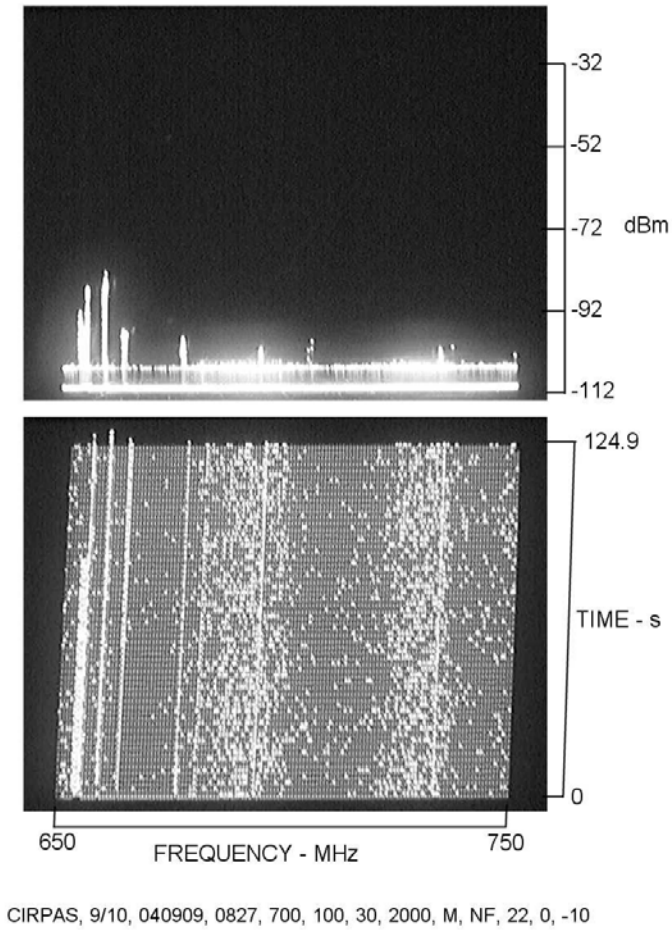


Figure 7 CIRPAS Site, Occupancy of the 650 to 750 MHz Band

While no strong signal was noted and large portions of the band did not contain signals detectable at this location by a standard UHF radio receiver, one unusual signal is shown. The upper view shows a very low-level signal at 700 MHz that is better documented in the data for the FP 13 location.

The two bands of increased background noise in the time-history view show that the noise floor of the preamplifier is not perfectly flat. They are not caused by external noise sources.

The license-exempt band from 2400 to 2483.5 MHz was of interest, and the population of signals in it was examined at the CIRPAS location. Figure 8 shows the result. There was a complete lack of emissions of any kind in the entire band. The two bands of slightly higher background noise shown in the time-history view shows that the preamplifier noise floor is not completely flat across the 100-MHz-wide band.

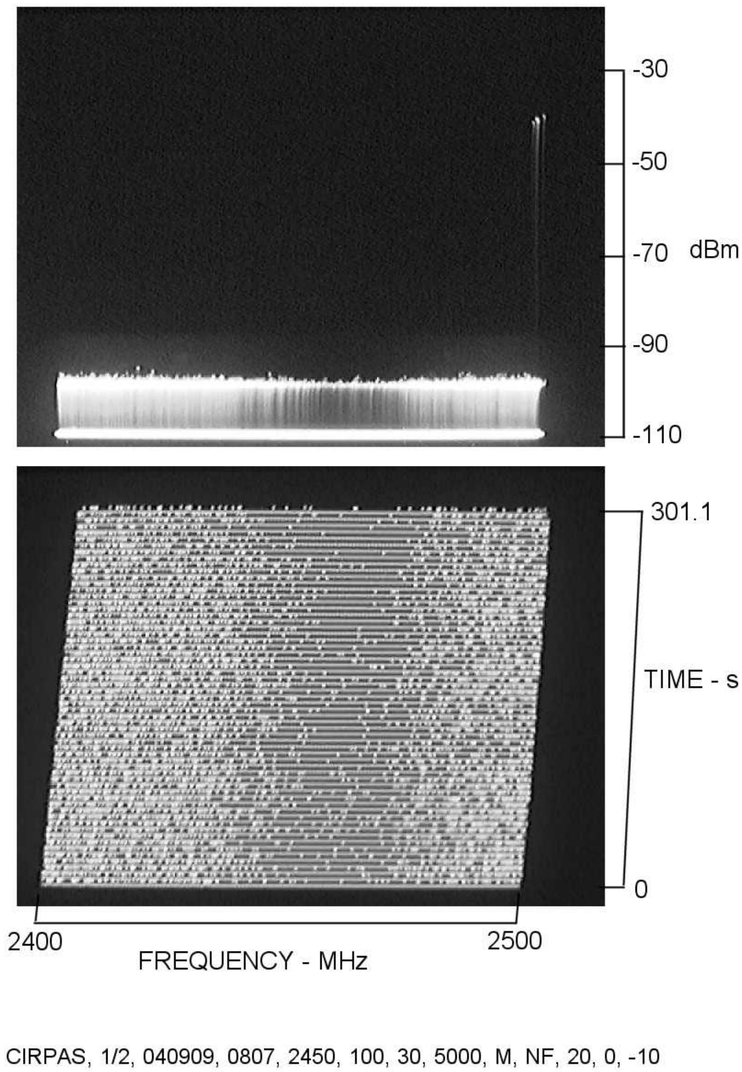


Figure 8 CIRPAS Site, Occupancy of the 2400 to 2500 MHz Band

The ambient occupancy of the 5.6-GHz license-exempt wireless radio band and other nearby frequencies was of interest. Figure 9 shows that no emissions were found that could be detected by a standard microwave receiver in the 4950- to 5450-MHz band. This frequency band was completely void of signals during the measurement period.

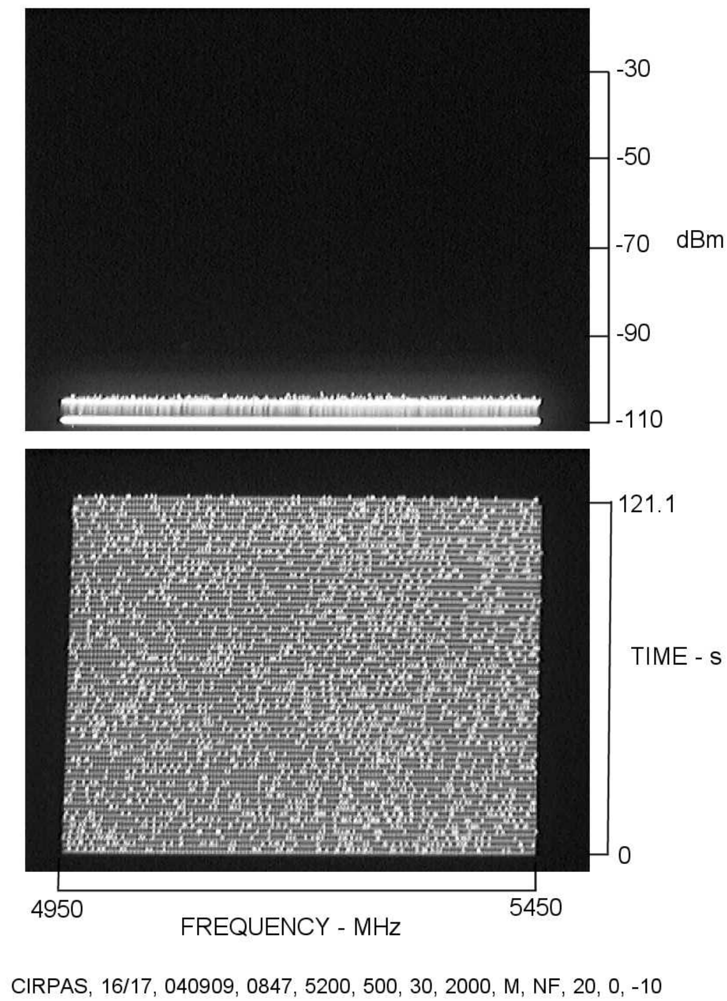


Figure 9 CIRPAS Site, Occupancy of the 4950 to 5450 MHz Band

The remainder of the 5.6-GHz license-exempt wireless band was covered by a second measurement. Figure 10 shows the lack of emissions of any kind in over the 5350- to 5850-MHz portion of the radio spectrum. To ensure that the entire region of interest was covered, there is a 100-MHz overlap in the data shown in Figures 9 and 10. The two figures cover nearly the entire license-exempt band of 5725 to 5875 MHz plus portions of the radio spectrum below the band.

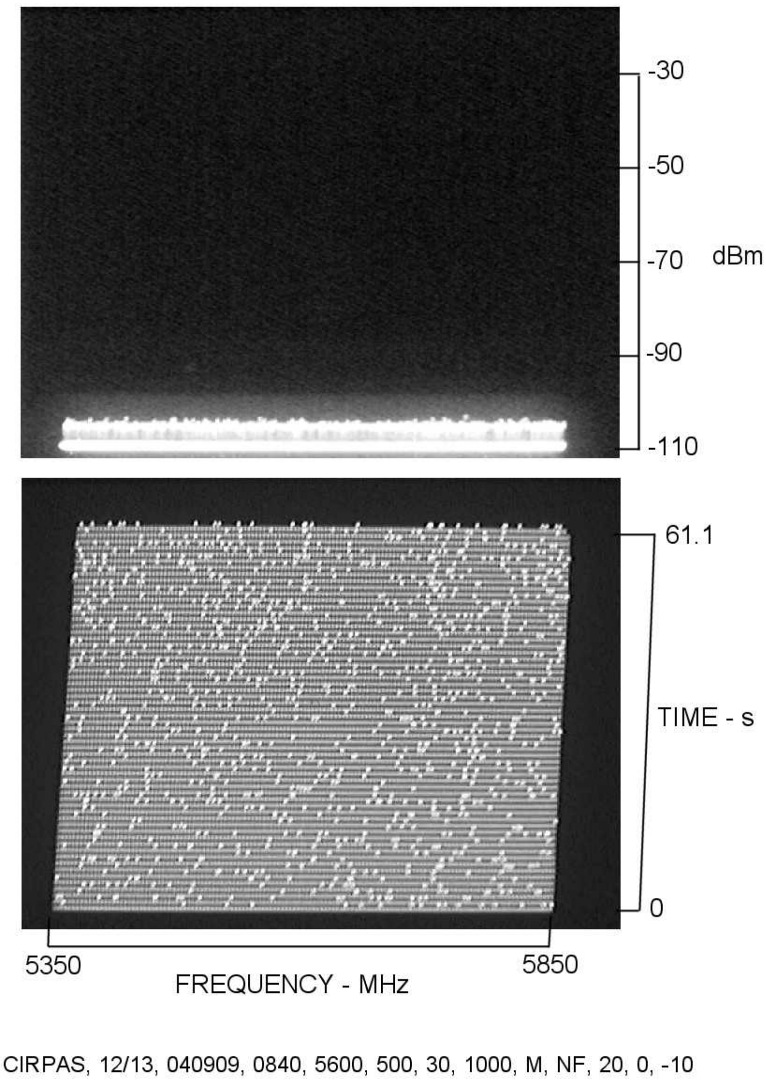


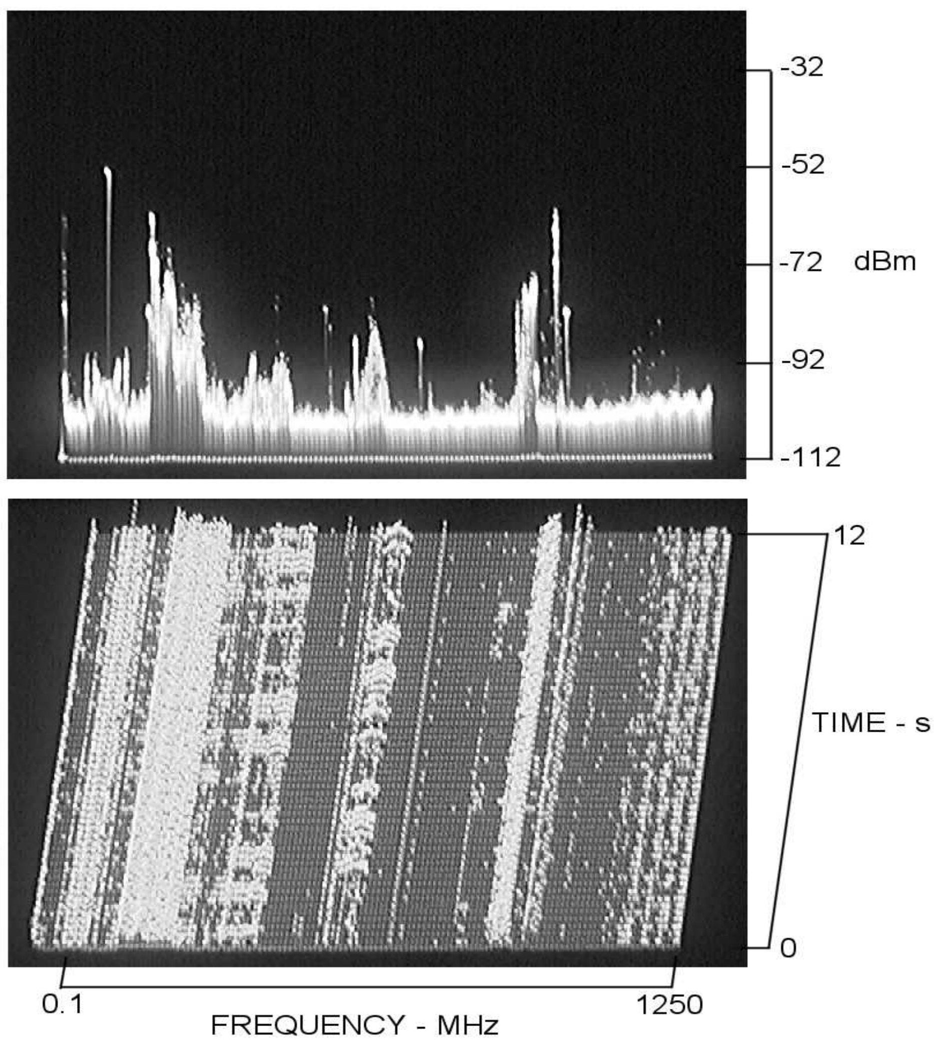
Figure 10 CIRPAS Site, Occupancy of the 5350 to 5850 MHz Band

3.2 B Scout Location

The instrumentation van was located at the start of the Boy Scout road. The elevation of this location was somewhat higher than further along the Boy Scout road and provided a better line of sight to possible signal sources than other locations further along the road. The location of the van from a GPS reading was:

35° 45.382’ N and 120° 48.603’ W at an elevation of 590 feet.

Figure 11 shows the signal population over the 0.1- to 1250-MHz band. The results were similar to those found at the CIRPAS location. The cluster of signals from 88 to 108 MHz is from FM stations located on distant mountaintops. Television signals were somewhat lower in strength than at the CIRPAS location.



B SCOUT, 20/21, 040909, 0922, 625, 1250, 30, 100(LS) M, NF, 22, 0, -10

Figure 11 B SCOUT Site, Occupancy of the 0.1 to 1250 MHz Band

Figure 12 shows a more detailed view of signals found in the 600- to 800-MHz band. No unusual signals were noted. One low-level signal at about 650 MHz at an amplitude of –100 dBm turned off about one-third of the way down the time axis. This was followed by a short-duration signal at an amplitude of about –80 dBm, however neither signal appeared unusual or of concern.

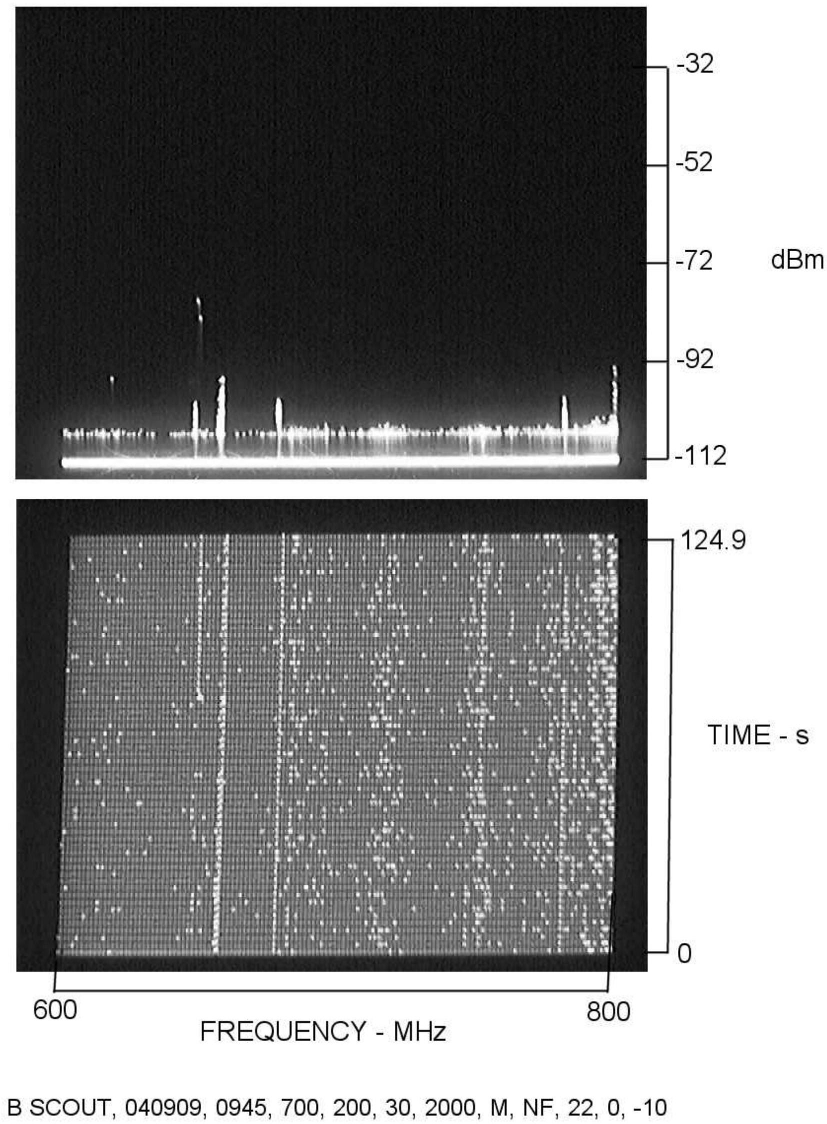


Figure 12 B SCOUT Site, Occupancy of the 600 to 800 MHz Band

Since the occupancy of signals in the vicinity of 700 MHz was of interest, this portion of the radio spectrum was expanded. Figure 13 shows the signal population in the expanded range of 650 to 750 MHz. Only a few signals low-level signals were found and no unusual signal activity was noted.

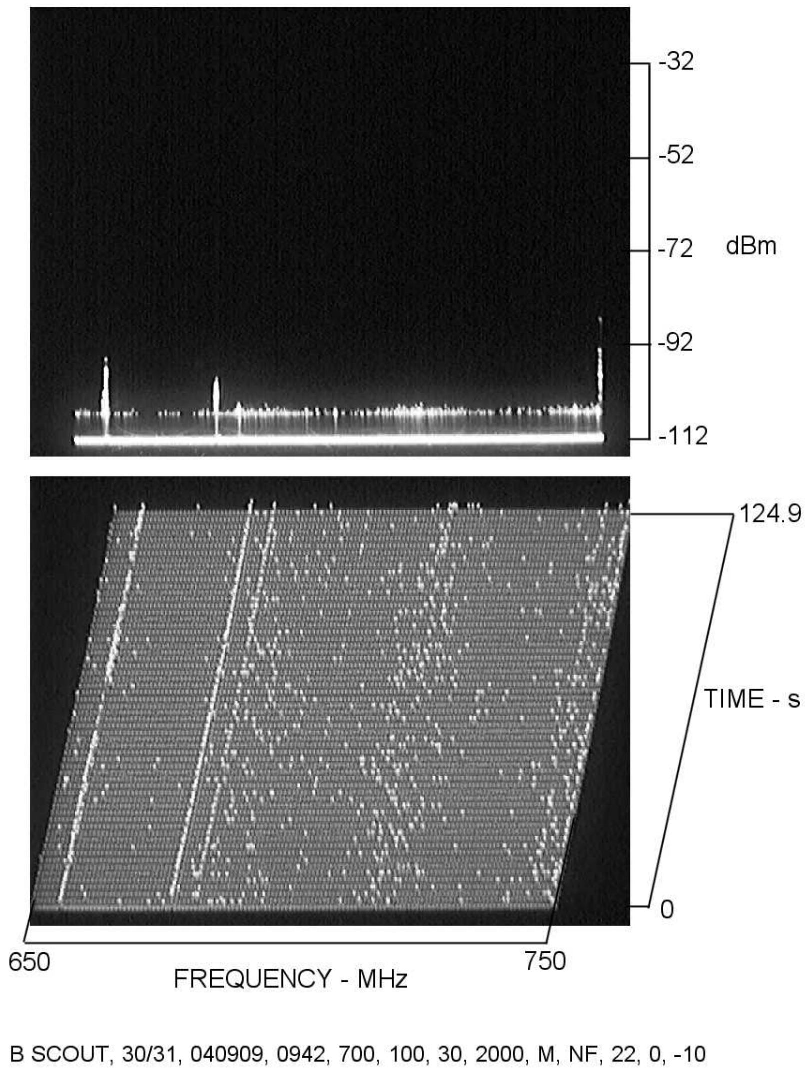


Figure 13 SCOUT Site, Occupancy of the 650 to 750 MHz Band

The population of signals in the 2.4-GHz license-exempt wireless-radio band was examined next. Figure 14 shows that no signals were found in the 2400- to 2500-MHz band. The two broad bands of increased noise level in the time-history view were caused by the non-frequency flat noise floor of the preamplifier and do not indicate the presence of any unusual broad-band emission.

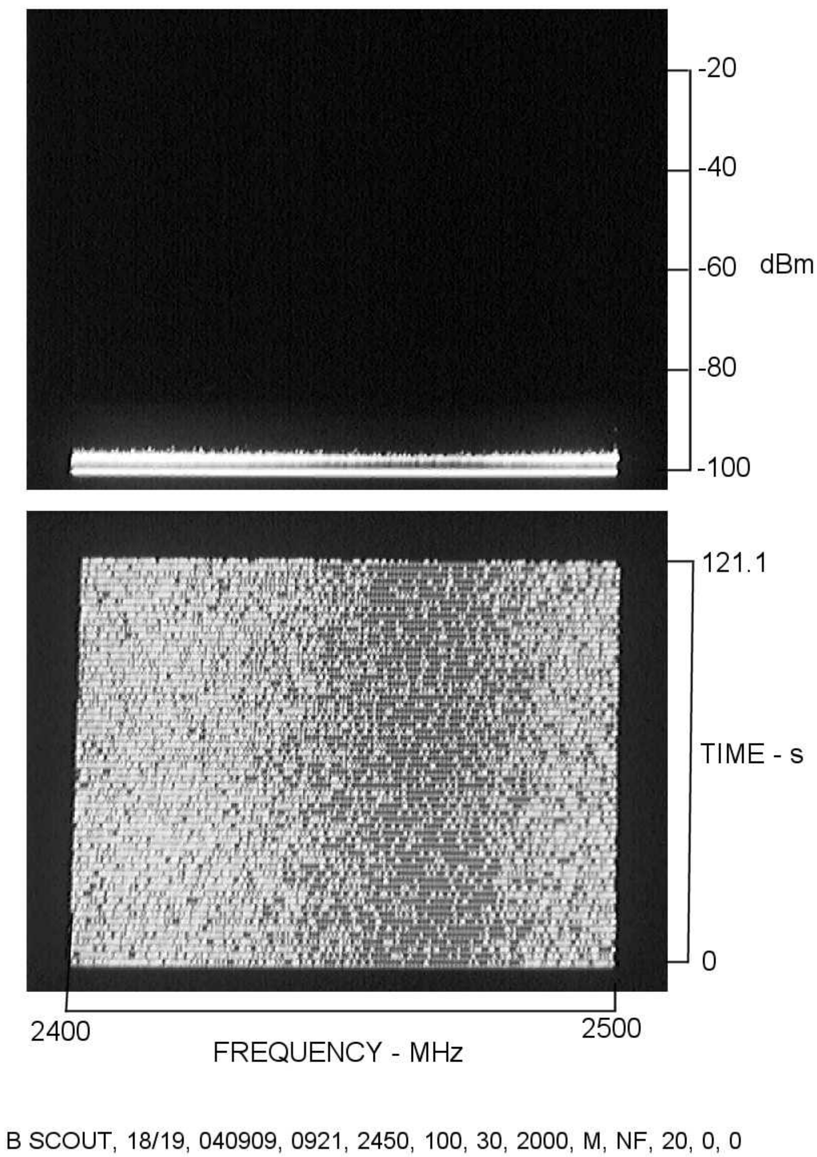


Figure 14 B SCOUT Site, Occupancy of the 2400 to 2500 MHz Band

The occupancy of portions of the band above and below the 2.4-GHz license-exempt wireless radio band was also examined at the B SCOUT location. Figure 15 shows the occupancy of the spectrum from 2350 to 2550 MHz that includes the 2.4-GHz license-exempt wireless radio band. No unusual activity was noted over the entire frequency range although the uneven noise floor of the preamplifier is clearly shown in the time-history view.

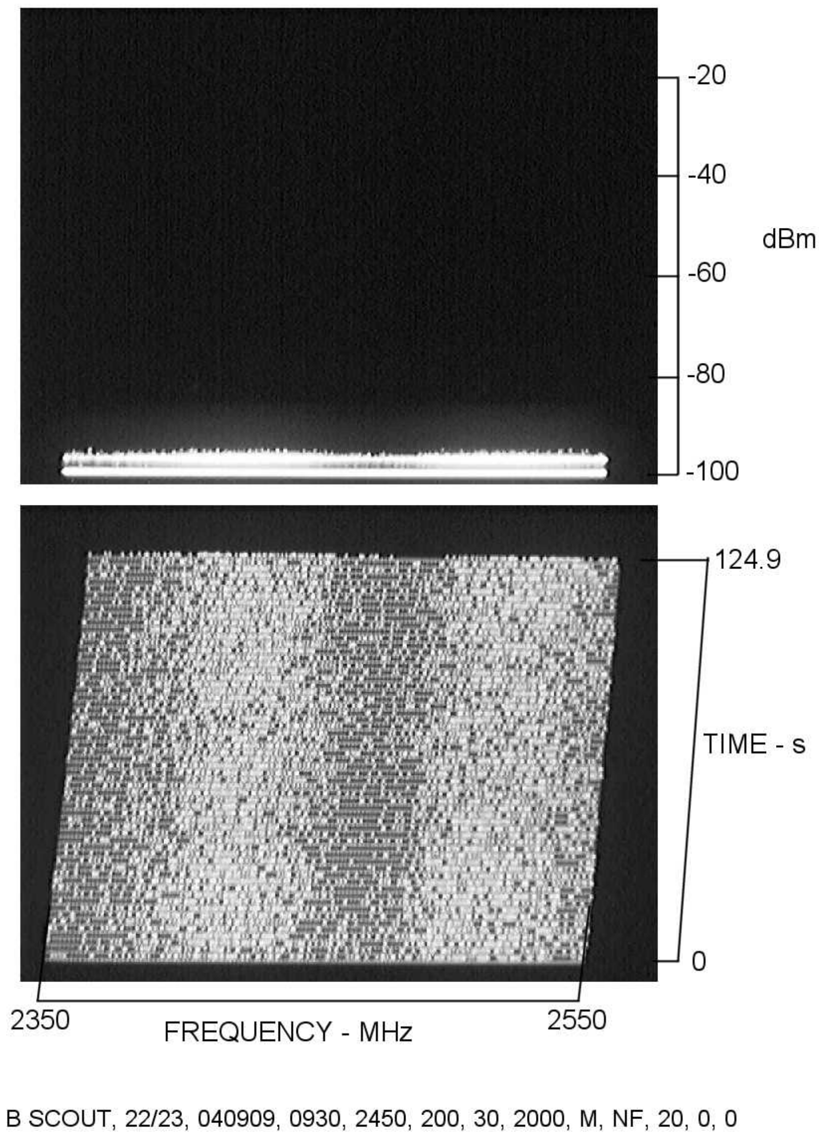


Figure 15 B SCOUT Site, Occupancy of the 2350 to 2550 MHz Band

The spectrum in and around the 5.6-GHz license-exempt wireless-radio band was examined at the B SCOUT location. Figure 16 shows the occupancy of the band from 4950 to 5450 MHz. No signals or emissions were found in the band.

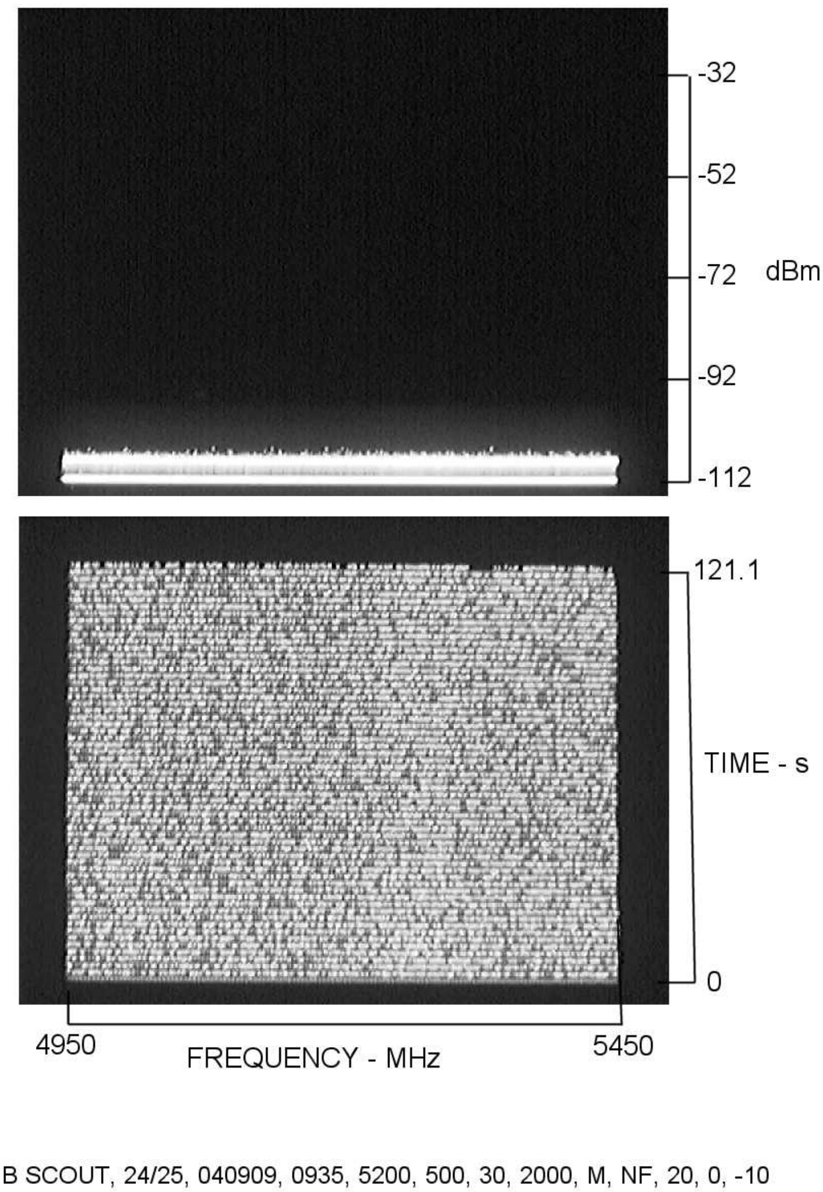


Figure 16 B SCOUT Site, Occupancy of the 4950 to 5450 MHz Band

To ensure that the entire portion of the spectrum of interest was covered, additional measurements were made of the occupancy of the 5.6-GHz region. Figure 17 shows the complete lack of signals in the 5350 to 5850 band.

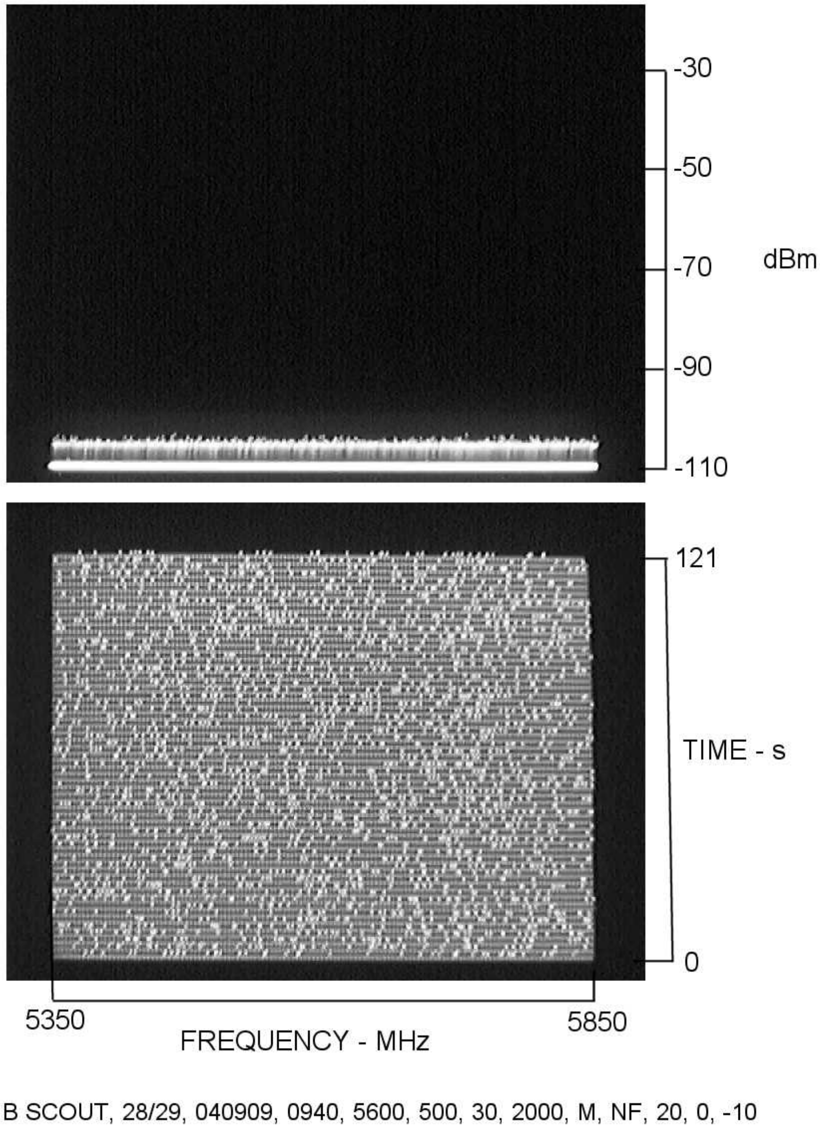


Figure 17 B SCOUT Site, Occupancy of the 5350 to 5850 MHz Band

3.3 FP 13 Location

The FP 13 measurements were made on a hilltop with excellent visibility of the surrounding area. The hilltop was the highest point in the vicinity, and it was considered an excellent location to examine the spectral use of all the bands of interest. The location of the van from a GPS reading was:

35^o 444.420' N and 120^o 47.267' W at an elevation of 1062 feet.

Figure 18 shows emissions in the band from 0.1 to 1250 MHz. Signals from stations in the FM broadcast band were lower in amplitude than at the prior two measurement sites. Television signals were stronger than for the other locations. Two strong signals near the center of the band were also noted.

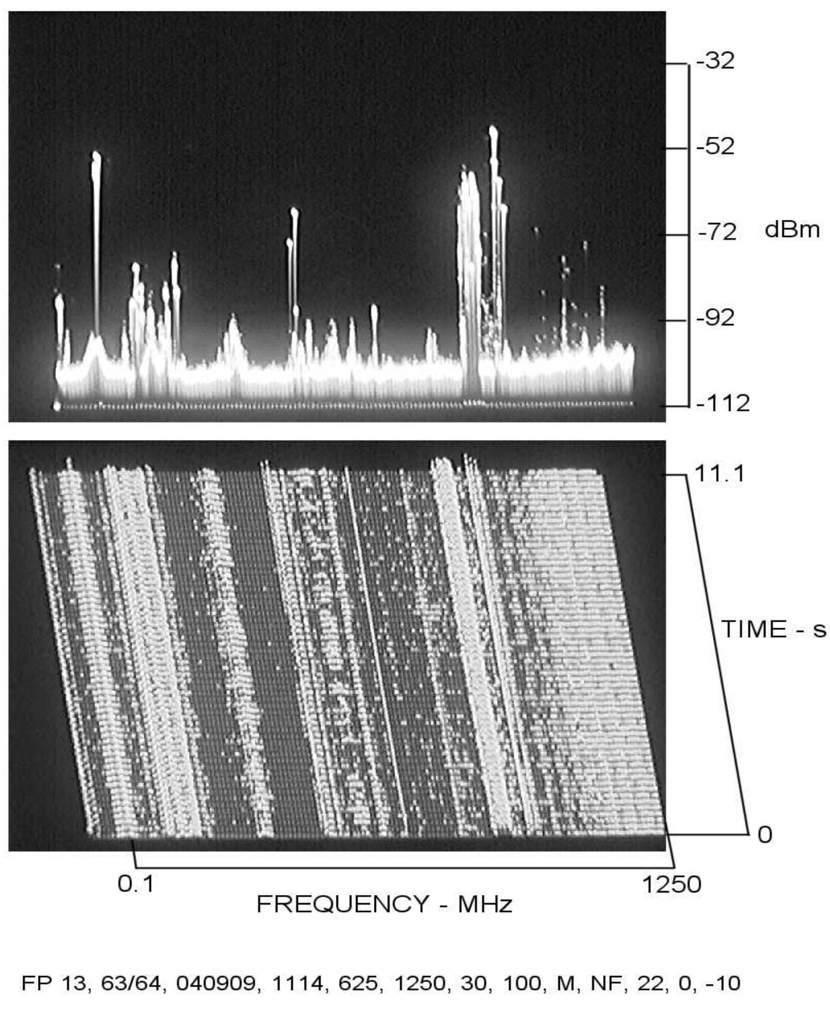


Figure 18 FP 13 Site, Occupancy of the 0.1 to 1250 MHz Band

Figure 19 shows the signal population in the band from 600 to 800 MHz at the FP 13 location. A number of low-level signals were found in this band. Of interest is one odd signal near the center of the frequency range that appears to be a short duration emission of multiple pulses. These pulses are on the top scan line of the time-history view, but the time and frequency resolution of this data is inadequate to show the details of the pulse emission.

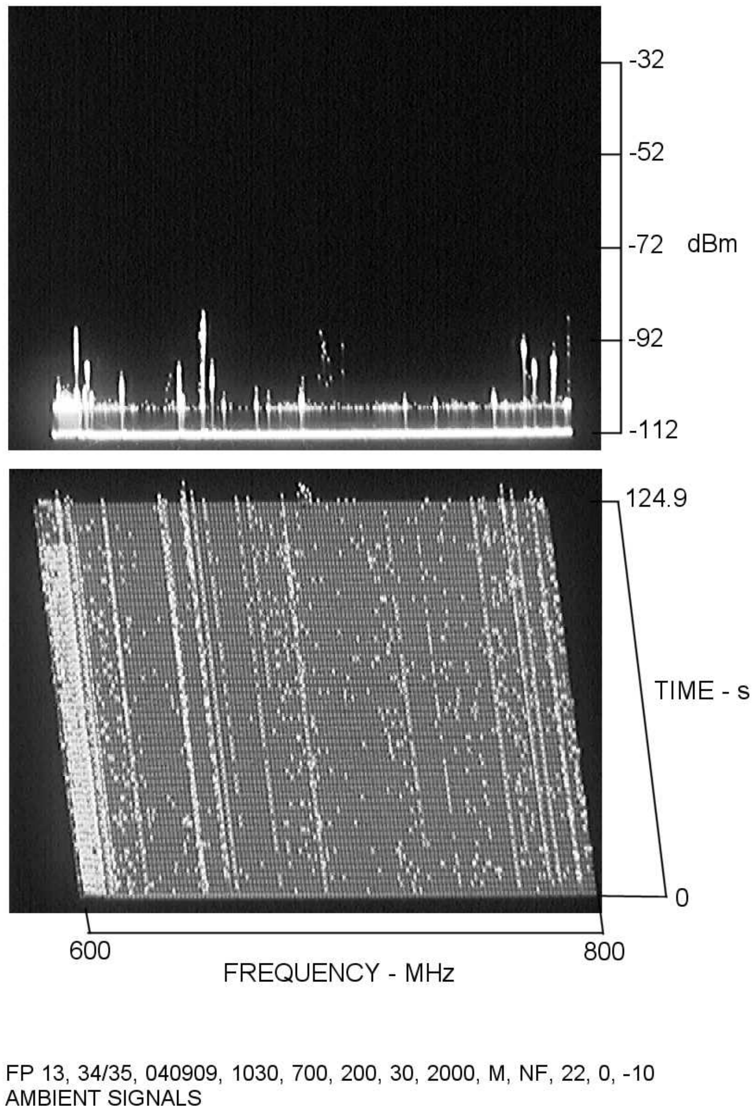


Figure 19 FP 13 Site, Occupancy of the 600 to 800 MHz Band

Figure 20 shows an expanded view of the signal population centered at 700 MHz. The signal level threshold in this example has been adjusted to eliminate most of the low-level signals and noise in both the amplitude-vs.-frequency and the time-history views. The small dots in the middle of the time-history view are pulses from the short duration emitter. The amplitude of these pulses is shown in the upper view.

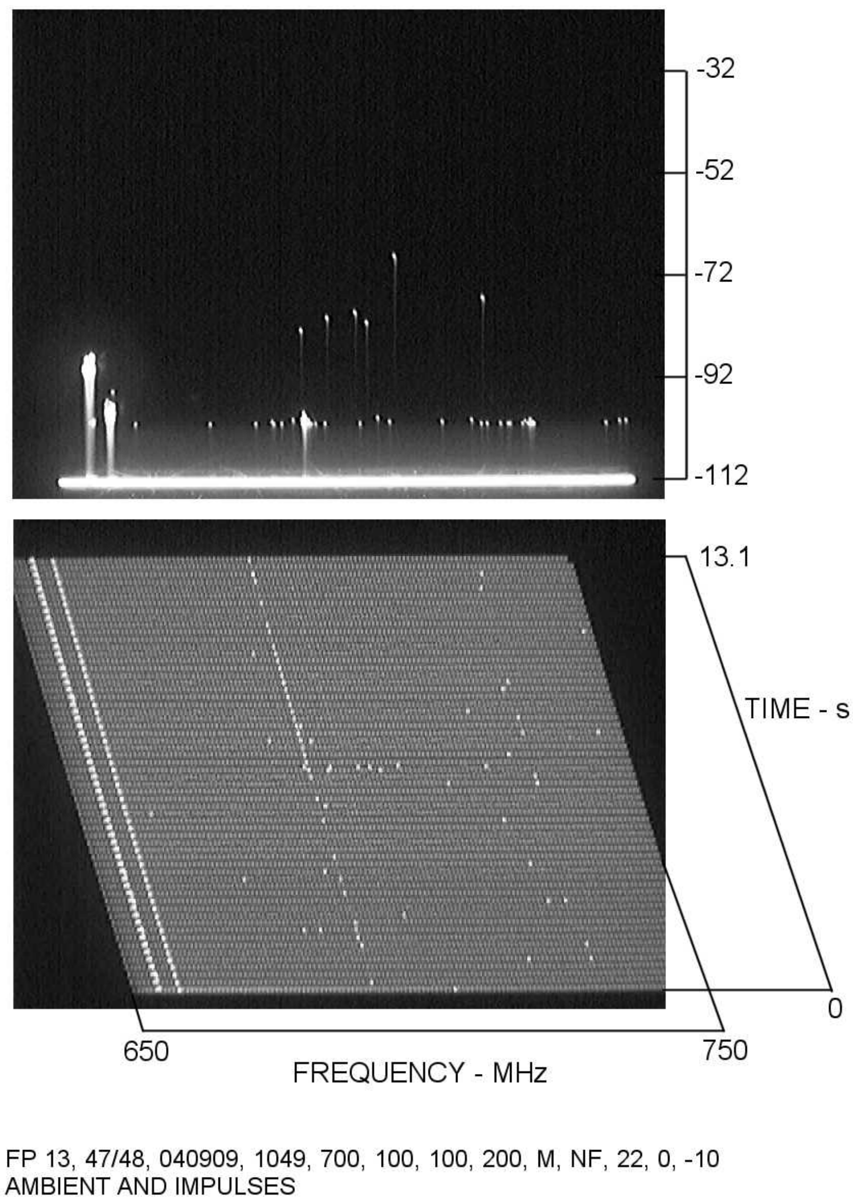


Figure 20   FP 13 Site, Occupancy of the 650 to 750 MHz Band

In order to learn more about the short-duration emission, the spectrum analyzer was tuned to 700 MHz and the frequency span was set at zero. This allowed the spectrum analyzer to perform as a standard radio receiver. Figure 21 shows the result using a 20-ms scan time. The time-history view shows pulses were received on multiple scans, indicating that additional pulses probably were not detected because they occurred during the dead time between scans.

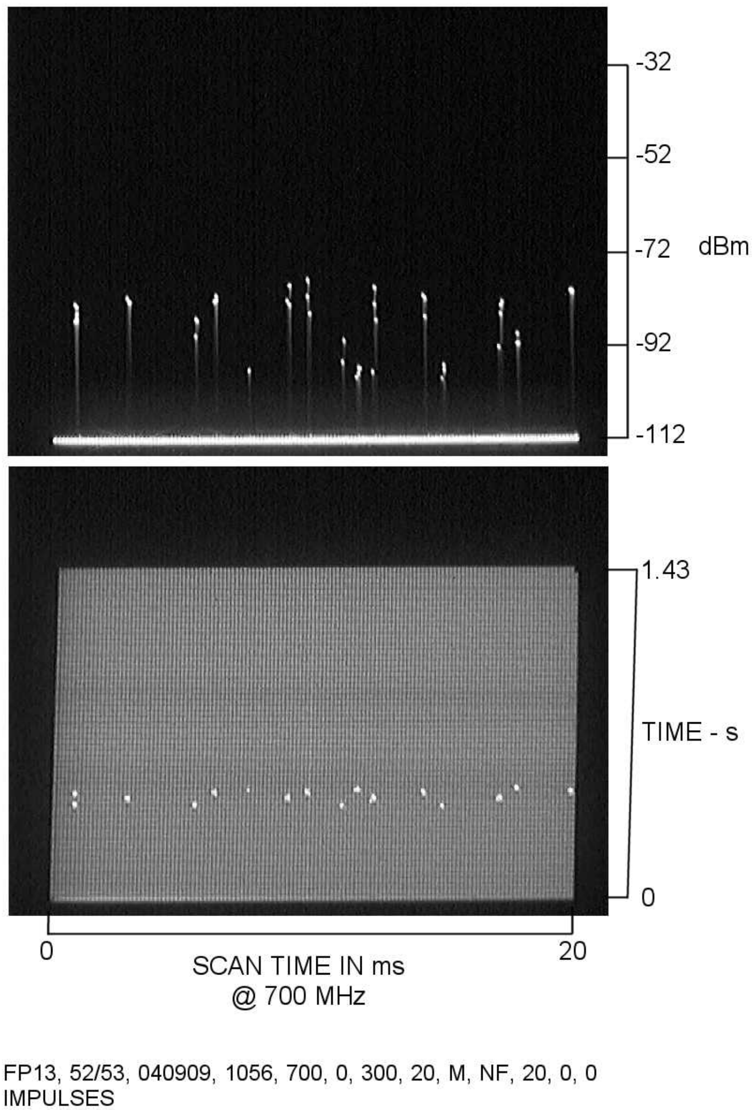


Figure 21 FP 13 Site, Pulse Signal Details, Scan Time 20 ms, Example 1

To better understand the number and spacing of the pulses shown in Figure 21, eight scan lines of the time-history view of Figure 21 were examined more closely. Figure 22 shows the pulses on four of the eight scan lines where each scan line shows pulses received during each 20-ms scan. The amplitude of the pulses is partly compressed to allow them to be shown without interference from pulses on an adjacent scan line. The pulse-to-pulse spacing varied from 3 ms up to a maximum of 6 ms. Since the spectrum analyzer had a dead time between scans of 4.1 ms (for the scan time of 20 ms), a few additional pulses probably were received during the dead time between scans and are not displayed.

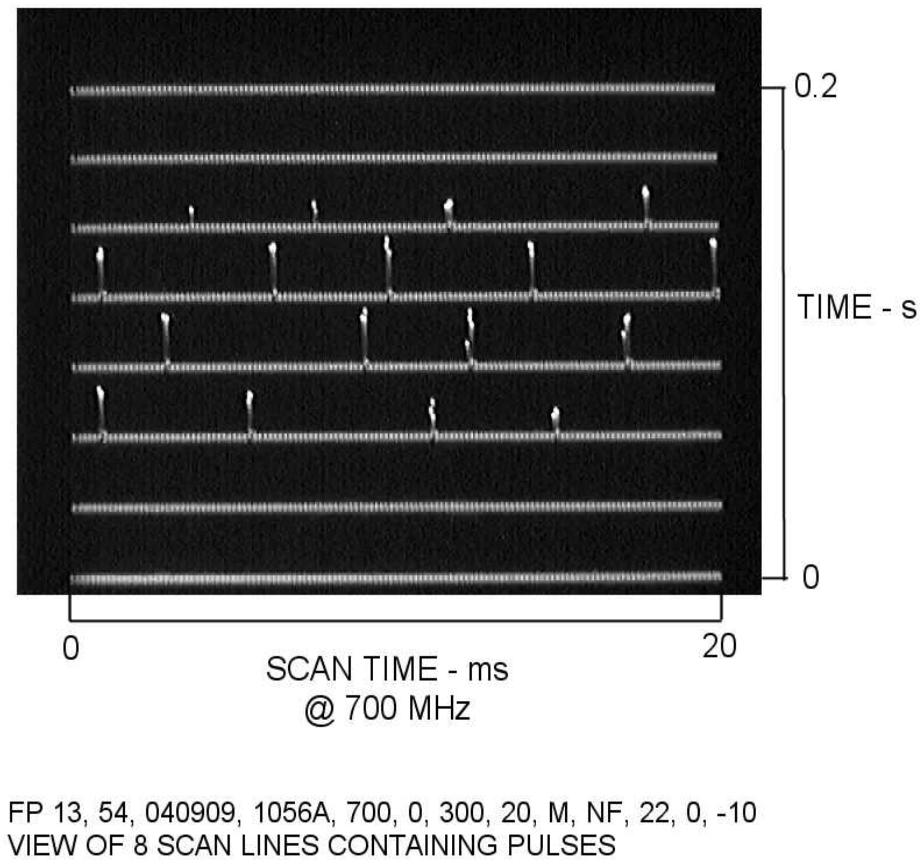


Figure 22 FP 13 Site, Pulse Signal Details, Scan Time 20 ms, Example 2

The scan time of the spectrum analyzer was increased from 20 ms to 200 ms to allow all pulses to be displayed on a single scan line and to show the pulses missed in the previous view due to the dead time of the spectrum analyzer. Figure 23 shows all of the pulses received (21 pulses) during a transmission of the short-duration emission. The uniform increase and decrease in signal level indicates one of two possibilities. First, the pulse-to-pulse amplitude is controlled. Second and more likely is that the frequency of each pulse is increased or decreased in uniform steps. Pulses at the low and high end of the scan time probably occurred on the lower and upper skirts of the Gaussian-shaped IF bandwidth of the spectrum analyzer. Those in the center of the pulse train were received near the center of the IF bandwidth and represent the amplitude of all pulses.

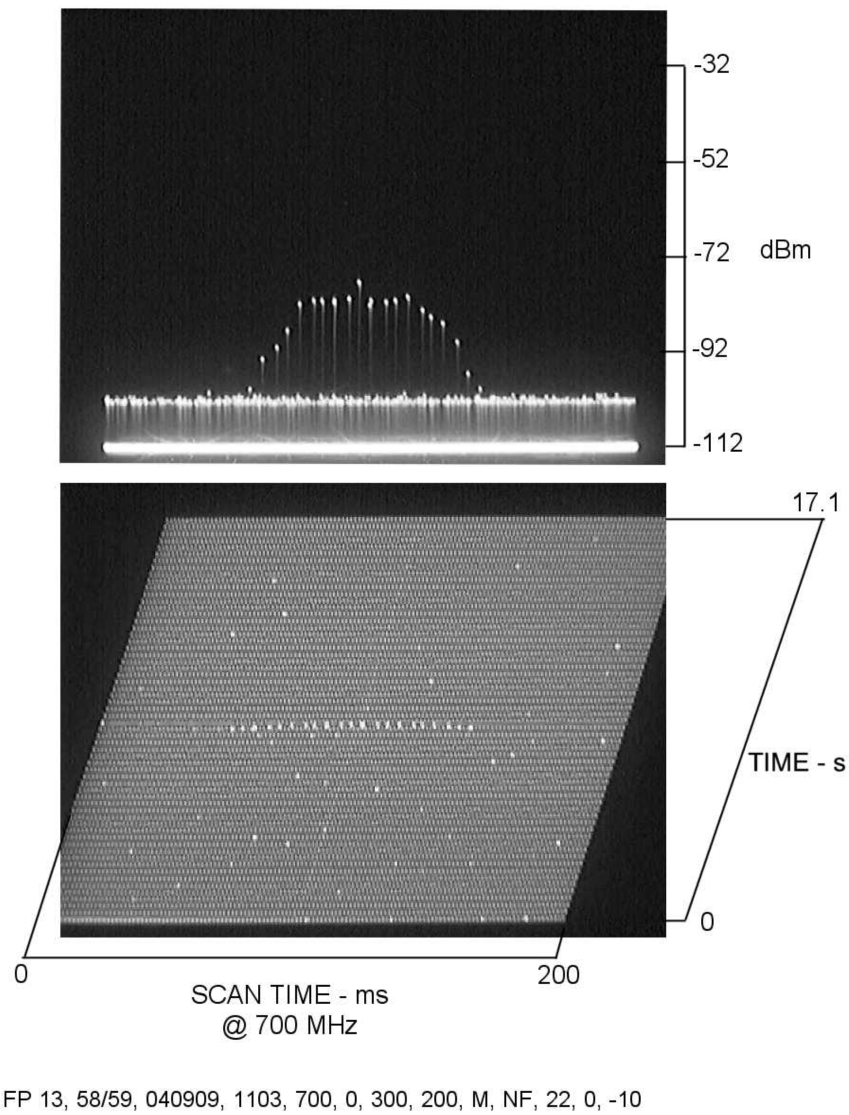


Figure 23 FP 13 Site, Pulse Signal Details, Scan Time 200 ms

Next the signal occupancy of the 2.4-GHz license-exempt wireless-radio band was examined at the FP 13 location. Figure 23 shows the band is completely void of signals at that location. Because of the high elevation of the FP 13 location the results indicate that this band was not in use in the back part of the Camp Roberts range at the time of the measurements.

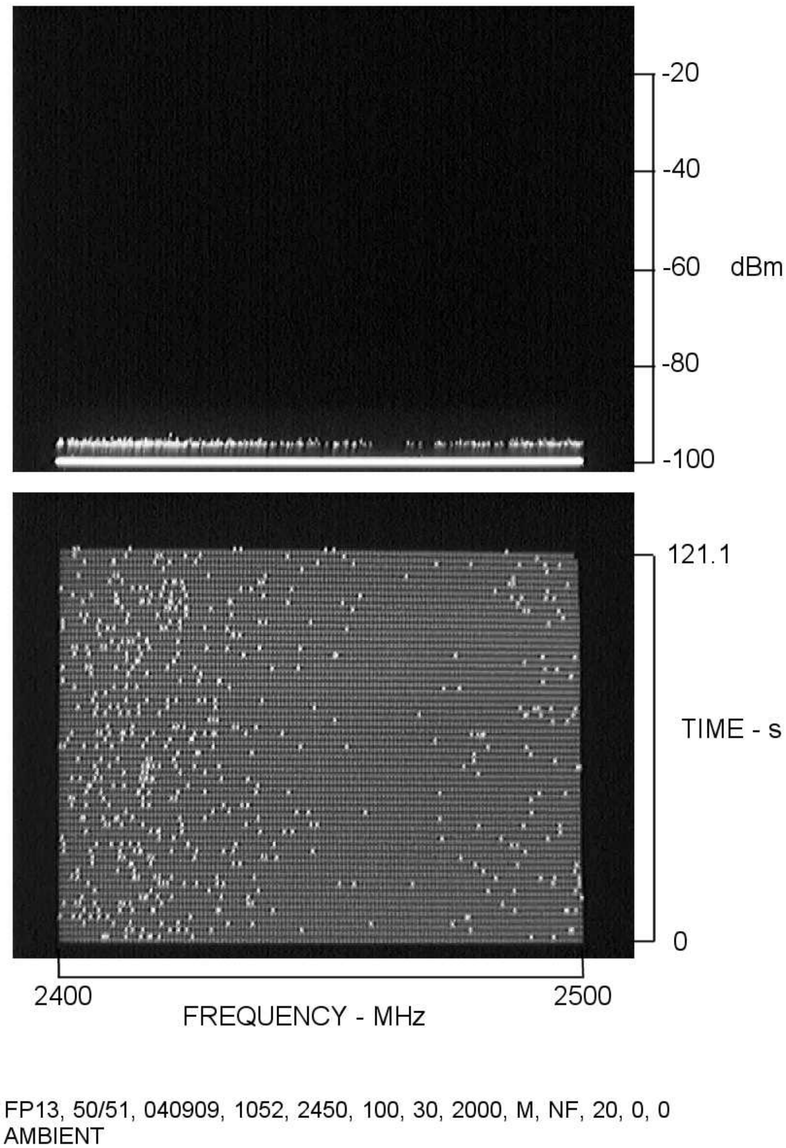


Figure 24 FP 13 Site, Occupancy of the 2400 to 2500 MHz Band

Portions of the spectrum above and below the 2.4-GHz license-exempt wireless-radio band were also examined. This was done to determine if any strong signals existed that might cause saturation to receivers operated in the wireless band. Figure 25 shows the results of the measurement. No signal was found in the entire 2.4-GHz band or at frequencies above and below the band within the frequency range of 2350 to 2550 MHz.

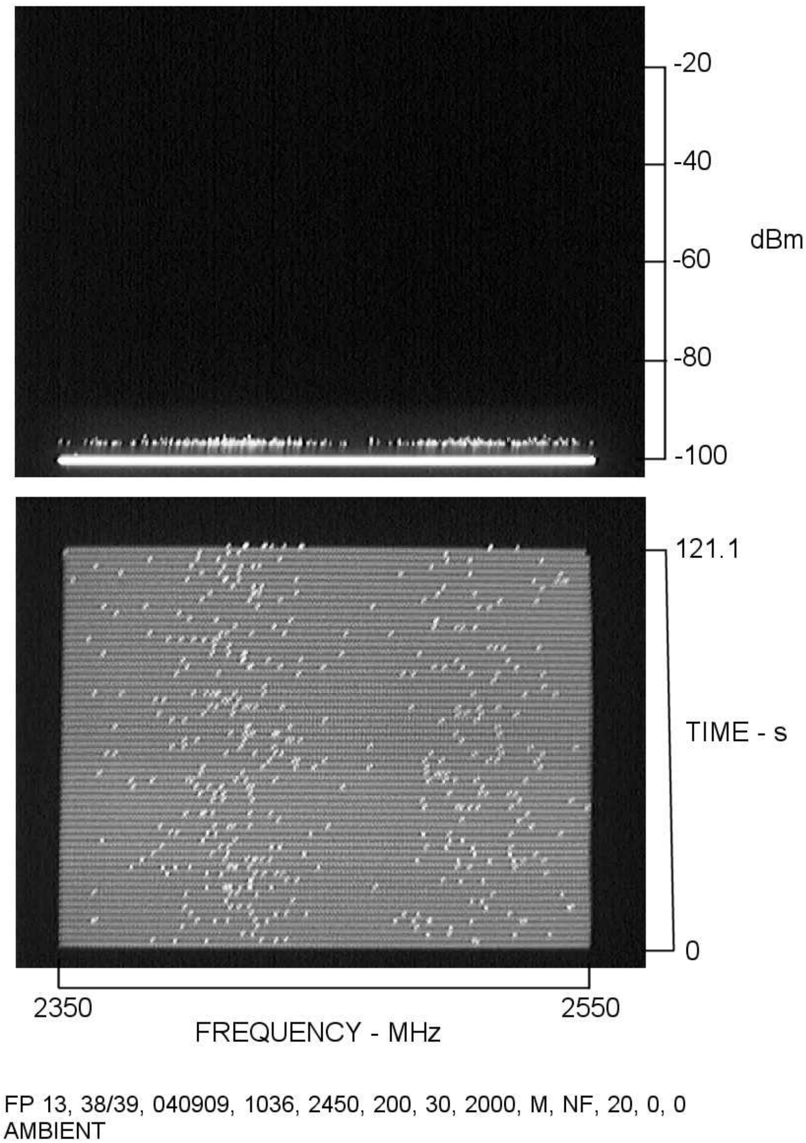


Figure 25 FP 13 Site, Occupancy of the 2350 to 2550 MHz Band

The occupancy of the 5.6-GHz license-exempt wireless-radio band and portions of the spectrum above and below the band was examined at the FP 13 location. Figure 26 shows that no signals were found in the band from 4950 to 5450 MHz.

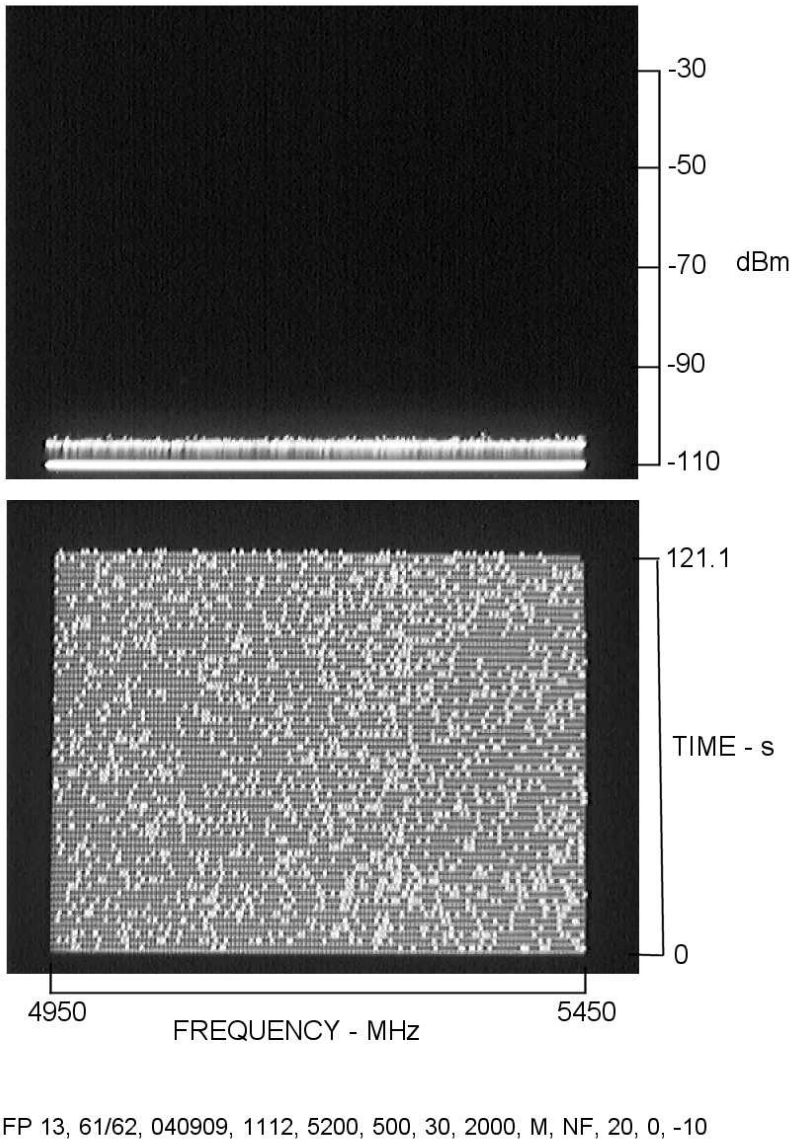


Figure 26 FP 13 Site, Occupancy of the 4950 to 5450 MHz Band

To complete the examination of the occupancy of the 5.6-GHz wireless band and a portion of the nearby spectrum, the band from 5350 to 5850 MHz was examined. Figure 27 shows that no signals were found in the band.

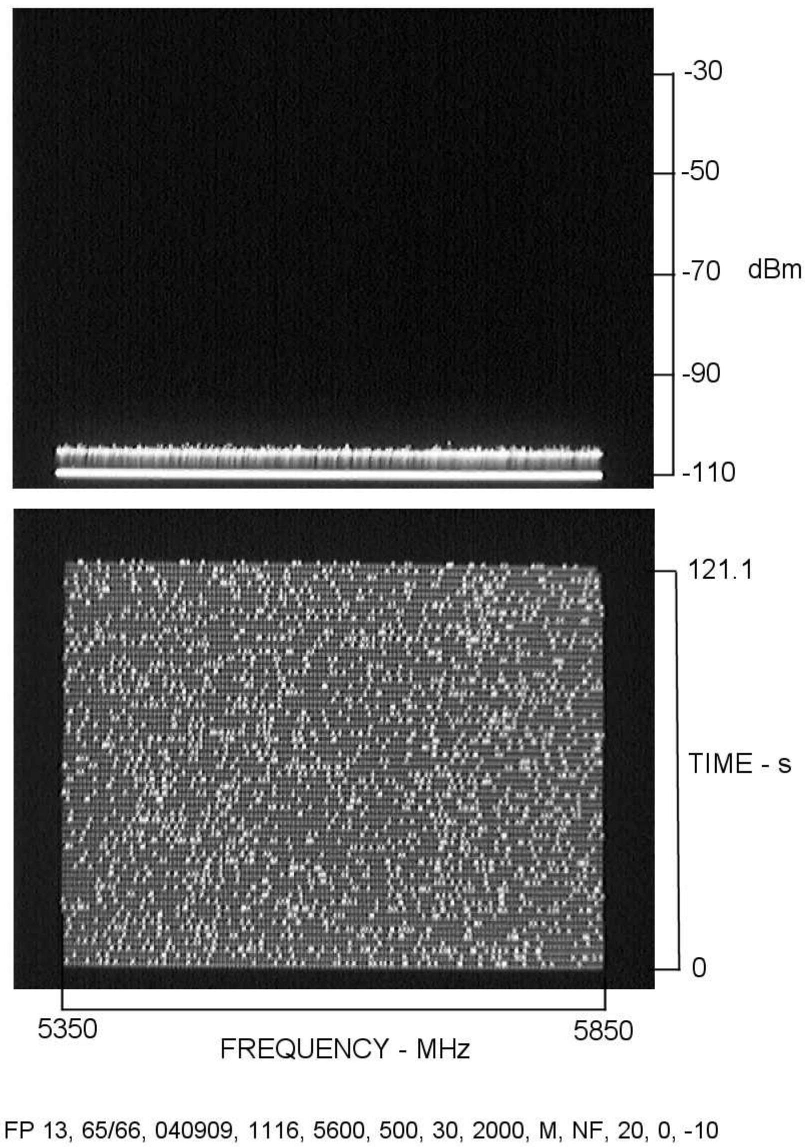


Figure 27 FP 13 Site, Occupancy of the 5350 to 5850 MHz Band

4.0 FINDINGS

The findings of the survey are summarized in the following comments:

- The radio spectrum from 4950 to 5850 MHz was entirely free of signals and noise at all three locations. This frequency range includes the entire 5.6-GHz license-exempt wireless-radio band plus frequencies above and below the band. It is possible that low-level signals might be found at higher elevations where line of sight to more distant sources occurs, but no significant high-level signals would be expected at higher elevations.
- The license-exempt wireless radio band from 2400 to 2483.5 MHz was entirely free of signals and noise at all three sites. The band from 2350 to 2550 MHz, which included the license-exempt band, was also examined at the B Scout and FP 13 sites, and no signals or noise were found over the entire range examined. It is possible that low-level signals might be found at higher elevations where line of sight to distant sources occurs, but no significant high-level signal would be expected at the higher elevations.
- One standard 802.11b emission in the 2.4-GHz band was detected only at the headquarters area near the entrance to Camp Roberts including the vicinity of the entrance gate. The signal appeared to be from standard low-power wireless device used for short-distant digital communications. This emissions was intermittent in operation.
- The band from 600 to 800 MHz was examined at all three locations. One unusual signal was noted at the FP-13 site near 700 MHz. This signal consisted of a brief series of at least 21 very narrow pulses spaced from 3 to 6 ms apart. The series repeated at intervals of about two minutes. The amplitude was very high at the FP location, apparently due to the high elevation and good line-of-sight visibility of that location to the source of the pulses.
- The 700-MHz signal was also noted in the data at the CIRPAS location but at a low level.
- The source of the 700-MHz pulses was not located during the survey. Direction finding equipment to determine the source of the pulses was not included in the instrumentation package used for these measurements. Since the source of the emission was not determined it is entirely possible it was partly terrain shielded from the FP 13 location and that even higher signal levels would be encountered at higher elevations. If this is the case, signal strengths high enough to intermittently saturate the RF components of UHF receivers or other wide-band receivers could be encountered.

Camp Roberts, 040909, Page 1 of 3

Location	Pic No	Date dd/mm/yy	Time Local	Freq. MHz	Span MHz	BW kHz	Scan Time ms	Source	Filter id	Preamp dB	RF Attn dB	Ref. dBm	Comments
CIRPAS	1T	040909	0807	2450	100	30	5000	M	NF	20	0	-10	No Signals El 920 ft
CIRPAS	2A	040909	"	"	"	"	"	"	"	"	"	"	35° 42.963N 120° 45.784W
CIRPAS	3T	040909	0815	700	200	30	2000	M	NF	22	0	-10	Ambient Signals
CIRPAS	4A	040909	"	"	"	"	"	"	"	"	"	"	"
CIRPAS	5T	040909	0819	2451	200	30	5000	M	NF	20	0	0	Ambient
CIRPAS	6A	040909	"	"	"	"	"	"	"	"	"	"	"
CIRPAS	7A	040909	"	"	"	"	"	"	"	"	"	"	"
CIRPAS	8	040909	0826										WRV Cal Shot
CIRPAS	9T	040909	0827	700	100	30	2000	M	NF	22	0	-10	Ambient Signals
CIRPAS	10A	040909	"	"	"	"	"	"	"	"	"	"	"
CIRPAS	11	040909	0830										NPS Cal Shot
CIRPAS	12T	040909	0840	5600	500	30	1000	M	NF	20	0	-10	Ambient
CIRPAS	13A	040909	"	"	"	"	"	"	"	"	"	"	"
CIRPAS	14T	040909	0843	625	1250	30	100	M	NF	22	0	-10	Preamp Upper Limit 1000
CIRPAS	15A	040909	"	"	"	"	"	"	"	"	"	"	"
CIRPAS	16T	040909	0847	5200	500	30	2000	M	NF	20	0	-10	Ambient
CIRPAS	17A	040909	"	"	"	"	"	"	"	"	"	"	
B SCOUT	18T	040909	0921	2450	100	30	2000	M	NF	20	0	0	Ambient El 590 ft
B SCOUT	19A	040909	"	"	"	"	"	"	"	"	"	"	"35° 45.382' N 120° 48.603' W
B SCOUT	20A	040909	0922	625	1250	30	100(LS)	M	NF	22	0	-10	
B SCOUT	21T	040909	"	"	"	"	"	"	"	"	"	"	
B SCOUT	22T	040909	0930	2450	200	30	2000	M	NF	20	0	0	Ambient
B SCOUT	23A	040909	"	"	"	"	"	"	"	"	"	"	"
B SCOUT	24T	040909	0935	5200	500	30	2000	M	NF	20	0	-10	Ambient
B SCOUT	25A	040909	"	"	"	"	"	"	"	"	"	"	"

Camp Roberts, 040909, Page 2 of 3

Location	Pic No	Date dd/mm/yy	Time Local	Freq. MHz	Span MHz	BW kHz	Scan T ms	Source	Filter id	Preamp dB	RF Attn dB	Ref. dBm	Comments
B SCOUT	26T	040909	0936	550	50	30	5000	M	NF	22	0	-20	Unknown Noise
B SCOUT	27A	040909	"	"	"	"	"	"	"	"	"	"	"
B SCOUT	28T	040909	0940	5600	500	30	2000	M	NF	20	0	-10	Ambient
B SCOUT	29A	040909	"	"	"	"	"	"	"	"	"	"	"
B SCOUT	30T	040909	0942	700	100	30	2000	M	NF	22	0	-10	Ambient Signals
B SCOUT	31A	040909	"	"	"	"	"	"	"	"	"	"	"
B SCOUT	32T	040909	0945	700	200	30	2000	M	NF	22	0	-10	Ambient Signals
B SCOUT	33A	040909	"	"	"	"	"	"	"	"	"	"	"
FP 13	34T	040909	1030	700	200	30	2000	M	NF	22	0	-10	Ambient Signals, El 1062 ft
FP 13	35A	040909	"	"	"	"	"	"	"	"	"	"	"35^{o} 44.42N 120^{o} 47.267W
FP 13	36T	040909	1034	700	100	30	2000	M	NF	22	0	-10	Ambient Signals
FP 13	37A	040909	"	"	"	"	"	"	"	"	"	"	"
FP 13	38T	040909	1036	2450	200	30	2000	M	NF	20	0	0	Ambient
FP 13	39A	040909	"	"	"	"	"	"	"	"	"	"	"
FP 13	40T	040909	1040	700	100	100	200	M	NF	22	0	-10	Impulses
FP 13	41A	040909	"	"	"	"	"	"	"	"	"	"	"
FP 13	42A	040909	"	"	"	"	"	"	"	"	"	"	"
FP 13	43A	040909	"	"	"	"	"	"	"	"	"	"	"
FP 13	44T	040909	1046	700	100	100	200	M	NF	22	0	-10	Impulses
FP 13	45A	040909	"	"	"	"	"	"	"	"	"	"	"
FP 13	46A	040909	"	"	"	"	"	"	"	"	"	"	"
FP 13	47T	040909	1049	700	100	300	200	M	NF	22	0	-10	Impulses
FP 13	48A	040909	"	"	"	"	"	"	"	"	"	"	"
FP 13	49A	040909	"	"	"	"	"	"	"	"	"	"	"

Camp Roberts, 040909, Page 3 of 3

Location	Pic No.	Date yymmdd	Time Local	Freq. MHz	Span MHz	BW kHz	Scan T. ms	Source	Filter id	Preamp dB	RF Attn. dB	Ref. dBm	Comments
FP13	50T	040909	1052	2450	100	30	2000	M	NF	20	0	0	Ambient
FP13	51A	040909	“	“	“	“	“	“	“	“	“	“	“
FP13	52T	040909	1056	700	0	300	20	M	NF	22	0	-10	Impulses
FP13	53A	040909	“	“	“	“	“	“	“	“	“	“	“
FP13	54A	040909	“	“	“	“	“	“	“	“	“	“	“
FP13	55T	040909	1059	700	0	300	100	M	NF	22	0	-10	Impulses
FP13	56A	040909	“	“	“	“	“	“	“	“	“	“	“
FP13	57A	040909	“	“	“	“	“	“	“	“	“	“	“
FP13	58T	040909	1103	700	0	300	200	M	NF	22	0	-10	Impulses
FP13	59A	040909	“	“	“	“	“	“	“	“	“	“	“
FP13	60A	040909	“	“	“	“	“	“	“	“	“	“	“
FP13	61T	040909	1112	5200	500	30	2000	M	NF	20	0	-10	Ambient
FP13	62A	040909	“	“	“	“	“	“	“	“	“	“	“
FP13	63A	040909	1114	625	1250	30	100	M	NF	22	0	-10	0 to 1250
FP13	64T	040909	“	“	“	“	“	“	“	“	“	“	“
FP13	65T	040909	1116	5600	500	30	2000	M	NF	20	0	-10	Ambient
FP13	66A	040909	“	“	“	“	“	“	“	“	“	“	“
FP13	67A	040909	1118	900	100	30	1000	M	NF	22	0	-10	Ambient
FP13	68T	040909	“	“	“	“	“	“	“	“	“	“	“
FP13	69T	040909	“	“	“	“	“	“	“	“	“	“	“

APPENDIX D. MISCELLANEOUS 915-MHZ BAND MEASUREMENTS

One document is provided in this appendix. It is:

- Technical Memorandum 031001, ***Ambient Signals and Noise in the 915-MHz Band***, December 1998

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AMBIENT SIGNALS AND NOISE IN THE 915-MHz ISM BAND

By:
Wilbur R. Vincent
Andrew Parker
Richard Adler

The noise level and signal population in the 915-MHz ISM band was examined at four locations in California. The objectives of these measurements were to find sites suitable for testing new communication systems and to conduct preliminary surveys of noise levels and the ambient signal population at the selected sites.

Four sites were selected for examination. The first was a residential area in Los Altos Hills, the next a business area in San Diego followed by a second business area site in Monterey and finally a remote area site in the former troop training area at the rear of Fort Ord. The Los Altos Hills site was used for field tests intermittently over a four year period. The other sites were used intermittently over shorter periods.

Figure 1 (990425 1547) shows ambient signals in the 915-MHz ISM band where the band is sandwiched between two cellular telephone bands containing strong signals. The data were taken at the Los Altos Hills residential area site. Two low-level discrete-frequency signals are shown along with one odd signal about of about one second in duration. In addition the background dots in the time-history view are from frequency-hopping sources. Later measurements determined that four different frequency-hopping sources were present.

Several minutes later, the one-second signal changed its modulation format during another one-second transmission. The temporal and spectral structure of the new emission is shown in Figure 2 (990425 1554). Frequency-hopping signals are shown in the background.

The signals shown in Figures 1 and 2 were present during all tests as well as other occasional and erratic emissions from unknown sources. Since most such signals were low in amplitude, communications system testing could proceed as long as proper precautions were taken concerning the ambient signal population. The occupancy of the band was monitored during all tests to take into account the impact of all harmful emissions observed in the band.

A business area site in San Diego was selected. A mobile receiver was used to explore reception at a number of different locations. A parking lot near the base station was selected for the first test location. Figure 3 (981111 1120) shows the presence of a very strong frequency-hopping signal at this location, and this undesired signal was present during most of the tests at this location. Since the interfering signal was very strong, the extensive documentation of its temporal and spectral properties was necessary to fully assess its potential and actual impact on a test communication system.

Figure 4 (981111 1117) shows the frequency-hopping signal along with the test signal. In this particular view, the frequency-hopping signal did not fall on top of the test signal, and the IF band pass of the test system successfully rejected the interference during the period shown.

Note: This memorandum was prepared in December of 1998. It was reprinted in October 2003 to provide historical information needed to understand differences in the use and occupancy of the 915-MHz Wireless-Radio band from 1998 to 2003.

Nevertheless, one must consider the possible impact of the high-amplitude frequency-hopping signal on the dynamic range of the RF stages of the test system receiver.

Figure 5 (981111 1350) shows the test signal as received at a more remote location. The test signal is near the noise floor of the receiving system, nevertheless successful reception was achieved due to the modulation format and error-correction coding. Note that the frequency-hopping signals are also present but at a low amplitude.

Additional tests were conducted using the Naval Postgraduate School as a base of operations. A test transmitter was installed on the roof of the engineering building, and signal reception was examined with a mobile receiver at various locations. Figure 6 (990426 1600) shows ambient signals at a distance of 2.39 miles which completely obliterated the test signal. High-level spread-spectrum and frequency-hopping interference was encountered at this location. These signals were traced to data-transmission systems operated by two nearby commercial facilities. Apparently, they could tolerate interference from each other since both had been in operation for a long period of time.

The test signal was received at another location where terrain features reduced the strength of the two interfering signals. Figure 7 (990426 1607) shows the test signal along with some frequency-hopping interference. Fading of the test signal was a result of multipath caused by reflections from passing automobiles.

Similar results were obtained during tests using the remote parts of Fort Ord. Terrain features reduced the interference to acceptable levels. Terrain shielding also had a significant impact on the levels of test signals for many test paths although excellent performance was achieved with line-of-sight and near line-of-sight paths.

In summary, ambient signals were present throughout the 915-MHz band at all test locations. Frequency-hopping and direct-sequence spread-spectrum signals were the most prevalent kind of signal although discrete-frequency signals and other unusual signals were frequently observed. At times it appeared that the band was used for the field testing of various new communication systems and modulation techniques. This might be expected at the Los Altos Hills test location which is near many organizations developing new wireless LANs and new wireless communication devices. The strong ambient signals at some test locations suggest that severe interference can sometimes be encountered by new users attempting to employ this portion of the spectrum. For example, a 915-MHz portable telephone could not be operated successfully with the interference shown in Figure 6.

Of interest is that no signal observed at any test location was ever traced to a user associated with the original intent of the band, the Industrial, Scientific or Medical service. All emissions in the band appeared to be from new kinds of communications services. The license-free portions of the spectrum apparently have considerable appeal to new kinds of users.

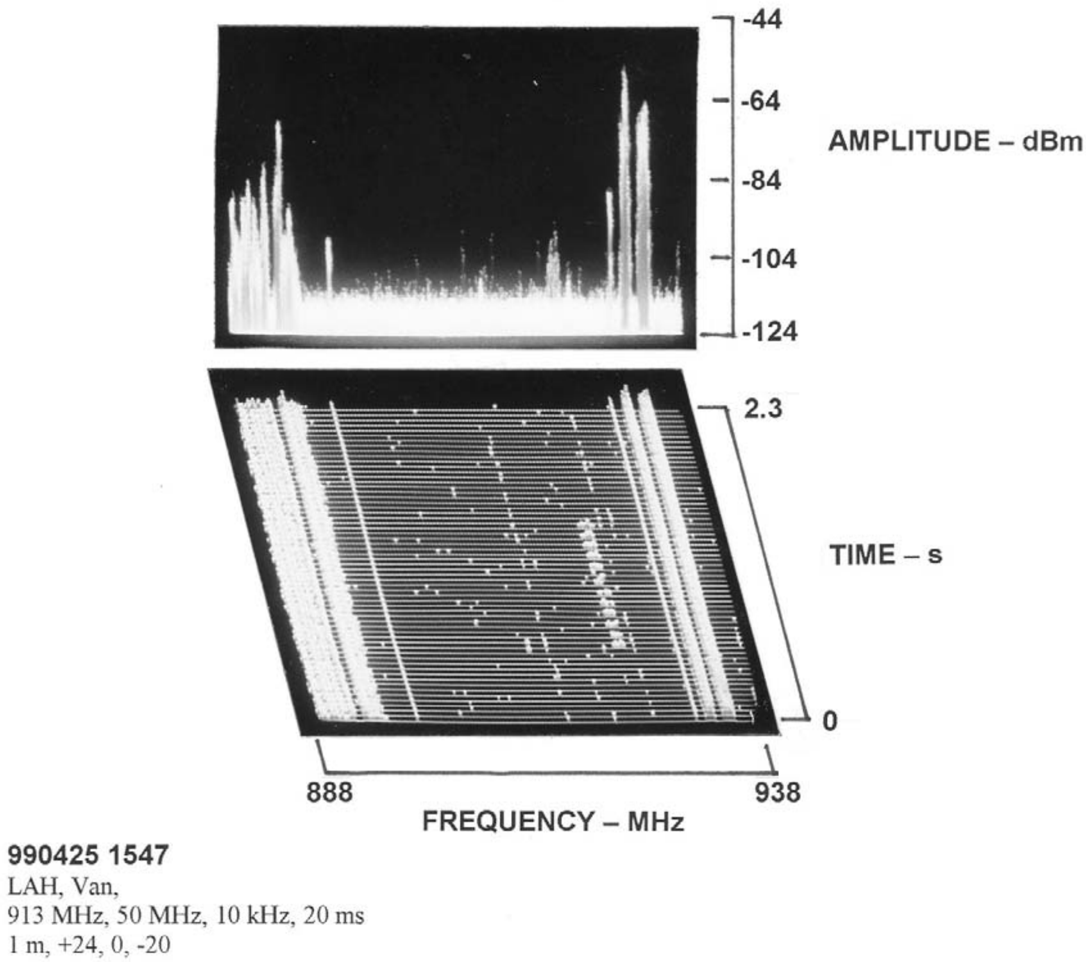
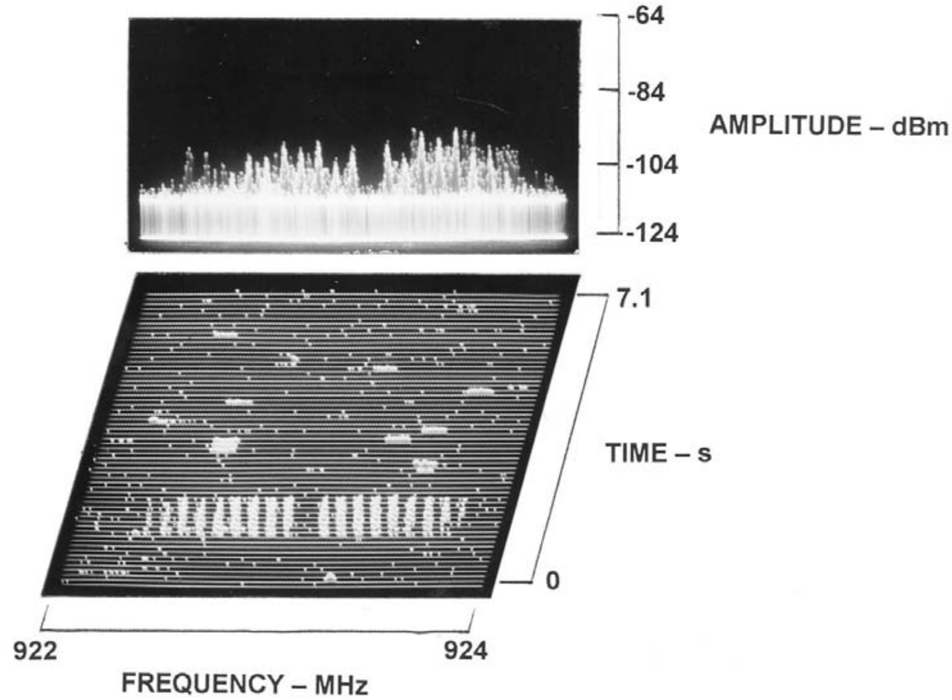


Figure 1

Coarse Scale Temporal and Spectral Views of the 915-MHz ISM Band



990425 1554
LAH, Van,
923 MHz, 2 MHz, 10 kHz, 100 ms
1 m, +24, 0, -20

Figure 2

Unusual Signal in the 915-MHz Band

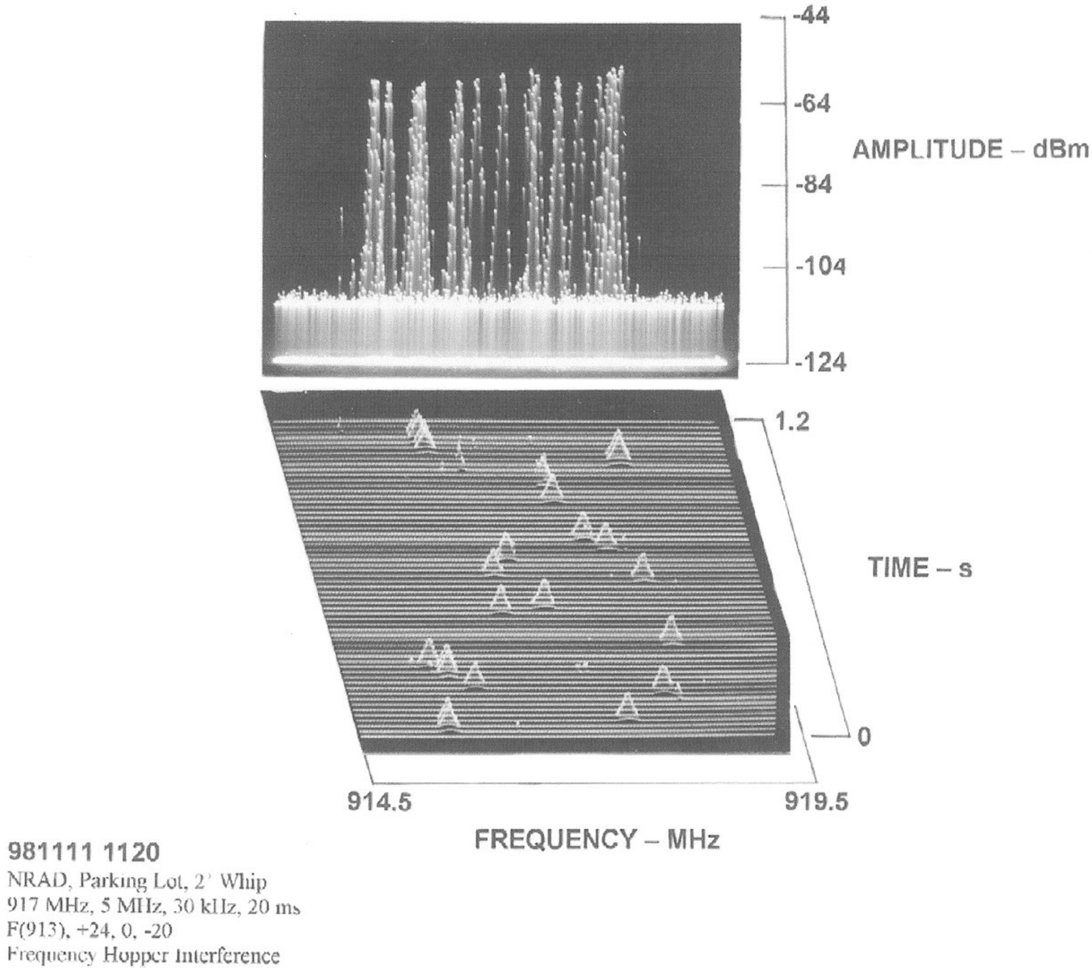
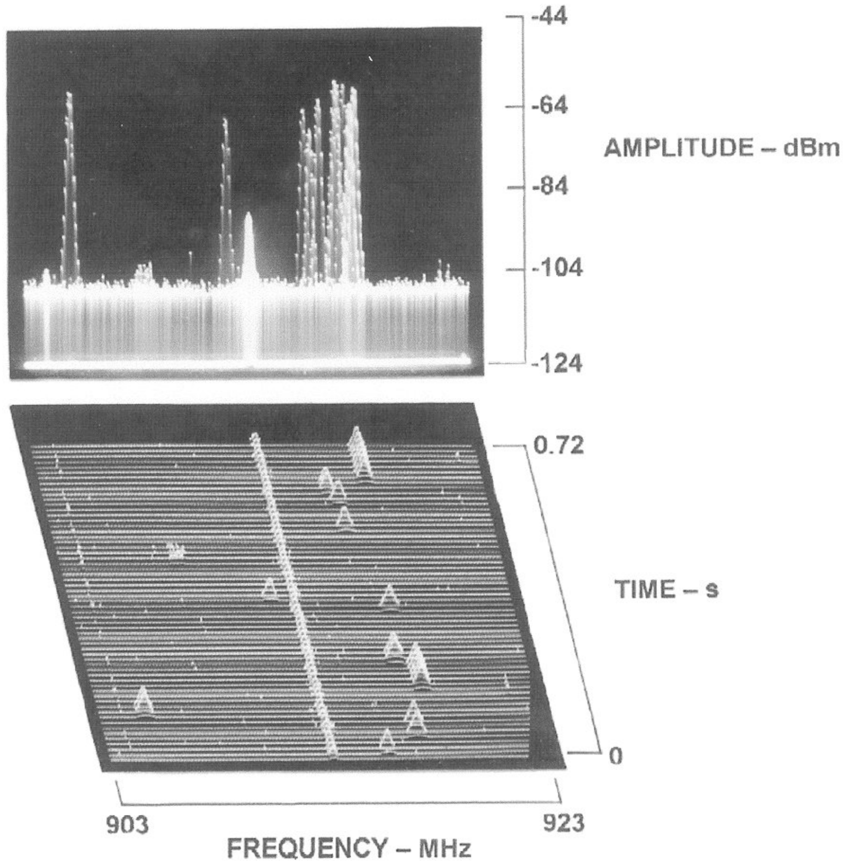


Figure 3

Example of Strong Frequency-Hopping Noise

Note: The original for this example could not be located. This example was scanned from a draft copy of the original memorandum

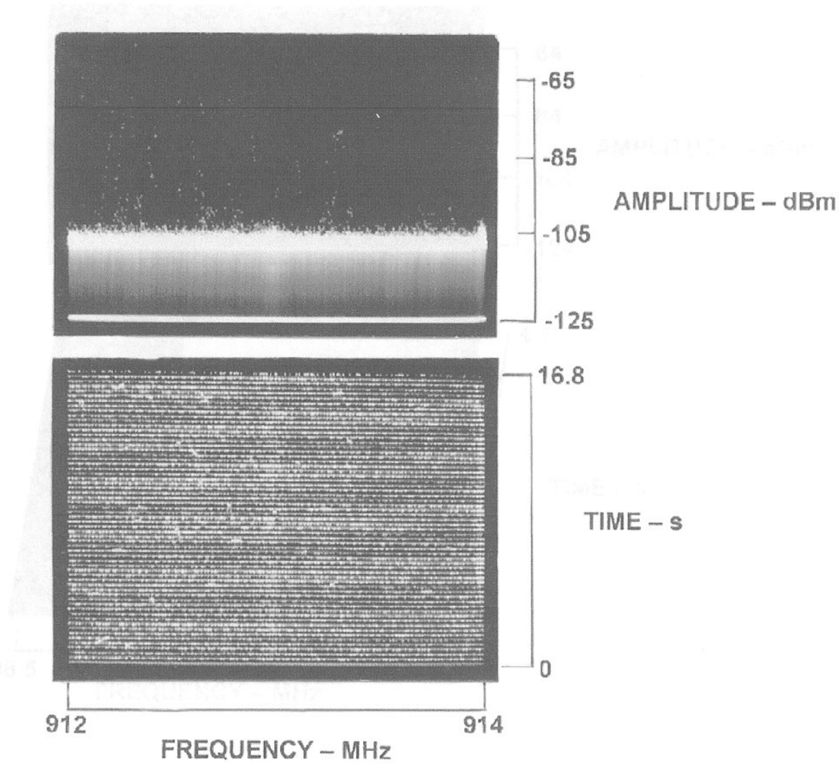


981111 1117
NRAD, Parking Lot, 2' Whip
913 MHz, 20 MHz, 100 kHz, 10 ms
F(913), +24, 0, -20
Source: NRAD SS at 100 μW
Frequency Hopper Interference

Figure 4

Frequency-Hopping Interference and a Test Signal

Note: The original for this example could not be located. This example was scanned from a draft copy of the original memorandum

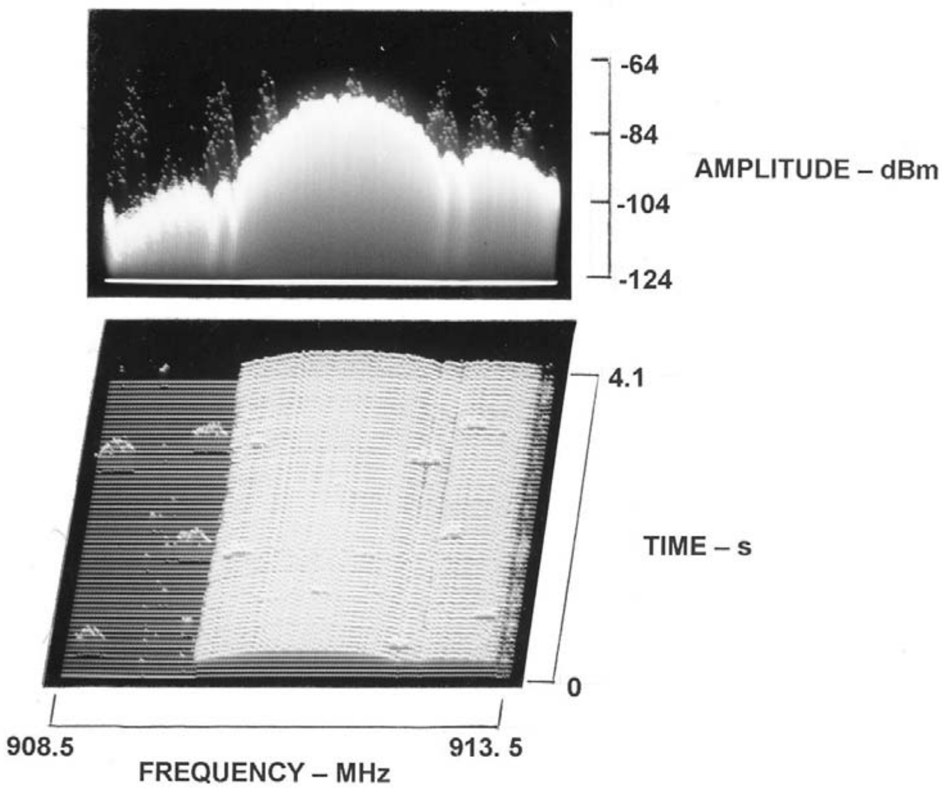


981111 1350
NAS San Diego, beach, 2' Whip
913 MHz, 2 MHz, 30 kHz, 200 ms
F(913), NPS Preamp, 0, -20
Source: NRAD SS at 100 µW
NRAD source, 913 MHz @100 µW

Figure 5

Low-Level Signal with Frequency-Hopping Interference

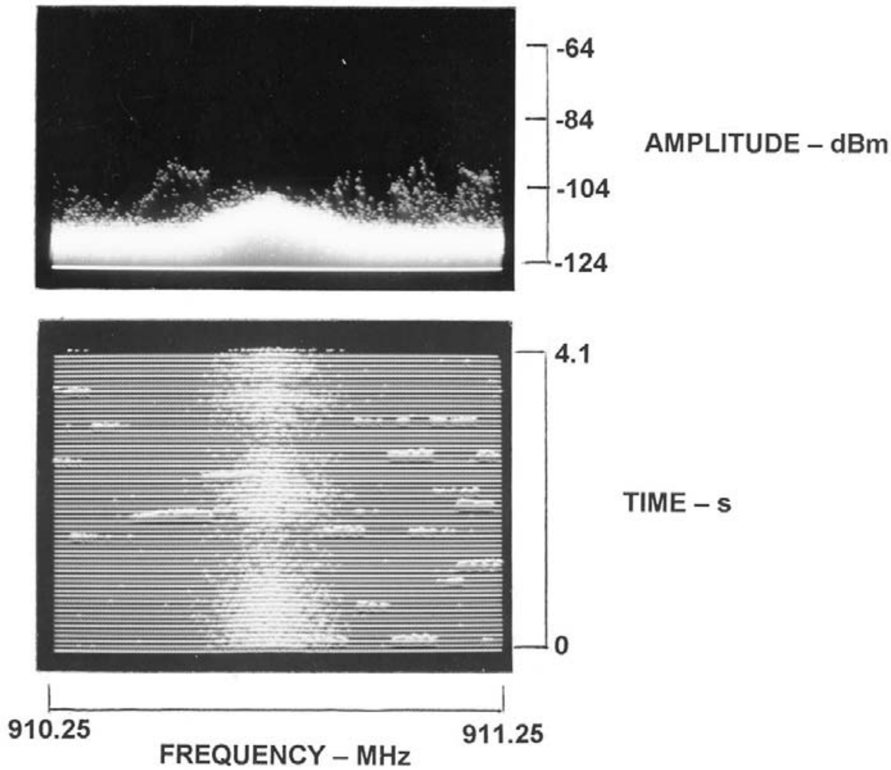
Note: The original for this example could not be located. This example was scanned from a draft copy of the original memorandum



990426 1600
NPS, LPI, 044°, 2.39 mi
911 MHz, 5 MHz, 30 kHz, 50 ms
Rod, +24, 0, -20
FH and SS Interference

Figure 6

High-Level Spread-Spectrum and Frequency-Hopping Interference



990426 1607
NPS, LPI, 041°, 2.65 mi
911 MHz, 500 kHz, 30 kHz, 50 ms
LPVP, +24, 0, -20
Reflections from autos

Figure 7

Interference from a Frequency-Hopping Signal and Fading due to Multipath

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APPENDIX E. OCCUPANCY AND USE OF A LICENSED BAND

One document is provided in this appendix. It is:

- Technical Memorandum 040115, *An Initial Examination of the Occupancy and use of the 804 to 940-MHz Band,* January 2004

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Technical memorandum 040115
Signal Enhancement Laboratory
Department of Electrical and Computer Engineering
Naval Postgraduate School
Monterey, CA 93943

January 2004

An Initial Examination of the Occupancy and Use Of the 806- to 940-MHz Band

by:
Wilbur R. Vincent
Richard W. Adler
Andrew A. Parker and
George F. Munsch

1. INTRODUCTION

Signals, interference, and radio noise in a portion of the spectrum used for licensed and regulated wireless communications (806 to 940 MHz) were examined at one location. This was an exploratory effort with two primary objectives. They are:

- To obtain initial information about the occupancy and use of a portion of the spectrum available to licensed wireless radio at one convenient location. This was done to test equipment and measurement procedures prior to the conduct of similar but more extensive measurements at other locations.
- To obtain practical experience with the use of a new digital oscilloscope camera prior to field measurements and to test new data-processing procedures associated with the digital camera.

All measurements were made inside a residence located in the northwestern part of Davis, CA. More specifically, they were made in the garage with the garage door closed because of inclement weather. The measurements represent typical conditions encountered by wireless-radio devices that are used inside a residence. Small movement of the receiving antenna resulted in significant changes in signal amplitude, indicating that the propagation path from most sources to the measurement site contained reflections from conducting objects. It was noted that signal levels increased somewhat when the garage door was opened for brief tests, thus the data presented in this report do not represent the outdoor use of wireless radio devices. In addition, the data presented shows a snapshot of conditions at only one location, one specific day, and during daytime hours. It is not feasible to extrapolate this data to other places or times. Nevertheless, the data shows trends in the use of the wireless bands, and it provides a base for comparison with data obtained from other locations, times, and conditions.

2. EXAMPLES OF DATA

2.1 Background

The first step was to review the Table of Frequency Allocations of the Federal Communications Commission.[25] This was done to obtain a rough understanding of the kinds of users in the bands of interest. The actual assignment of users to sub bands and channels can vary from one part of the country to another, but the allocation tables provide a good start at understanding the kinds of users involved.

Figure 1 shows the primary users of portions of this spectrum of interest during this effort. The diagram provides a simplistic view of users of this portion of the band investigated since other users can be assigned to portions of the band and multiple users can share portions of the band.

In Figure 1 the letter "B" identifies portions of the spectrum allocated on a primary basis to various business activities. The word "Cell" identifies portions of the spectrum allocated on a primary basis to "Cellular Telephones". The words "No License" identifies that portion of the spectrum allocated and assigned to license-exempt wireless-communications devices, Industrial, Scientific, and Medical devices, and other similar activities. Amateur radio is also allocated this band. The frequency limits for each type of use in MHz are listed below the horizontal line as well as the width of each sub band in MHz. Narrow bands separate each sub band. These sub bands are allocated to other types of licensed users who require only narrow portions of the radio spectrum.

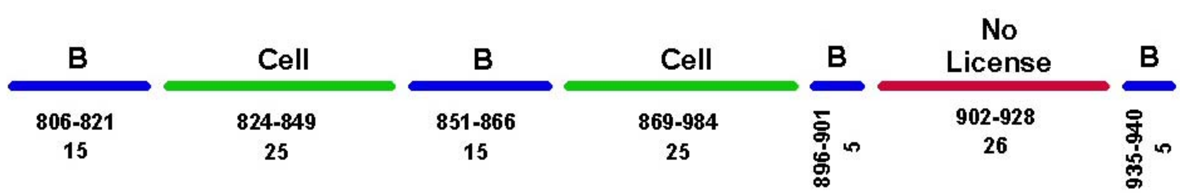

Figure 1

Primary Users of a Portion of the UHF Band

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25 On-Line Table of Frequency Allocations, Federal Communications Commission, Published by the Federal Register, Revised as of February 28, 2002

2.2 915-MHz License-Exempt Band

Since there presently is high interest in the occupancy and use of the license-exempt bands, the band from 902 to 928 MHz was first examined. Past informal inquiries into this band at the Davis location indicated its occupancy was often low. The low occupancy of the band was observed again on the morning of the first day the data in this document was collected. At about 0900 on this day, an unusual emission appeared that covered the entire license-exempt band. Figure 2 shows an example of the coarse-scale spectral and temporal properties of this emission. The primary feature is multiple discrete-frequency components spaced slightly less than 1-MHz apart. The emission has a total of thirty-eight or thirty-nine such components. The amplitude of each component is shown in the upper amplitude- vs.-frequency view of Figure 2. The time-history view shows the spectral components were generally stable over the 7.1 seconds of the data. A few time-varying signals from other sources appear near the upper-frequency edge of the components of the unusual wide-band emission, and they appear to be standard communications signals.

A careful examination of the time-history view reveals that weak slanting lines appear diagonally across the view. These slanting lines imply that some form of pulse modulation is associated with the spectral components. Data shown later provides additional information about this modulation.

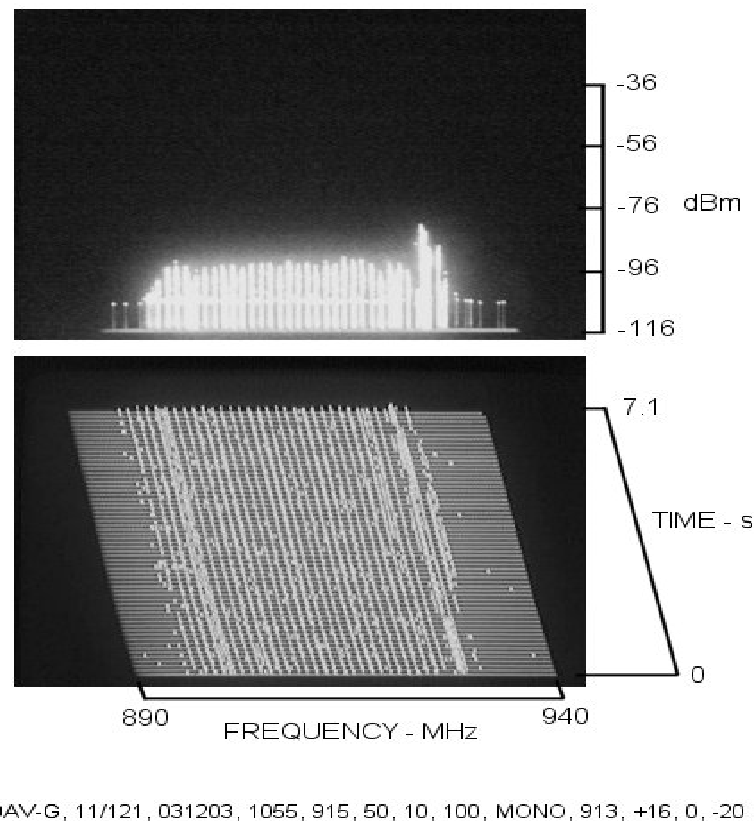


Figure 2

Unusual Emission in the 915-MHz Band

Figure 3 shows a view of a portion of the wide-band emission. The multiple spectral components of the emission were separated by using a smaller frequency span of 20 MHz in place of the 50-MHz span of the previous example. In addition, the time scale was increased to permit viewing the emission over a longer period of time. Additional features of the signal appear in this example. Three brief bursts of signal appear between the second and third spectral components on the left edge of the data. These bursts are identical in amplitude to the adjacent components, and they occur at 10-second intervals. The pulse modulation does not appear in this example.

A very low-level signal also appears between the two spectral components at the center of the view. This signal is much lower in amplitude than the discrete-frequency components, and it may not be associated with the emission.

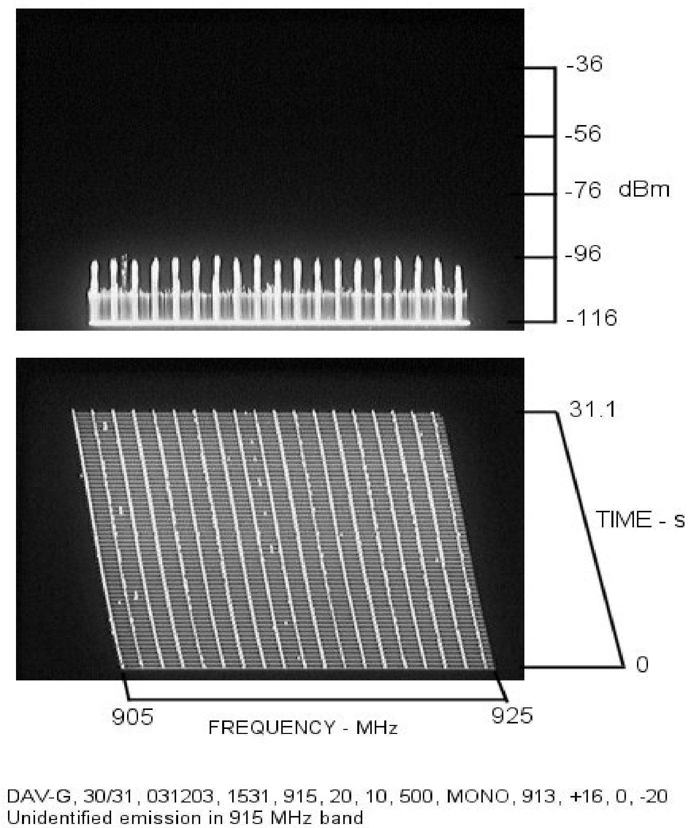


Figure 3

Unusual Emission in the 915 MHz Band, Example 2

Figure 4 shows an example of still another aspect of the wide-band emission found in the 915-MHz band. In this case additional structure appeared between some of the spectral components as shown in the time-history view. The slanting lines of the additional structure are caused by repetitive wave shape of these additional components. While there is insufficient data to accurately scale the frequency of the additional structure, a crude scaling indicates the emission is modulated at a rate of about 30 Hz. In addition to the additional structure, a single pulse similar to those found in Figure 3 is shown between the second and third spectral components on the left side of the time-history view. This duration of this pulse is about one second.

The reason for the unusual time-varying substructure of the wide-band emission shown in Figure 4 is not understood at this time. The details are documented to provide a basis for further investigation of the substructure at a future time.

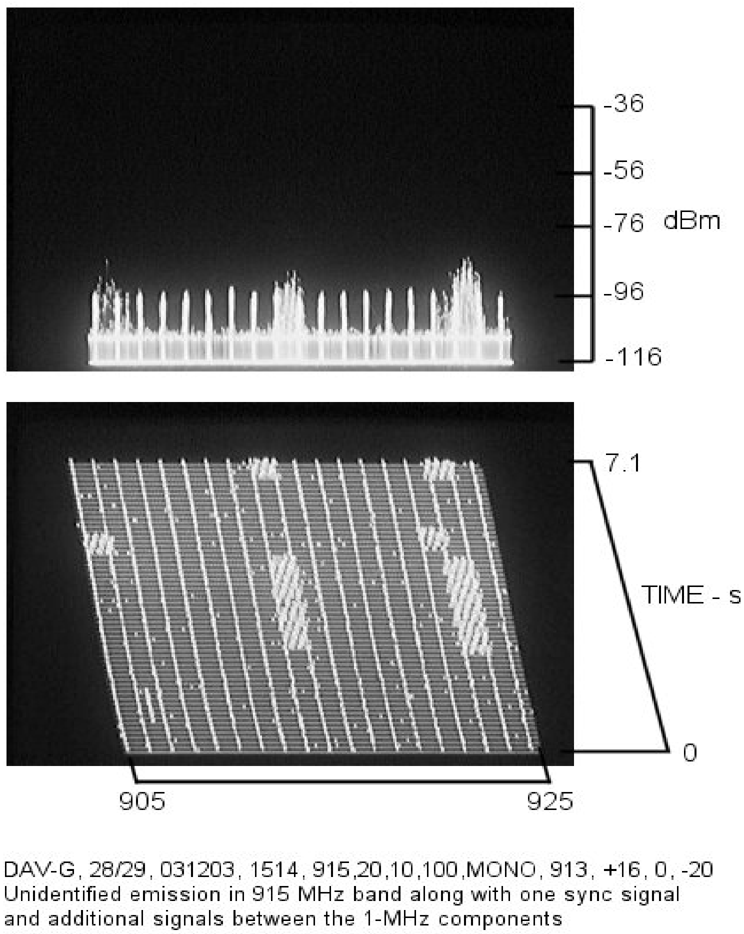


Figure 4

Unusual Emission in the 915 MHz Band, Example 3

One of the individual spectral components of the wide-band emission was examined in more detail by reducing the frequency span to 100 kHz. Figure 5 shows the component consists of a primary spectral component plus side bands spaced at intervals of 25 kHz from the primary signal. In addition a pulse of very short duration is shown on each side of the primary component. These short pulses amplitude modulated the primary spectral component. Since the bandwidth of the pulses is larger than the bandwidth of the analyzer, their amplitude is suppressed.

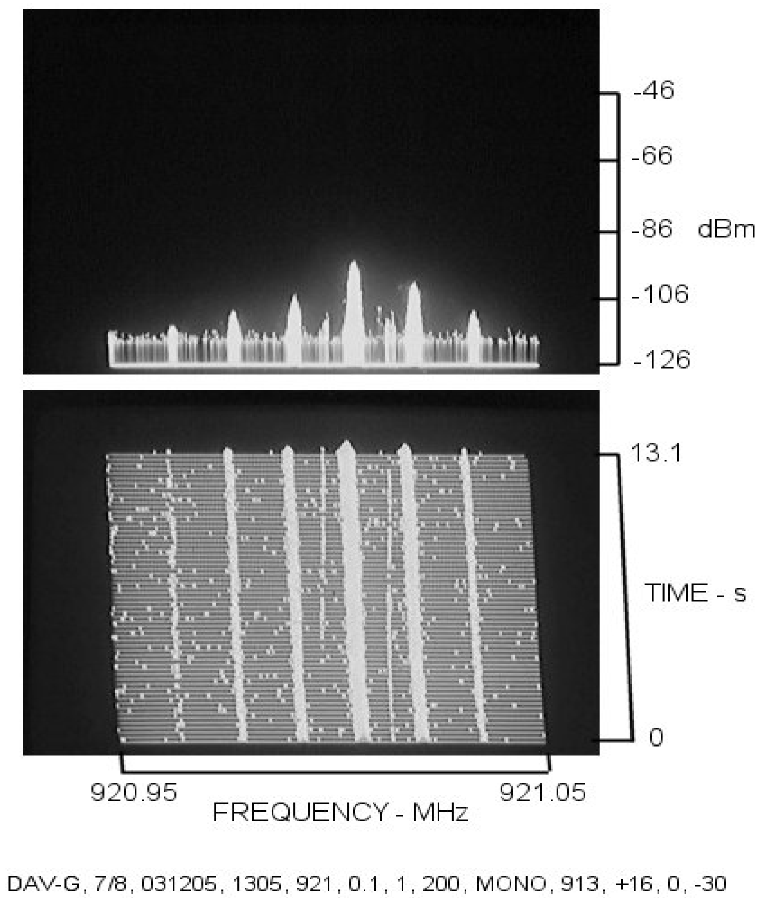


Figure 5

Unusual Emission in the 915 MHz Band, Example 4

The two slanting lines shown in the time-history view by successive pulses indicate they are not synchronized to the sweep time of the spectrum analyzer. Setting the spectrum analyzer in a line-sync mode caused the lines caused by the pulses to run parallel to the time axis, indicating the pulse rate was synchronized to the power-line frequency. The spacing between pulses is about 32 microseconds. This unusual spacing suggests the pulse source was triggered by a divide-by-two counter. The role of this narrow pulse is not understood at this time.

2.3 806 to 902 MHz Licensed Band

A useful examination of emissions in the total 806- to 940-MHz band shown in Figure 1 was not feasible due to the massive number of signals in portions of the band. The visual resolution of the time-history display was insufficient to permit a meaningful presentation of emissions in the total band, however portions of the band were individually examined.

The occupancy of the business band from 806 to 821 MHz was examined and only a few weak signals were found. This was expected since the low elevation of the measurement equipment, the internal location of the instrumentation, and its small antenna could not be expected to seem many signals from mobile and hand-held users occupying this band. In addition, the city of Davis would have only a few licensed business users in this band. In some respects this observation presents an unfair account of the use of this band since the users would normally be communicating through repeaters located on hills, towers, and other high locations. A more realistic set of data would require that the instrumentation to be located at an elevated site, and this was not done during this exploratory effort.

Similar results were obtained in the 824- to 849-MHz allocation used by hand-held cell phones. Again only a few signals were found, but the low elevation of the measurement system did not provide a realistic assessment of the use of this band.

Figure 6 show signals found in the 855- to 905-MHz frequency range. Only a few signals were noted near the low edge of the band. A massive number of signals are shown from 869 to 984 MHz, the popular cell phone base-station band. Additional signals occupied the narrow band from 896 to 901 MHz, a band allocated for business. No signals were found in the small band separating the cell-phone repeaters from the 896- to 901-MHz business band.

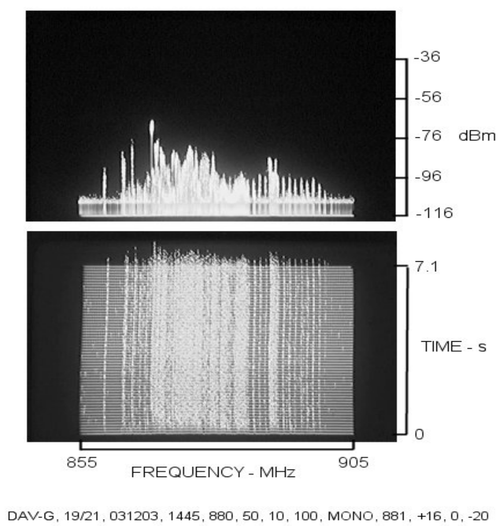


Figure 6

Signals and Interference in the 855 to 905 MHz Band

Additional spectral components are shown in the upper half of the frequency range of Figure 6. These spectral components are from the same wide-band emission found in the license-exempt band (see Figures 2 through 5). This unusual wide-band emission causes considerable interference to the reception of signals from licensed users at the measurement location.

A close examination of the cell phone base station band showed it contained a variety of signal types. Figure 7 shows a number of narrow-band signals in the 868- to 870-MHz frequency range. Most of these signals were present during all measurement sessions, but a few near the low-frequency end of the band turned on and off. The data indicate that most of the channels allocated to base-station operation in the Davis, California area are highly used.

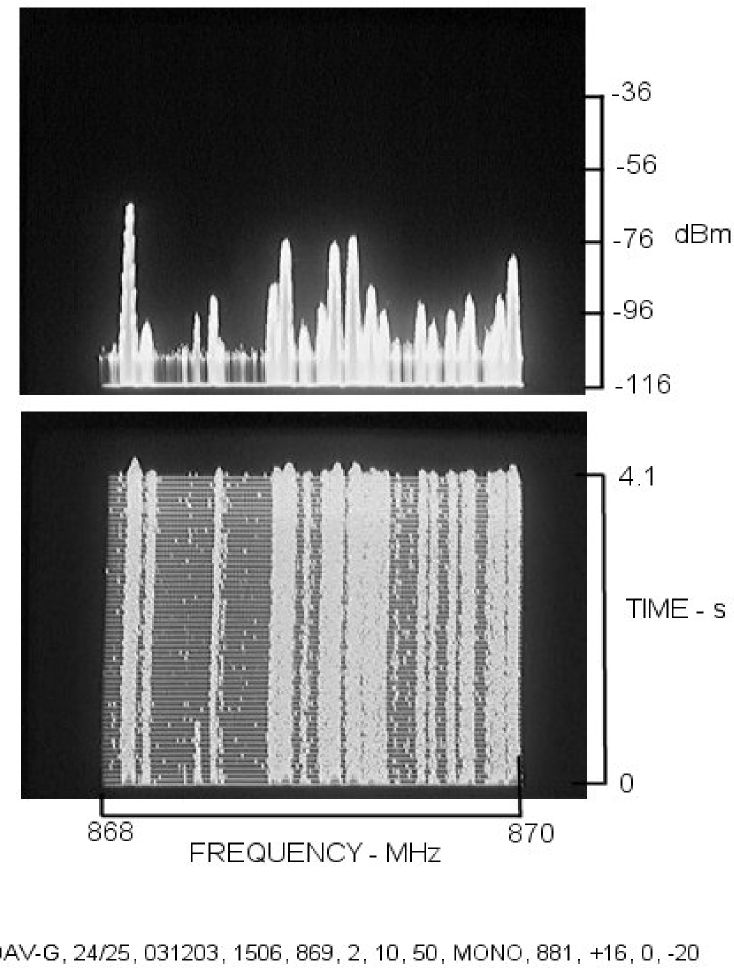
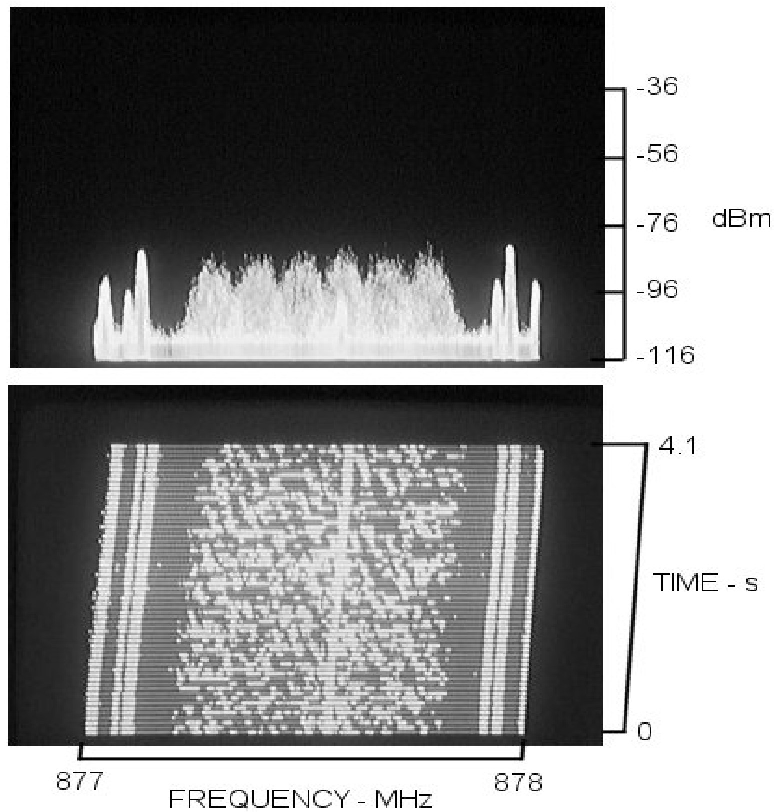


Figure 7

Signals in the 868 to 870 MHz Band

A 1.3-MHz wide portion of the cell phone band contains frequency-hopping emissions from a base station employing this form of modulation, and Figure 8 shows the two complementary views of these emissions. The data suggest that the band is sub divided into five segments as indicated by the peaks and nulls of the amplitude-vs.-frequency view. The slanting lines in the time-history view indicate the hopping period for all five segments is controlled from a single synchronizing source. Of interest is that a discrete-frequency signal appears slightly above the center of the hopping pattern. The amplitude of the discrete-frequency signal is about 10-dB lower than the peak of the hopping signals. It is the only potential source of interference found in the sub band used for cell phones.



DAV-G, 22/23, 030203, 1500, 878, 2, 10, 50, MONO, 881, +16, 0, -20

Figure 8

Signals in the 877 to 878 MHz Band

Spread spectrum signals appear in a 10-MHz wide band slightly higher in frequency than the frequency hopping signals. Figure 9 shows the spread spectrum signal. The variations in signal amplitude implied by the horizontal striations in the time-history view indicate this signal is affected by time-varying multipath effects. Of further interest is that the fine-scale structure of the amplitude-vs.-frequency view and the time-history view indicate the band was subdivided into four subbands, each about 5-MHz wide. The four emissions were tightly packed into the band with little if any space between the spread spectrum signals.

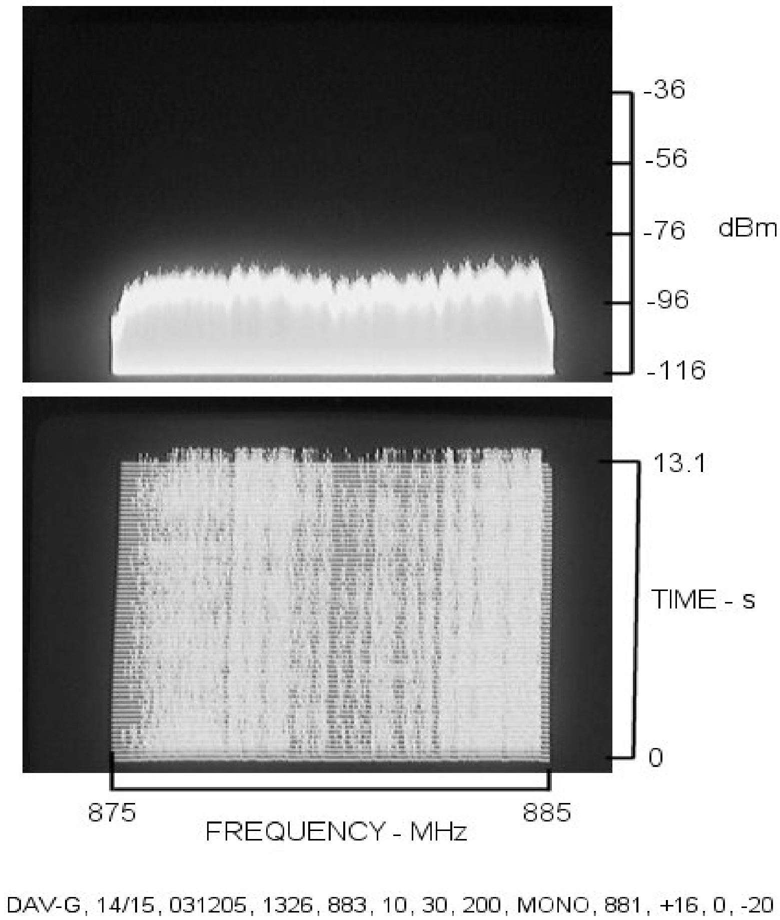


Figure 9

Signals in the 875 to 885 MHz Band

3. DISCUSSION

The unusual emissions described in Section 2.3 and illustrated in the figures for that section were not understood during the collection of data for that section. Diagnostic measurements after the completion of the measurement effort identified the source as unwanted radiation from a USB cable connecting the new digital camera used to obtain the data and the laptop computer used to record data files. Knowledge of the source allowed corrective actions to be taken to eliminate this particular source of interference to the reception of signals. The data is included in this document to show that precautions must be taken to ensure that sources of noise from digital devices associated with instrumentation can result in contaminated data.

The initial data on the occupancy and use of the licensed bands was of considerable interest, but the amount of data obtained is limited, and it does not cover all of the bands allocated to the licensed wireless-radio services. Additional measurements are planned. Nevertheless the limited data collected permitted an initial comparison to be made between the occupancy and use of the licensed bands to the unlicensed bands. To be fair one must also consider that users in the licensed bands are highly regulated and users in the unlicensed bands are not hindered by regulations.

Emissions from the licensed bands exhibited well designed signal formats with different signal formats placed in different sub-bands. An almost complete lack of interference was noted in the licensed band data. Emissions in the unlicensed bands comprised of a collection of overlapping emissions with different formats along with numerous cases of radio interference and noise to the reception of desired signals.

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