3 FIELD MEASUREMENTS DESCRIPTION

This section describes the measurement method and requirements, system configurations, and calibrations.

3.1 Measurement Requirements

The major objective in making these LMR measurements was to determine, for various detection thresholds, the proportion of time that a given channel (or group of channels) is carrying traffic. To meet these objectives, several requirements, as described in Table 5, were imposed with regard to sensitivity, antenna characteristics, dynamic range, frequency resolution, out-of-band rejection, noise suppression, speed of acquisition, and location.

Table 5. Measurement Requirements

Parameters	Requirement
Threshold	Minimum threshold for signal detection set as low as possible, which for this measurement system is 8 dB above median system noise. This translates to a field strength of approximately 8 dB µV/m. (The noise figure referenced to the output of the antenna terminals for the 162-174 MHz and 406-420 MHz systems is 13.9 dB and 11.9 respectively.)
Instantaneous Dynamic Range	84 dB between point of measurement system front-end compression and arithmetic mean system noise power.
Channel Resolution	12.5 kHz, 70 dB below the channel center frequency.
Out-of-band Rejection	Preselection filtering to reduce total passband power so that sensitivity and dynamic range requirements can be maintained.
Noise Suppression	Process data to achieve a probability of no greater than 0.01% that an instantaneous system noise level will exceed the median system noise by more than 8 dB.
Speed of Acquisition	Acquire and store data every 1 second.
Antenna Characteristics	Omnidirectional; vertically polarized; Gain = 1 dBi.
Location	Place measurements system in the center of the city with the highest elevation possible.

The measurement of LMR signal usage can be technically very demanding. The detection of very weak LMR signals transmitted by distant transmitters requires the use of a very good system noise figure. However, the possible presence of relatively strong signals from close-in transmitters means that strong signals can occasionally push the measurement system amplifiers into a non-linear region of operation and produce intermodulation (IM) products. These IM products appear like real signals to a measurement system. To minimize the undesired generation of unwanted signals from IM effects, a measurement system that has a large instantaneous dynamic range is required.

Strong signals can also mix with local oscillator (LO) noise sidebands (what is left after the pure sinusoidal signal is subtracted from a local oscillator). These LO noise sidebands create a region of higher system noise for many channels on either side of the strong signal. To minimize the effects of LO noise sidebands, it is necessary to obtain “cleaner” LO signals or to somehow avoid strong signals in the receiver. Sideband noise can also be due to jitter in the analog-to-digital converter (ADC), and sidebands created when applying a window function to the raw digitized data; therefore, a high quality ADC and a carefully chosen window function are required.

Because of the numerous unwanted effects of very strong LMR signals, great care is taken to keep strong signals out of the measurement receivers. Measurement sites are selected on the basis of having at least a minimum geographical separation from known sites with strong transmitters. The measurement system is often used with narrowband preselection filters, whose function is to limit the frequency range over which strong signals can enter the measurement system. Known strong signals (e.g., transmitted from a nearby transmitting tower) can be specifically rejected by tunable notch filters or other techniques. Unfortunately, some of these techniques to control unwanted strong signals also tend to increase the measurement system noise figure. Therefore, the actual performance of the measurement system is often determined by a difficult set of compromises and adjustments that depend partly on the specific characteristics of the local signal environment.

3.2 Site Selection

These LMR channel occupancy measurements were made using NTIA’s Radio Spectrum Measurement Science (RSMS) mobile laboratory at a site on the grounds of the partially-abandoned Saint Elizabeth’s Hospital located at coordinates N38° 51.427', W77° 0.013' (Figure 1). The measurements were conducted 24 hours per day over the course of 8 consecutive days (Tuesday, October 26 to Wednesday, November 3, 2004), which included the Presidential Election Day. The site was chosen for several reasons. It is centrally located in Washington, D.C., and is elevated above the surrounding area. Because it is partially abandoned, there is little LMR activity in close proximity. In addition, there are relatively few strong base stations nearby that could overdrive the measurement system.

Figure 2 shows an aerial view of the Washington, D.C., area with a marker designating the location of the measurement system. Figures 3 and 4 show coverage plots using the Longley-Rice irregular terrain model (maximum receiver sensitivity) for three different transmitter scenarios: 1) a 100-W transmitter with 3-dBi gain and a 30-meter antenna height (typical base station), 2) a 50-W transmitter with 0-dBi gain and a 1.5-meter antenna height (typical mobile unit), and 3) a 10-W transmitter with -3-dBi gain and a 1.0-meter antenna height (typical portable unit).[3] Figures 3 and 4 are for frequency bands 162–174 MHz and 406–420 MHz respectively.

Figure 1. RSMS mobile lab at the St. Elizabeth's Hospital site.

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[3] More realistically, portable units have a maximum output of 5–6 W, and therefore, the coverage plot for portable units may be slightly less than that shown in the diagrams.

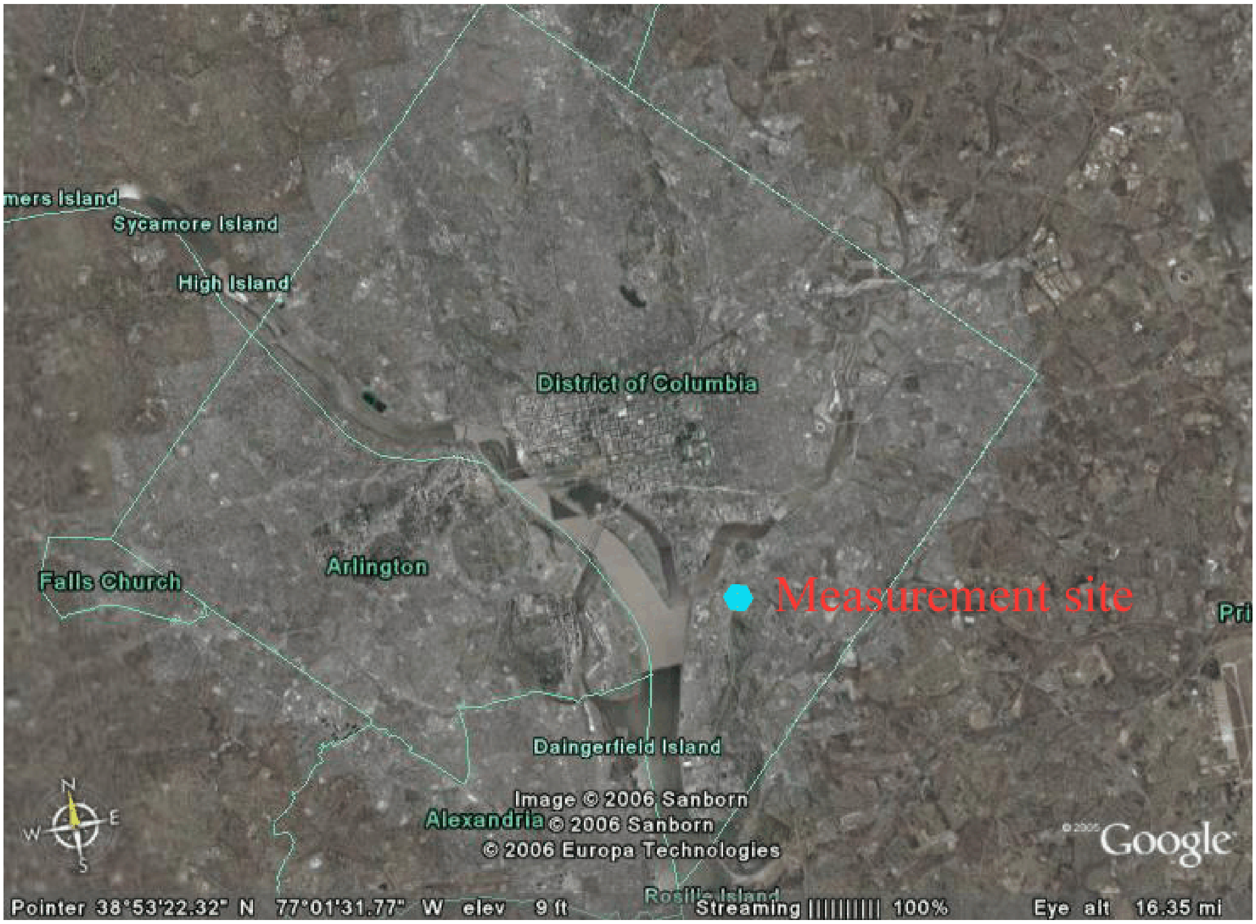

Figure 2. Aerial view of Washington, D.C., area showing location of measurement system.

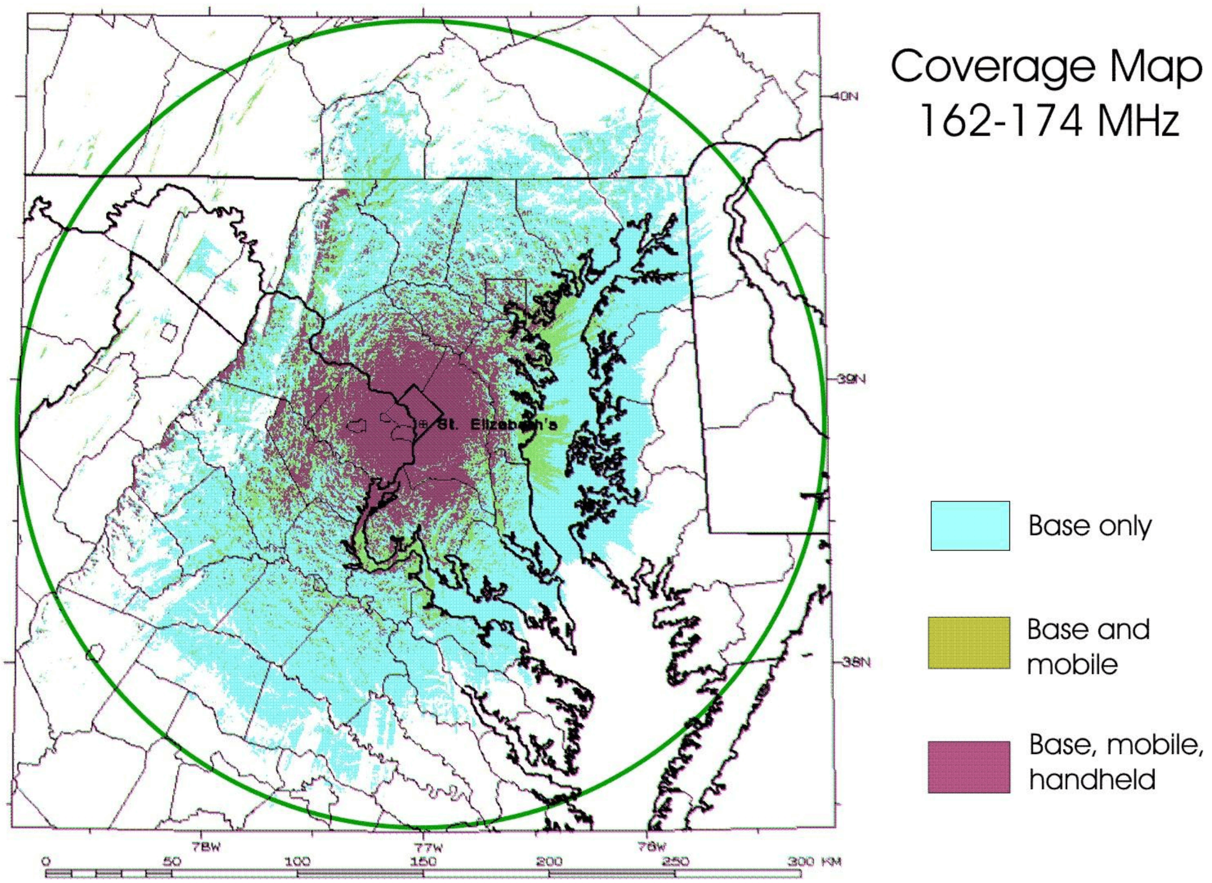

Figure 3. Coverage plots for the 162–174 MHz band using the minimum receiver threshold.

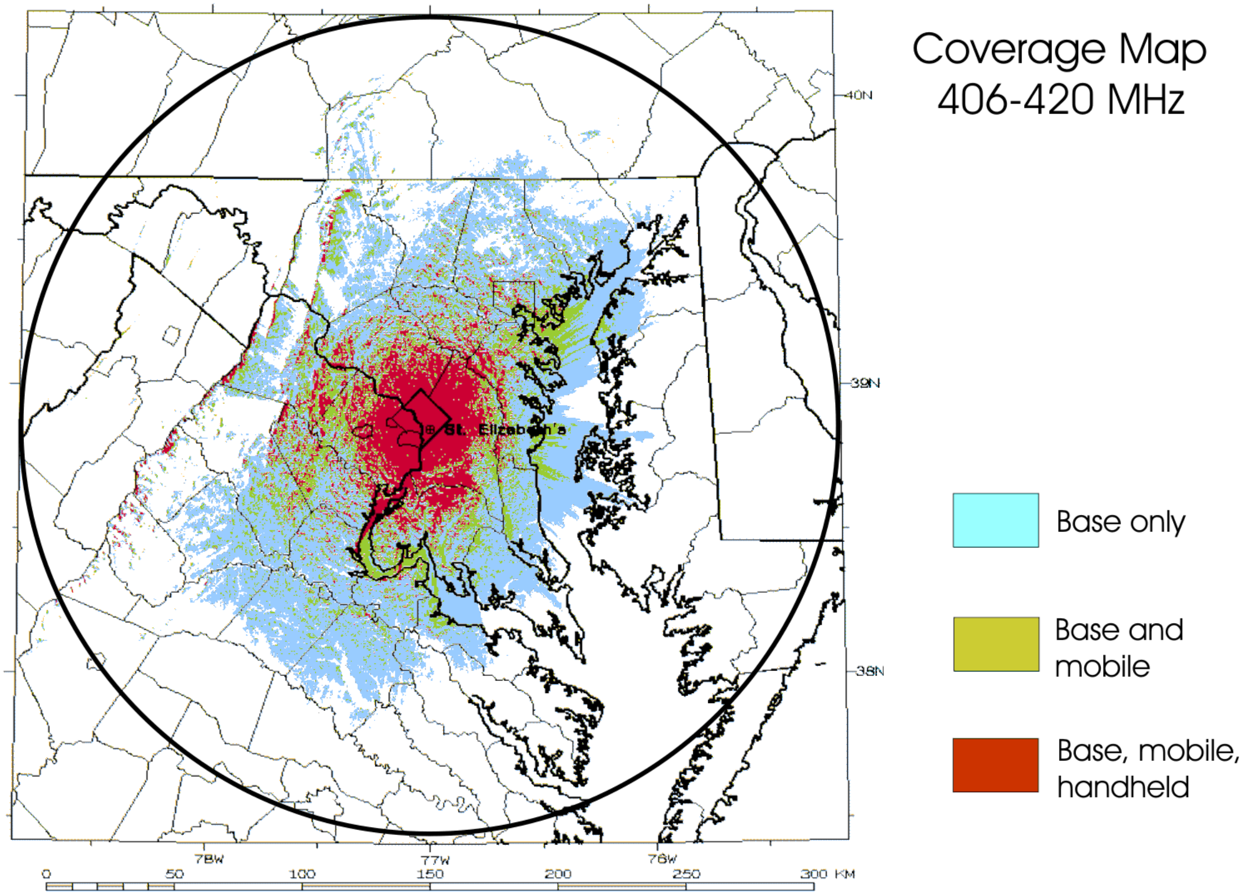

Figure 4. Coverage plots for the 406–420 MHz band using the minimum receiver threshold.

3.3 System Hardware Components

A generic block diagram of the measurement system is shown in Figure 5. Two separate fully automated systems were run simultaneously, one to collect data in the 162–174 MHz band and the other to collect data in the 406–420 MHz band. Two separate vertically polarized discone antennas, one optimized for each measurement frequency band, were positioned on top of 10-meter masts. The preselector unit consists of a variable attenuator to reduce system sensitivity in cases of strong local in-band signals, bandpass filters to reduce strong signals outside the measurement band so that sensitivity and dynamic range requirements can be maintained, and a low-noise amplifier to improve the system sensitivity by reducing the noise figure. The output of the preselector is passed to an Agilent E4440A spectrum analyzer that downconverts and digitally processes the signal in a specialized "Base" mode configuration.[4] A computer controls the spectrum analyzer and the preselector. The computer also processes the data and saves it to storage for further post processing and analysis. The preselector filters for the 162–174 MHz band consist of 3 separate bandpass filters in the following 1-dB bandwidths: 159–164 MHz, 164–169 MHz, and 169–174 MHz. The filters are inserted into the path through an automated switching routine controlled by the acquisition software. The 406–420 MHz system has a single bandpass filter with cutoff frequencies at the edges of the band.

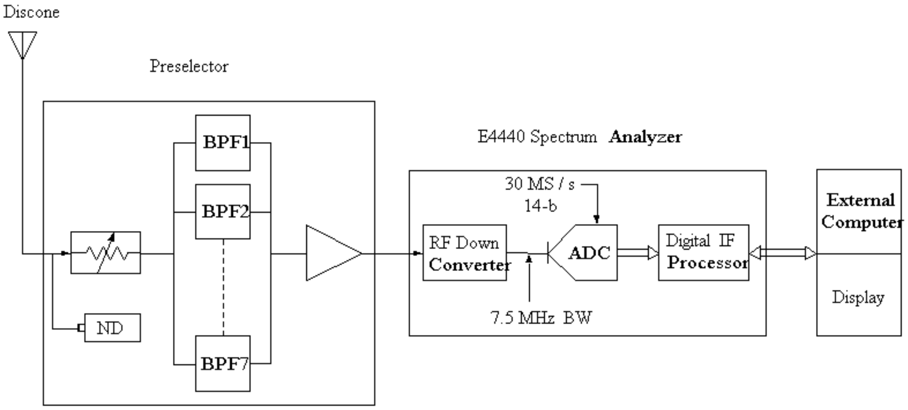

Figure 5. Block diagram of measurement system.

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[4] "Base" mode on an Agilent E4440A spectrum analyzer provides FFT spectrum analysis, as opposed to swept frequency analysis typically utilized for most spectrum analyzers.

3.4 Measurement Procedures

The 162–174 MHz band and the 406–420 MHz band were each measured in contiguous several-MHz-wide blocks, beginning at the lowest frequency block, continuing in several-MHz steps until the highest frequency block in the band was reached, and then restarting at the lowest frequency block in the band. Within each block, signals were measured at 12.5-kHz channel spacings so that the data could be analyzed for both the old 25-kHz channels and the new 12.5-kHz channels by processing with the frequencies assigned to the respective channelization schemes (described in Section 2.1). The 162–174 MHz band was measured in 3 separate frequency blocks: 162–164 MHz (158 channels), 164–169 MHz (400 channels), and 169–174 MHz (400 channels). Though there is only one bandpass filter that covers the entire frequency range of the 406–420 MHz band, the measurements were divided into 3 separate frequency blocks, with each having a span no greater than 5 MHz; these consist of the blocks 406–411 MHz (400 channels), 411–416 MHz (400 channels), and 416–420 MHz (319 channels). As with the 162–174 MHz band, signals in the 406–420 MHz band were measured at 12.5-kHz channel spacings.

By setting the proper acquisition time period and using a Flattop window [7], a 1-dB resolution bandwidth of 5.5 kHz is achieved. This results in a 70-dB suppression for signals outside a 15-kHz range, as demonstrated in Figure 6 which shows a fast Fourier transform (FFT) of a continuous wave (CW) signal with the same settings used in the LMR measurements. Figure 7 shows multiple FFT traces of a carrier signal FM-modulated with 3-kHz band-limited Gaussian noise and a ±3-kHz maximum frequency deviation. Figure 8 shows the same thing but with a ±6-kHz maximum frequency deviation.[5] The digital acquisition time is short enough that, for any one acquisition, the signal is relatively stationary at a very narrow range of frequencies. For the different traces, the carrier is shifted in frequency by the modulating signal but with a shift no greater than the maximum frequency deviation. However, because there is still a small shift in frequency during the acquisition, the spectrum of any single trace is "spread," as compared to that seen with a CW signal. Using this measurement scheme, it can be seen, therefore, that for two adjacent channels (*C1* and *C2*) and an FM modulated signal *S* with a center frequency at *C1*, essentially no power from *S* is detected at *C2* by as much as 70 dB below the peak power of *S* when the channel separation is greater than 12.5 kHz for a ±3-kHz maximum frequency deviation and 15 kHz for a ±6-kHz maximum frequency deviation. Therefore, irrespective of the channel spacing, this resolution bandwidth can resolve adjacent FM modulated, LMR-type channels as specified in the measurement requirements (Table 5).

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[5] Frequency deviation for all FM or PM station classes are not to exceed 5 kHz for analog wideband emissions, 2.5 kHz for analog narrowband emissions, and 3.11 kHz for digital emissions.

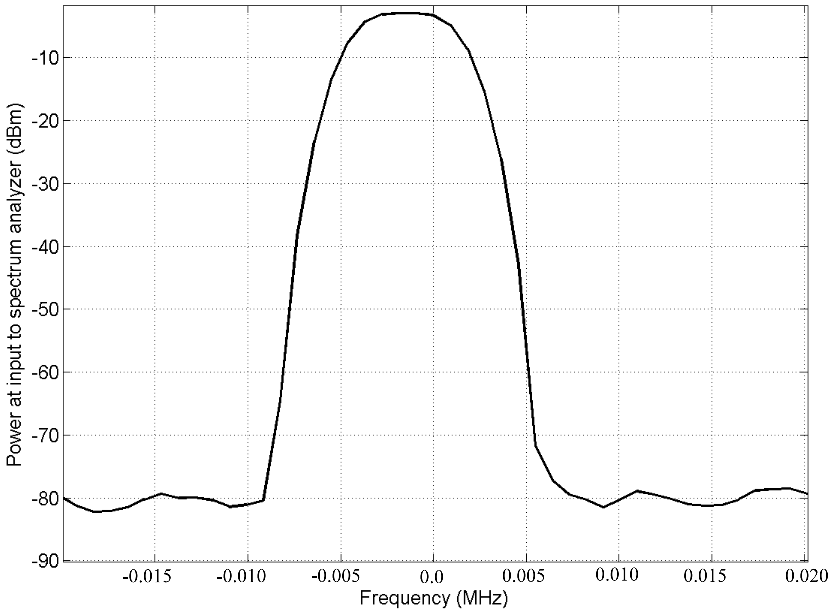

Figure 6. FFT of CW signal using LMR measurement parameters.

Since a typical conversation on these Federal channels will last several seconds or more, there is little advantage in measuring each channel more often than once every second (since most of the additional measurements will give statistically-redundant information). In most (but not all) of these LMR systems, the transmitter will be turned on only when the channel is carrying a message. For these signals, the presence of a message can be detected by tuning to the channel and noting whether a transmitted signal is present. Usually, this can be done most easily by simply measuring the amount of RF energy received within the channel bandwidth, and inferring the presence of a signal if the measured received power is larger than the power that could reasonably be present from measurement system noise only. Based on the measurement system noise figure and the windowing bandwidth, a specific “detection threshold” is calculated, such that any measured channel power higher than the detection threshold is assumed to indicate the presence of a transmitted signal.

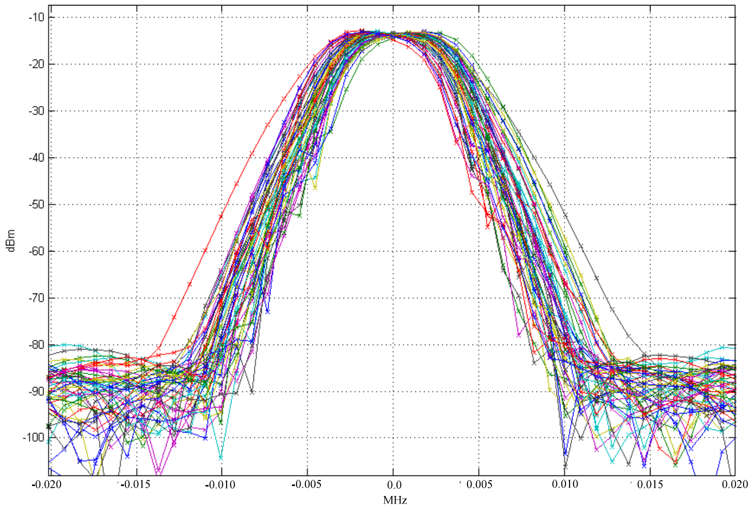

Figure 7. Multiple FFT traces of a carrier signal FM modulated with 3-kHz band-limited Gaussian noise and a 3-kHz maximum frequency deviation.

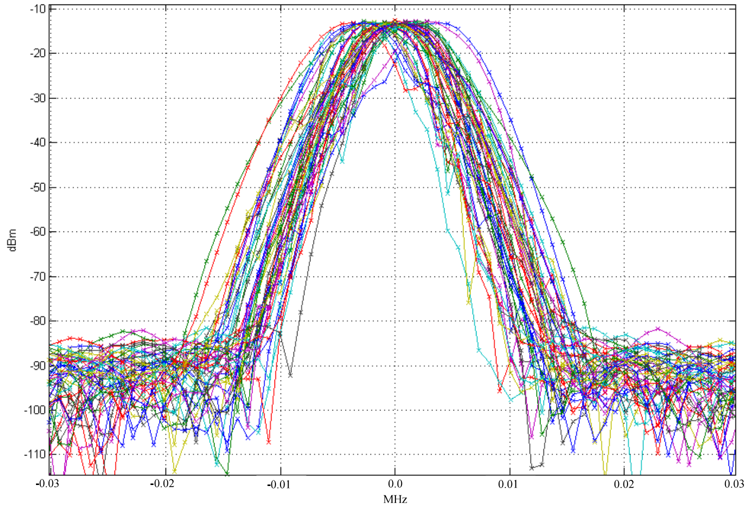

Figure 8. Multiple FFT traces of a carrier signal FM modulated with 3-kHz band-limited Gaussian noise and a 6-kHz maximum frequency deviation.

The actual percentage of time that a given LMR channel is in use will be expected to change, depending upon the specific function served by that channel, the time-of-day and day-of-week, and the random occurrence of specific individual emergencies and other important events. Therefore, a minimum set of measurements for LMR channel usage should include data acquisition on each channel over a period of at least one week (including weekends) on a 24-hr per day basis. Although it is not required that each channel be measured continuously, it is desirable to include sufficient measurements to characterize every channel on at least an hourly basis.

As diagramed in Figure 9, all the channels in a given several-MHz frequency block were measured for 4 minutes, giving 240 measurements on each channel. At the end of 4 minutes, measurement frequencies were shifted to the next-higher frequency block. Each frequency block was re-measured every 36 minutes for the 162–174 MHz band and every 12 minutes for the 406–420 MHz band.[6] Thus, although a given frequency block was not measured continuously, it was sampled for a 4-minute period interleaved with either 32 or 8 minutes with no measurement (while other frequency blocks were being measured). This was continued for 24 hours per day throughout the 8-day period. Thus each frequency in the 162–174 MHz band was measured 240 x 40 = 9600 times per day, spread out over 24 hours, giving 76,800 total measurements over an 8-day period. Frequencies in the 406–420 MHz band were measured about three times more often. The resulting measurement data were saved for further analysis in the NTIA/ITS laboratory in Boulder, Colorado.

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[6] There is an hourly synchronization (± 4 minutes) of data acquisition for the 406-420 MHz band, This could skew the mean usage (either up or down) if a significant number of transmissions are keyed up at specified times each hour – though we have no knowledge of this type of timed usage.

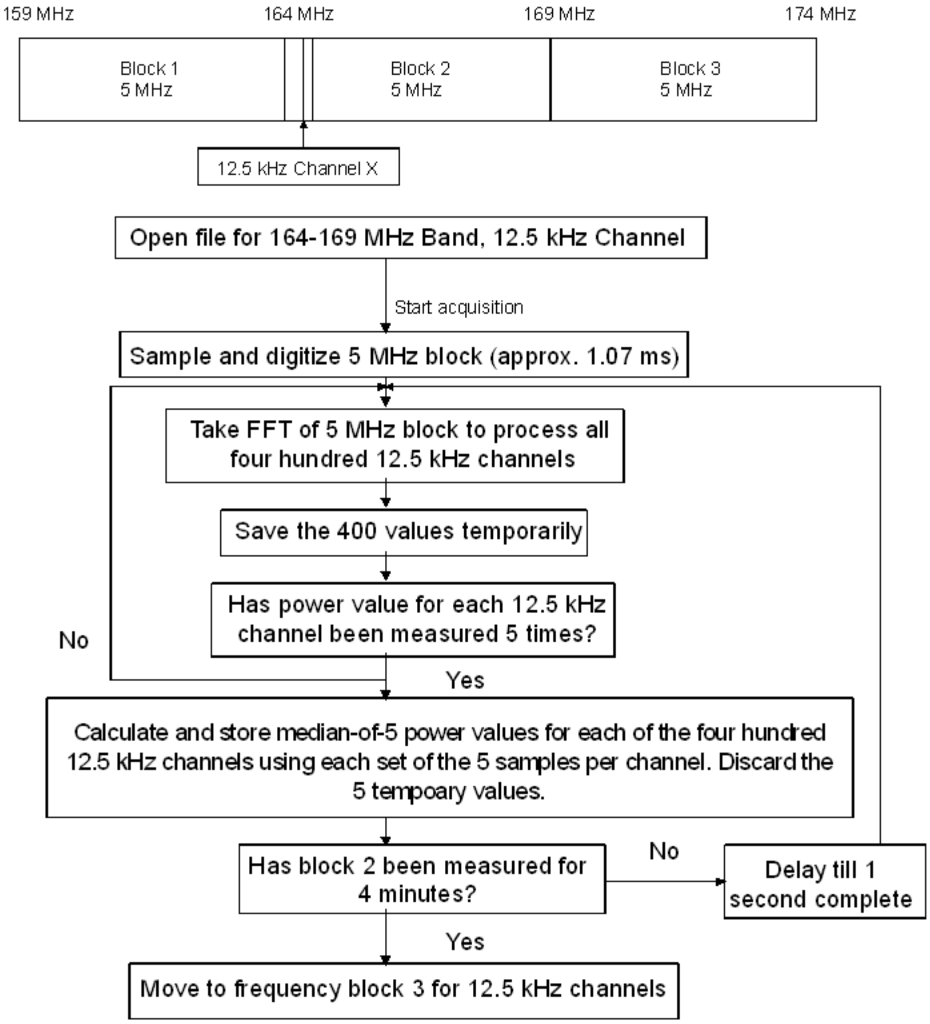

Figure 9. Flow diagram of channel power measurements.

3.5 Real-time Signal Processing

The measurements were performed using some of the specialized hardware and software features of the Agilent E4440A spectrum analyzer. The spectrum analyzer provides high-dynamic-range down-conversion to an IF signal with a bandwidth up to 8 MHz wide. The 8-MHz bandwidth IF signal is digitized with 14 bits of resolution at a 30 MS/s sample rate. Using the “Base” mode software package, the digital data were processed on a real-time basis, using a library of software signal processing routines.

The hardware-software package typically produced a measurement of the estimated received power in each of 400 channels in a 5-MHz band during each 1-second period in a 4-minute measurement block. The process used to produce these 400 measurements each second is described in the following paragraphs.

Once the spectrum analyzer is tuned to the center frequency of the 5-MHz frequency band, the 14-bit digitizer acquires ADC readings for 1.07 ms, producing a digital record containing about 32 kilo-samples (where sample size is dependent upon resolution bandwidth specifications). These 32 kilo-samples are processed inside the spectrum analyzer with firmware that produces a reading for the RF power at the center frequency of each of the 400 channels in the frequency block. The system has an 84-dB dynamic range, but if a strong signal overloads the digitizer (approximately -22 dBm at the antenna terminals), an alarm flag causes the 32 kilo-samples to be discarded and the digitizing process will repeat. The digital data is windowed and then processed with an FFT to give a resolution bandwidth of 5.5 kHz, after which the data is decimated[7] to give a power reading at the center frequency of each of the 400 LMR channels (spaced at 12.5 kHz).

These 400 *Channel Power Readings* are displayed on the front panel of the spectrum analyzer and also transferred via an ethernet local area network to an external controller/computer. The process of digitizing, computing, and transferring data for the frequency block requires about 150 ms, with a majority of the time used by the data transfer process. The digitizing, computing, and transfer process is repeated five times, ending when 5 sets of 400 data points are obtained, representing five *Channel Power Readings* of each channel in the frequency block. At this point, the computer determines the median value from the 5 measurements for each channel, and the set of 400 median values for each channel – also referred to as the *Channel Power Values* – becomes the data output set for that respective 1-second measurement period. The system then waits until the beginning of the next 1-second measurement period, when the median-of-5 measurement cycle begins again to produce another set of *Channel Power Values*.

The median-of-5 processing was selected to minimize the effect of amplitude variations caused by signal modulation, measurement system noise, and external impulsive noise. The importance of this processing for minimizing errors in determining channel occupancy is discussed in more detail in section 4.

The *Channel Power Values* for each of the channels in the frequency block are also incorporated into a continuously updated (every second) data display on the external computer as shown in Figure 10. This external display shows the most recent 1-second *Channel Power Value* (referenced to the spectrum analyzer input) for each measured channel (blue "+" symbols), as well as a peak value for each channel updated over the current 4-minute frequency block (black "+" symbols). The operator can position a cursor over a particular frequency and obtain readouts of these quantities, as well as the exact frequency of

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[7] Decimation, in this case, is the process of eliminating unnecessary data points that occur between center frequencies of the channels.

the selected channel (e.g., this allows a receiver/demodulator to be tuned to a channel-of-interest). The display on the external computer is continually updated with data from the most recent 1-second *Channel Power Value*, while the spectrum analyzer shows a display of the current 5-per-second instantaneous *Channel Power Reading* from the measurement process.

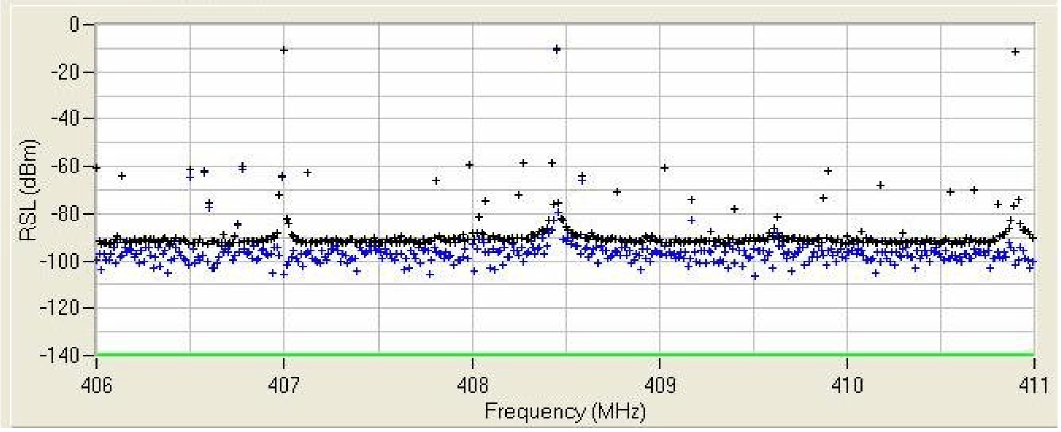

Figure 10. "Data display" as viewed on the computer (power referenced to spectrum analyzer input).

3.6 Calibrations

System calibrations using the noise source Y-factor method were performed immediately prior to the measurements and again at the end of the week.[8] Certain signals of known power and 100 percent usage were also checked on a daily basis to monitor the integrity of the system. Gain factors, as determined by the calibration, were later subtracted from the measured power levels to reference the power to the output of the antenna terminals. Noise-figure values were used to determine detection thresholds for signal-occupancy processing.

All of the antennas were calibrated at a certified laboratory within 6 months of the measurements. Antenna correction factors were then used to determine the field strength based on the received power at the input.

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[8] The Y-factor calibration technique is used here to determine the noise factor and gain of the system [8].