NTIA Report 01-388

Implementation and Testing of a Software Defined Radio Cellular Base Station Receiver

Jeffery A. Wepman
J. Randy Hoffman

U.S. DEPARTMENT OF COMMERCE
Donald L. Evans, Secretary

July 2001

Product Disclaimer

Certain commercial equipment, instruments, or materials are identified in this paper to specify adequately the technical aspects of the reported results. In no case does such identification imply recommendation or endorsement by the National Telecommunications and Information Administration, nor does it imply that the material or equipment identified is necessarily the best available for the purpose.

CONTENTS

Page

FIGURES

Page

IMPLEMENTATION AND TESTING OF A SOFTWARE DEFINED RADIO CELLULAR BASE STATION RECEIVER

Jeffery A. Wepman and J. Randy Hoffman[1]

Software defined radios (SDR's) represent a departure from traditional radio design. There is some mystique about what SDR's are, how they are designed, how they operate, and how performance is determined or verified. This report provides insight into some of these SDR aspects by presenting a detailed example SDR receiver design along with a set of performance measurements at various stages of the receiver. For this example, an Advanced Mobile Phone System (AMPS) cellular B-band base station receiver was configured using SDR technology. The architecture consists of a cellular B-band analog downconverter and digitizer, a digital downconverter that operates in a personal computer, a first-in, first-out (FIFO) buffer memory board, and an analog audio processor. The modular architecture permits signals to be observed at several stages of processing: the digitized IF output, the digitally downconverted and filtered baseband output, the digital FM demodulator output, and the analog audio output. A wide variety of measurements under various RF input signal conditions were made at each of the processing stages. Results of particular interest include the effects of aliasing and the ability to detect a low-level desired signal in the presence of a high-level, in-band interfering signal. The SDR AMPS receiver, while possessing the inherent flexibility advantages of SDR's, easily met the TIA/EIA-712 cellular base station standards for adjacent and alternate channel desensitization, intermodulation spurious response attenuation, and protection against spurious response attenuation.

Key words: aliasing; analog-to-digital converter; baseband; demodulation; digital downconverter; downconverter; intermediate frequency; intermodulation; radio frequency; software defined radio; spurious response

1. INTRODUCTION

Within the past decade, the field of software defined radios (SDR's) has experienced rapid growth. SDR research and development efforts continue to proliferate and have resulted in several products that are now available on the open market. While results are certainly being published more frequently and in greater quantity, design details of specific systems are often not published. Even though many support the development of an open-architecture SDR, the SDR field is competitive and many organizations consider the details of their designs to be proprietary.

[1]The authors are with the Institute for Telecommunication Sciences, National Telecommunications and Information Administration, U.S. Department of Commerce, Boulder, CO 80305.

Additionally, since SDR's represent a departure from traditional radio design [1], there is some mystique about what SDR's are, how they are designed, how they operate, and how performance is determined or verified. In this report we seek to provide insight into some of these aspects of SDR's by presenting a detailed example of an SDR receiver design along with a set of performance measurements at various stages of the receiver.

A universally accepted definition of an SDR has not yet emerged since there are differing opinions as to just what an SDR is. However, a good general definition is found in [2]:

> An SDR consists of a receiver and/or transmitter with the following properties: (a) the received signal is digitized and then processed using software-programmable digital signal processing techniques (digitization may occur at the RF, IF, or baseband); (b) the modulated signal to be transmitted is generated as a digital signal using software-programmable digital signal processing techniques. The digital signal is then converted to an analog signal for transmission (the conversion to analog may occur at baseband, IF, or RF).

A key factor in SDR's is that software programmability allows easy changes of the radio's fundamental characteristics such as modulation types, operating frequencies, bandwidths, multiple access schemes, source and channel coding/decoding methods, frequency spreading/despreading techniques, and encryption/decryption algorithms. Traditional, hardware-based radios require hardware changes to modify these fundamental characteristics.

There are many different ways to design an SDR. The primary differences in SDR designs are the digital signal processing platform used (which affects the software that needs to be developed) and whether digitization in the receiver and conversion to analog in the transmitter occurs at the RF, IF, or at baseband. The digital signal processing platform can be based on application specific integrated circuits (ASIC's), digital signal processors (DSP's), field programmable gate arrays (FPGA's), general purpose processors, or any combination of these [3].

The typical SDR receiver being implemented today consists of an analog downconversion to an IF and then digitization at the IF. This is true because ADC's that are fast enough for digitization at the RF usually do not have the spurious free dynamic range (SFDR) that is required [4]. (Note that some receivers such as satellite receivers may have low enough SFDR requirements to make digitization at the RF possible with current technology.) While both SDR's employing digitization over a narrow bandwidth and SDR's employing digitization over a wide bandwidth are currently being developed, we chose to design a wide bandwidth system because this better illustrates the full capability of SDR receiver technology. With modifications in the SDR software, a wide bandwidth SDR can be used to implement a greater variety of radios than a narrow bandwidth SDR.

Ideally, we wanted to configure a wideband SDR receiver that had a very wide RF tuning range (for example 20 - 2000 MHz). This would provide the basis for the SDR receiver to be able to implement many different types of systems via software changes. However, to the best of our knowledge, at the commencement of this project in June 1997, a downconverter that covered this frequency range and provided a digitized IF output was not readily available as an economical, commercial off-the-shelf product.

As a practical alternative, we chose to configure an 800-MHz cellular base station receiver as our example wideband SDR receiver. The cellular base station is one example of an actual current application of an SDR using digitization at the IF.

Our SDR implementation of the cellular base station receiver is configured using a commercially available, wideband cellular downconverter with a digitized IF output and a programmable, digital downconverter board that operates in a personal computer to carry out the digital signal processing. This type of SDR represents an example of a design where the digital signal processing is performed by an ASIC combined with a digital signal processor.

For this report, the cellular base station receiver is configured as an AMPS (Advanced Mobile Phone System)[2] cellular B-band base station receiver (referred to as the AMPS receiver in the remainder of this report). Section 2 describes the receiver architecture in detail. A description of how the signals are accessed, to permit making measurements at various stages within the receiver architecture, is given in Section 3. Section 4 then describes the setup, procedure, and results of the measurements made at the various stages of the receiver. A summary of the work is provided in Section 5 along with some conclusions.

2. RECEIVER SYSTEM ARCHITECTURE

The architecture of our implementation of the AMPS receiver is shown in Figure 1. The system consists of four basic blocks: the Watkins-Johnson (WJ) analog cellular B-band downconverter, the Sigtek ST-114 digital downconverter board that operates in a personal computer,[3] the analog audio processor, and the Analog Devices first-in first-out (FIFO) buffer memory board.[4] (In the remainder of this report, these blocks are referred to as the cellular downconverter, digital downconverter, analog audio processor, and FIFO buffer board, respectively.[5])

---

[2] AMPS is a cellular telephone standard that uses a frequency division multiple access (FDMA) scheme with analog frequency modulation (FM) for the traffic channels. The cellular B-band used for AMPS includes 416 channels, each with a 30-kHz bandwidth, centered at frequencies from 835.02 to 844.98 MHz and from 846.51 to 848.97 MHz.

[3] The Sigtek ST-114 digital downconverter board is an evaluation board for the Harris HSP 50214 programmable downconverter integrated circuit (IC).

[4] Certain commercial equipment, instruments, or materials are identified in this paper to specify adequately the technical aspects of the reported results. In no case does such identification imply recommendation or endorsement by the National Telecommunications and Information Administration, nor does it imply that the material or equipment identified is necessarily the best available for the purpose.

[5] The output of the cellular downconverter provides differential ECL signals, and the input to both the digital downconverter and the FIFO buffer board requires TTL signals. Therefore, an ECL to TTL converter board is needed when connecting the cellular downconverter to the digital downconverter or the FIFO buffer board.

Figure 1 shows the typical configuration of the system when it is configured as an entire receiver, i.e., to produce an analog audio output from a frequency modulated RF input signal.[6] In this case, the cellular downconverter, digital downconverter, and the analog audio processor are connected together but the FIFO buffer board is not used. The FIFO buffer board is used solely for testing the digitized IF output and will be discussed in more detail in Section 3.

2.1 Cellular Downconverter

In this entire receiver configuration, RF input signals in the 835- to 845-MHz and 846.5- to 849-MHz ranges are downconverted to IF signals in the 0.68- to 10.68-MHz and 12.18- to 14.68-MHz ranges, respectively, by the cellular downconverter. The cellular downconverter then digitizes this IF with a 12-bit analog-to-digital converter (ADC) at a 30.72 Msample/s rate producing differential ECL data signals. The differential ECL data (and differential ECL clock) signals are converted to TTL signals by the ECL to TTL converter board that is attached to the digital downconverter. The TTL data representing the digitized IF from the cellular downconverter is the input to the digital downconverter.

2.2 Digital Downconverter

The configuration of the digital downconverter is controlled by software that operates on a Windows 95 platform. The software allows the user to easily configure the digital downconverter parameters including those for downconversion, channel filtering, demodulation, and other receiver functions [5]. Figure 2 shows a simplified block diagram of the processing performed by the digital downconverter in the specific configuration for the AMPS receiver [6]. The digitized IF input is multiplied by a digital cosine and sine wave (generated by a numerically controlled oscillator) at the IF that represents the center frequency of the desired cellular channel. This digitally downconverts the IF signal to digital baseband in-phase (I) and quadrature phase (Q) signals. Processing of the digital I and Q signals is then carried out along two identical paths, one for the I signal and one for the Q signal [6].

2.2.1 Channel Filtering

After downconversion to baseband, channel filtering along each I and Q path must b employed to pass frequencies within the desired 30-kHz cellular channel and eliminate frequencies outside of this desired channel. The channel filtering that is employed in a digital downconverter is somewhat different than that in an analog system. Channel filtering in the digital downconverter is accomplished in three different stages using a cascaded integrator comb (CIC) filter, a set of up

---

[6] Note that our AMPS receiver implementation is not an entire operating base station. The AMPS cellular base station functionality that is implemented provides downconversion to baseband of any of the 416 B-band channels and demodulation of analog voice/audio transmissions. None of the signaling and control capabilities have been implemented; i.e., detection and processing of the Supervisory Audio Tones (SAT's), the 10-kHz Signaling Tones (ST's), and the 10-kbps Manchester-encoded data used for signaling and control have not been implemented.

to 5 halfband filters, and a baseband finite impulse response (FIR) filter. Each of these stages of filtering plays an important role.

CIC Filter

The CIC filter is a digital filter that provides out-of-band (low pass) filtering and decimation. It has a wide passband and a wide stopband. This filter decimates the input sampling rate of 30.72 Msamples/s by a factor of 16 to provide a sample rate at the output of the CIC filter of 1.92 Msamples/s. The frequency domain magnitude response of the CIC filter (normalized to a DC value of 1), for frequencies up to the input sampling rate, is given by

$$\frac{|H(f)|}{|H(0)|} = \left| \frac{\sin\left(\frac{\pi f}{f_0}\right)}{R \sin\left(\frac{\pi f}{R f_0}\right)} \right|^5 \quad (1)$$

where f_0 is the output sampling rate [7, 8]. The output sampling rate f_0 is the input sampling rate f_s divided by the decimation factor R. The first null of $\frac{|H(f)|}{|H(0)|}$ occurs at f_0. Subsequent nulls of $\frac{|H(f)|}{|H(0)|}$ occur at integer multiples of f_0. A plot of the magnitude response of the CIC filter for frequencies of up to one-half of the input sampling rate is shown in Figure 3.

Halfband Filters

The next stage of filtering available on the digital downconverter consists of the halfband filters. The digital downconverter software allows the selection of up to 5 halfband filters placed in series along each of the I and Q processing paths. The halfband filters include: 7-tap, 11-tap, 15-tap, 19-tap, and 23-tap filters. Each halfband filter provides a decimation of 2 and has a 6-dB bandwidth of approximately one quarter the input sampling rate, where the input sampling rate is defined at the input of each halfband filter. The transition between pass and stop bands is steepest for the 23-tap filter and decreases for each subsequent lower-tap halfband filter. In this implementation, 4 of the 5 halfband filters are used along each of the I and Q processing paths to provide a decimation of 16. Therefore, the sampling rate at the output of the halfband filters is 120 ksamples/s.

Baseband FIR Filter

The halfband filters are followed by a programmable, baseband FIR filter that provides a steep transition from passband to stopband and the narrow bandwidth that is required in the channel filter. Up to 255 taps are available. The baseband FIR filter that is implemented for the AMPS receiver is a 205-tap low-pass filter with no decimation. Therefore, the output sample rate of the baseband FIR filter remains at 120 ksamples/s. The magnitude response of this filter is given in

Figure 4. The baseband FIR filter defines the response of the channel filter from DC to 60 kHz. Since the FIR filter is a digital filter, its passband is actually repeated at integer multiples of the sampling frequency (120 ksamples/s). Therefore, the halfband filters and CIC filter are required to provide the stopband attenuation for the channel filter for frequencies above 60 kHz. The baseband FIR filter has a bandwidth of 15 kHz (the double-sided bandwidth equals the 30-kHz AMPS channel bandwidth). As seen from Figure 4, this filter far exceeds the AMPS cellular channel bandwidth (single-sided) specifications that are given in Table 1.[7]

Table 1. AMPS Cellular Single-Sided Channel Bandwidth Specification

Frequency	Attenuation
16 kHz	6 dB
29 kHz	48 dB
40 kHz	65 dB

2.2.2 Demodulation

After the baseband FIR filter, digital automatic gain control (AGC) is used to keep the baseband signal level constant before going to the digital demodulator. In the digital demodulator, the phase of the received signal is first computed from the I and Q signals as $\tan^{-1}(Q/I)$. The phase is then digitally differentiated to generate the demodulated FM audio output.

2.3 Audio Output Processing

As required in an AMPS cellular system, the demodulated audio output is bandpass filtered, de-emphasis is applied, and the signal is expanded in amplitude. As specified in [9] the TIA/EIA-712 standard, "Recommended Minimum Standards for 800 MHz Cellular Base Stations," the bandpass filter must ensure an audio frequency response that decreases by at least 24 dB per octave below 240 Hz and decreases by at least 36 dB per octave above 3800 Hz. De-emphasis requires that the audio frequency response between 300 and 3000 Hz decreases by 6 dB per octave (within the tolerance limits specified in [9]). The expander provides an output level change of 2 dB for an input level change of 1 dB with response time specifications given in [9].

[7]These specifications were obtained in a private communication with Gary Katz of Motorola, Inc. in Libertyville, IL. The specifications were taken from an EIA Communication Interim Standard document dated Jan. 3, 1983. The title of the document is not known.

2.3.1 Audio Processing Performed on the Digital Downconverter

The low-pass filter portion of the audio bandpass filter is implemented with the discriminator FIR filter on the digital downconverter using all of the 63 available taps.[8] The output of the discriminator FIR filter is converted to an analog signal by the audio digital-to-analog converter (DAC). This provides the pre-processed analog audio output from the digital downconverter.

2.3.2 Audio Processing Performed on the Analog Audio Processor

As shown in Figure 1, the input to the analog audio processor is the pre-processed analog audio output. The analog audio processor provides the high-pass portion of the required bandpass filtering, de-emphasis, and amplitude expansion using standard analog circuitry.[9]

3. SIGNAL OBSERVATION, PROCESSING, AND DISPLAY AT VARIOUS RECEIVER STAGES

The configuration shown in Figure 5 is used to observe the received signal at the digitized IF output. The differential ECL data and clock signals from the cellular downconverter are converted to TTL signals by an ECL to TTL converter board that is attached to the FIFO buffer board. The FIFO buffer board transfers the digitized IF data to the personal computer through the parallel port. (Although the parallel port on personal computers is typically used to output data to a printer, it is actually a bi-directional port and may be used for data input.)

The following procedure is used for the capture, recording, processing, and display of the digitized IF output data. First, 16,384 samples of the digitized IF output data are recorded in a data file on the computer's hard disk. This process is repeated until ten data captures have been taken and recorded. For each data capture, a 4-term Blackman-Harris window is applied and a 16,384-point FFT is computed. The magnitude of each FFT is then determined and converted to a power spectrum. The ten power spectrums are then averaged to produce an average power spectrum that is used to display the digitized IF output. This averaging reduces the noise floor, thus allowing lower-level spurious responses to be seen.

While the capability of observing the IF signal before digitization (to compare it with the digitized IF signal) would have provided additional insight into the operation of SDR receivers, this capability is not available for this architecture.

---

[8] The entire audio bandpass filter cannot be implemented with the discriminator FIR filter since the audio bandpass filter for an input sample rate of 120 ksamples/s requires more than the available number of taps.

[9] All of the required bandpass filtering, de-emphasis, and amplitude expansion could have been performed entirely on the digital downconverter using the on-board, programmable discriminator FIR filter and Texas Instruments TMS 320C50 digital signal processor. However, to decrease software development time, external analog circuitry was used instead of the digital signal processor to implement the high-pass portion of the bandpass filtering, de-emphasis, and amplitude expansion.

With the system configured as shown in Figure 1, received signals can be observed at baseband, at the output of the digital FM demodulator (after the discriminator FIR filter), and at the analog audio output. The digital downconverter software allows the user to observe either the baseband I and Q output or the demodulated FM output as a power spectrum displayed on the personal computer monitor. As shown in Figure 2, either the baseband I and Q output or the demodulated FM output is selected (via the digital downconverter software) and sent to the FIFO buffer IC.[10] The digital downconverter software then applies a Blackman window to the data. A 1024-point FFT is performed on the windowed data. The FFT is limited to a maximum of 1024 points due to the size of the FIFO buffer IC located on the digital downconverter. The magnitude of the FFT is determined and then converted to a power spectrum for display on the personal computer monitor.

Signals at the analog audio output are observed by connecting the output of the analog audio processor to a standard commercial radio test set. Among other measurements, standard analog audio test equipment provides a measurement of the signal-plus-noise-plus-distortion to noise-plus-distortion ratio (SINAD) of the analog audio signal.

4. RECEIVER TEST PLAN

The architecture of our implementation of the AMPS receiver permits testing of the receiver at several different stages of processing: the digitized IF output, the digitally downconverted and filtered baseband, the digital FM demodulator output (after the discriminator FIR filter), and the analog audio output. The capability of observing the signals at all of these outputs is exploited in the testing of the receiver to help gain insight into the operation of SDR receivers using digitization at the RF or IF. Testing procedures for each one of these outputs are discussed in separate subsections.

4.1 Digitized IF Output Testing

The configuration of the AMPS receiver for the digitized IF output testing is shown in Figure 5. Testing at the digitized IF output includes the self-generated spurious response test, the desired signal spectrum test, the aliasing test, the small signal plus large signal test, and the image frequency test. These tests are described in more detail in the following subsections. The results of the tests are shown as plots of the average power spectrum.

4.1.1 Self-Generated Spurious Response Test

The self-generated spurious response test is performed to establish a baseline of the spurious responses that appear in the spectrum of the digitized IF output when no RF input signals are present. This helps to identify spurious responses that are due to specific RF inputs in the

[10] Note that the FIFO buffer IC on the digital downconverter (shown in Figure 2) is a separate device from the FIFO buffer board shown in Figure 5.

remaining digitized IF output tests. The self generated spurious response test is executed with the receiver system setup as shown in Figure 5 except that a 50-ohm load is connected directly at the RF input of the cellular downconverter instead of the signal generator, bandpass filter, and attenuators.

Figure 6 shows the averaged power spectrum of the digitized IF output. Several characteristics of Figure 6 that are common to all of the digitized IF output spectrum plots that follow need to be mentioned. First, note that the y-axis scale is in units of decibels relative to full scale (dBFS). The averaged power spectrum has been normalized so that 0 dB represents the power of a full-scale sinusoidal IF output signal. The full-scale sinusoid ranges from an ADC output of 0 to 65,520, where 65,520 represents all ones in the 12 most significant bits and all zeros in the 4 least significant bits of a 16-bit digital word. The x-axis shows frequencies in megahertz (MHz) from 0 to 15.36 MHz, one-half of the sampling frequency (often called the Nyquist frequency).

The wideband signal appearing between 0 and roughly 500 kHz is the intentionally added dither noise for the ADC. Note the spike in the spectrum that occurs at the far right of Figure 6. This spike occurs one sample point below the Nyquist frequency (15.36 MHz). The spike is a spurious response caused by the 15.36-MHz reference frequency used for the local oscillators in the cellular downconverter. Another spurious response occurs at 11.44 MHz and is caused by a combination of the 2^{nd} local oscillator (LO) in the cellular downconverter and the 2^{nd} harmonic of the sampling clock. The dither noise, the spike occurring one sample point below the Nyquist frequency, and the spur at 11.44 MHz appear in all of the digitized IF output spectrum plots. These signals are not detrimental to the receiver since they actually fall outside of the desired IF band that extends from 0.68 to 10.68 MHz and 12.18 to 14.68 MHz. The level of the spurious responses within the desired IF band is about 88 dB or more below full scale.

4.1.2 Desired Input Signal Spectrum Test

The desired input signal spectrum test is performed to show normal operation (without noise or interference) of the cellular downconverter portion of the receiver under various input signal frequencies and levels. The test is performed with the test setup shown in Figure 5. Signal Generator #1 is used to inject a continuous wave (CW) signal into the RF input of the receiver. A bandpass filter is used to reduce the level of the harmonics produced by the signal generator. Signal Generator #1 is phase-locked to Signal Generator #2, a low phase noise signal generator that serves as the sampling clock for the cellular downconverter. Measurements are made at frequencies that are based on the channel assignments for the base station receiver in the cellular B-band. The 416 channels in the cellular B-band (each 30-kHz wide) are assigned the channel numbers 334 to 666 and 717 to 799. Channel numbers 334 to 354 are reserved for control channels. The control channels will be included in testing done before demodulation but not after, since this implementation of the AMPS receiver does not provide processing of the control signals.

To find the center frequency of a channel given a specific channel number (N) the following equation is used:

$$\text{Base station receive center frequency} = \{(0.03\,N) + 825\}\ \text{MHz.} \quad (2)$$

Therefore, channel numbers 334 to 666 correspond to center frequencies from 835.02 to 844.98 MHz, and channel numbers 717 to 799 correspond to center frequencies from 846.51 to 848.97 MHz. The frequencies chosen for testing are channel center frequencies at the edges and center of both of these bands. The IF output frequency of the cellular downconverter for a given RF input frequency within the 835- to 845- and 846.5- to 849-MHz bands is given by

$$\text{IF frequency} = \text{RF frequency} - 834.32\ \text{MHz}. \qquad (3)$$

The signal levels at which measurements are made include -110 dBm (near the receiver sensitivity level), -60 dBm (10 dB below the approximate maximum level at which the signal path through the cellular downconverter is linear), -40 dBm (near the level where the AGC begins to operate), and -15 dBm (the maximum input under normal operating conditions). The resulting IF output spectrum is observed and recorded for each combination of input signal level and frequency discussed above. Table 2 summarizes the combinations of input RF signal level and frequency used for the desired input signal spectrum test. The channel number and corresponding RF and IF center frequencies are also given.

Figures 7 to 10 show example results of this test for an RF input frequency of 835.02 MHz (IF output frequency of 0.70 MHz) at the -15, -40, -60, and -110 dBm input signal levels, respectively. For the -15 and -40 dBm input signal levels, the automatic gain control (AGC) is in operation and the IF output signal level varies very little (less than 1.5 dB). At the -60 dBm input signal level, the IF output signal level is about -25 dBFS. Input signal levels of -60 dBm and below are well within the linear operating range of the cellular downconverter. Therefore, as expected, the -110 dBm input signal level has an IF output signal level of about -75 dBFS. Results of the measurements at the other channels were similar.

Table 2. Desired Input Signal Test Frequencies and Levels

Channel Number	Input RF Center Frequency (MHz)	Output IF Center Frequency (MHz)	RF Input Levels (dBm)
334	835.02	0.70	-110, -60, -40, & -15
500	840.00	5.68	-110, -60, -40, & -15
666	844.98	10.66	-110, -60, -40, & -15
717	846.51	12.19	-110, -60, -40, & -15
758	847.74	13.42	-110, -60, -40, & -15
799	848.97	14.65	-110, -60, -40, & -15

4.1.3 Aliasing Test

One of the major differences between radio receivers using digitization at the RF or IF and traditional analog receivers is the potential for spectrum overlap (aliasing) to occur due to the sampling process. Sampling, analog anti-alias filtering, and spectrum overlap are discussed in detail in Section 2.1 of [10]. In our implementation of the AMPS receiver, sampling occurs at the IF. The sampling rate f_s is set for the cellular downconverter at 30.72 Msamples/s. Aliasing will occur when any signals greater in frequency than $f_s/2$ (15.36 MHz) are present before analog-to-digital conversion. Signals present before analog-to-digital conversion that are greater in frequency than $f_s/2$ appear within the 0 to $f_s/2$ frequency band after analog-to-digital conversion.

As discussed in Section 2, the cellular downconverter downconverts RF signals in the 835- to 845-MHz band to IF frequencies of 0.68 to 10.68 MHz, and RF signals in the 846.5- to 849-MHz band to IF frequencies of 12.18 to 14.68 MHz. Because the highest IF frequency from desired RF signals (14.68 MHz) is below $f_s/2$, some oversampling is actually occurring. This oversampling allows the anti-aliasing filter to provide greater attenuation of aliased signals.

The following equation gives the frequencies of all the aliased components based on the sampling frequency and digitized IF frequency used:

$$\text{Frequency of the aliased component} = \pm\,\text{IF frequency} + n f_s \quad \text{where } n = \pm 1, \pm 2, \pm 3, \ldots . \tag{4}$$

Since IF frequencies greater than 14.68 MHz are attenuated in the cellular downconverter, and we are interested in aliased components that appear within the 0 to $f_s/2$ band, (4) can be written as

$$\text{Frequency of the aliased component} = f_s - \text{IF frequency}. \tag{5}$$

Both an in-band and an out-of-band aliasing test are performed. The in-band aliasing test is performed with an undesired signal that produces an aliased component at the upper frequency end (near 14.68 MHz) of the desired IF bands. The out-of-band aliasing test is performed with an undesired signal that produces an aliased component above 14.68 MHz but below $f_s/2$. The anti-aliasing filter is expected to attenuate aliased signals that occur below 14.68 MHz more than those that occur between 14.68 MHz and $f_s/2$.

Both the in-band and out-of-band aliasing tests use the test setup shown in Figure 5, with the same RF input signal generator, bandpass filter, and attenuators used for the desired signal spectrum test. In the aliasing test, a single CW undesired signal is injected into the RF input and the resulting IF output spectrum is observed. The RF input signal level is set to -40 dBm, high enough for the effects of aliasing to be easily observed.

For the out-of-band aliasing test, we generate an aliased component that occurs just below $f_s/2$. An RF input signal of -40 dBm at 849.8 MHz is applied to the AMPS receiver. The averaged power spectrum of the digitized IF output is shown in Figure 11. The signal appearing at 15.24

MHz is the aliased signal. This is expected since, using (3), an RF input signal of 849.8 MHz produces a 15.48-MHz IF signal before digitization. The 15.48-MHz IF signal generates a 15.24-MHz aliased signal as predicted by (5). Note from Figure 11 that the aliased component has an amplitude of about -69 dBFS. As a reference, a desired RF input signal of -40 dBm at 848.97 MHz was shown to produce an IF output signal of about -5 dBFS. Therefore, this aliased signal is significantly attenuated by the filtering in the cellular downconverter.

For the in-band aliasing test, we generate an aliased component that occurs just below the upper frequency end of the desired IF bands. An RF input signal of -40 dBm at 850.39 MHz is applied to the AMPS receiver. The averaged power spectrum of the digitized IF output is shown in Figure 12. The signal appearing at 14.65 MHz is the aliased signal. This is expected since, using (3), an RF input signal of 850.39 MHz produces a 16.07-MHz IF signal before digitization. The 16.07-MHz IF signal generates a 14.65-MHz aliased signal, as seen by applying (5). Note from Figure 12 that the amplitude of the aliased signal is about -77 dBFS. Therefore, this in-band aliased component is more attenuated than the out-of-band aliased component shown in Figure 11. As the RF input frequency is increased beyond 850.39 MHz, the frequency of the aliased component decreases below 14.65 MHz. The amplitude of the aliased component should also decrease due to the anti-aliasing filter.

4.1.4 Image Frequency Test

The image frequency test shows how signals outside of the desired signal RF frequency bands can appear in the desired signal IF frequency bands due to the first mixing stage of the cellular downconverter. The image frequencies are attenuated by the RF bandpass filter before the first mixer; however, these frequencies receive no other attenuation in the cellular downconverter. The image frequencies for the cellular downconverter are found as

$$\text{Image frequency} = (2 * f_{LO}) - \text{Desired RF frequency} \tag{6}$$

where f_{LO} is the frequency of the first LO (907.2 MHz) [11]. The image frequencies are 965.4 to 967.9 and 969.4 to 979.4 MHz and correspond to IF frequencies, 14.68 to 12.18 and 10.68 to 0.68 MHz, respectively. The image frequency test gives an indication of the amount of attenuation of the image frequencies. The setup for this test is identical to that used for the desired signal spectrum test described in Section 4.1.2. The RF input signal is set to 965.4 MHz at a level of -50 dBm.

Figure 13 shows the averaged power spectrum of the corresponding digitized IF output. The image frequency of 965.4 MHz (at a -50 dBm input level) produces a 14.68-MHz IF output at a level of approximately -65 dBFS. From the results of the desired input signal test, the expected IF output level at 14.68 MHz is roughly -12 dBFS for the corresponding -50 dBm desired RF input (849 MHz). Therefore, the image frequency is attenuated about 53 dB by the cellular downconverter.

4.1.5 Small Signal Plus Large Signal Test

The small signal plus large signal test is a measure of how well a low-level desired signal will be received in the presence of a high-level, in-band, interfering signal. This is a particularly difficult problem for a wideband receiver such as our AMPS receiver. The reason for this is that the AGC responds to digitized signals at the output of the ADC that are within the desired IF frequency bands and are above a given level. The AGC operates by increasing the RF input signal attenuation before the first mixer as the output of the ADC increases beyond a certain level. This maintains the output level of the ADC at a relatively constant level for a wide range of RF input signal levels (approximately -43 to -15 dBm). Large in-band signals cause the RF attenuation to increase and may prevent low-level desired signals from being received. Figure 5 shows the setup for this test. One of the two signal sources within Signal Generator #1[11] is set to provide the desired signal to the RF input of the receiver. This desired signal is a CW signal at 840.0 MHz with an RF level of -100 dBm. The other signal source within Signal Generator #1 provides the high-level, in-band, interfering signal.

Initially, measurements are taken of the digitized IF output with the desired signal input but no interfering signal applied. Measurements of the digitized IF output are then taken with the desired signal input in the presence of an 840.6-MHz CW interfering signal at three different RF input signal levels: -15, -30, and -40 dBm. Figures 14a and 14b show the averaged power spectrum of the digitized IF output for the desired signal input with no interferer and with the -15 dBm interferer, respectively. Note that the desired signal with no interferer appears at an IF output frequency of 5.68 MHz at -62 dBFS. With the interfering signal level of -15 dBm, the desired signal level is reduced to -80 dBFS making it more difficult to detect. Lower level desired signals might be detectable with no interfering signal present but not detectable with the -15 dBm interfering signal present.

4.2 Digitized Baseband Output Testing

The configuration of the AMPS receiver for the digitized baseband output testing is shown in Figure 15. Testing at the digitized baseband output includes the channel filter test and the desired signal spectrum test. These tests are described in more detail in the following subsections.

4.2.1 Channel Filter Test

The channel filter test provides a measurement of the response of the channel filter in our implementation of the AMPS receiver. The channel filter test is performed with the test setup shown in Figure 15. Note that for this test, the digital AGC implemented on the digital downconverter is disabled. Signal Generator #1 is used to inject a CW signal into the RF input of the receiver. A bandpass filter is used to reduce the level of the harmonics produced by the signal generator. The level of the RF input into the receiver is set to -50 dBm. The RF frequency

[11]Signal Generator #1 includes two separate, internal signal sources, an internal power combiner, and an external input into the power combiner to allow the addition of a third signal.

input is set to 840 MHz, the digitized baseband output spectrum is observed, and the level of the baseband signal (in units of dBFS) is recorded. This process is repeated for RF frequencies incremented in 2-kHz steps from the center frequency of the channel (1-kHz steps are used near the 15-kHz cutoff frequency and 4-kHz steps are used well above the cutoff frequency). The measurements of the baseband signal level at each RF frequency show the frequency response of the channel filter. Examples of some of the baseband output spectrum plots used to determine the filter frequency response are given in Figure 16. Figures 16a - 16d represent the baseband output spectrum plots for the center frequency plus 0 kHz, 15 kHz, 16 kHz, and 17 kHz, respectively.

Figure 17 shows the measured frequency response of the channel filter along with its theoretical response. Relative power (relative to the maximum output level) is shown as a function of frequency. Both the passband and stopband responses are shown in Figure 17a while the response of the transition band is detailed in Figure 17b. As seen in Figures 17a and 17b, the measured frequency response follows the theoretical frequency response very well.

4.2.2 Desired Input Signal Baseband Spectrum Test

The desired input signal spectrum test is performed with the test setup as shown in Figure 15. The test follows a similar procedure as that of the desired input signal spectrum test described in Section 4.1.2 except that the digitized baseband output spectrum is observed and recorded instead of the digitized IF output spectrum.

The test is performed to show normal operation (without noise or interference) of the receiver at the baseband output under various RF input signal frequencies and levels. The RF input signal frequencies and levels used in this test are shown in Table 2. The spectrum of the digitized baseband output is observed and recorded for each combination of input frequency and signal level, first with the digital AGC of the digital downconverter enabled and then with it disabled.

Figures 18a - 18d show examples of the output baseband spectrum with the digital AGC enabled for an 840-MHz RF input signal at -15, -40, -60, and -110 dBm input signal levels, respectively. Note that for the 95-dB variation in RF input signal level, the baseband signal level varies by roughly 12 dB. For RF input levels between -60 dBm and -110 dBm (where linearity in the cellular downconverter is ensured), the baseband signal level remains essentially constant.

Figure 19 shows the same examples as in Figure 18 but with the digital AGC disabled. Note from these plots that the baseband signal level changes very little for RF input levels between -15 dBm and -40 dBm due to the AGC in the cellular downconverter. For RF input levels between -60 dBm and -110 dBm, the baseband signal level now changes by about 43 dB. Recall that for the same variation in RF input levels when the digital AGC was enabled, the baseband signal level remained constant. Thus, the digital AGC in the digital downconverter has a significant effect on the output baseband signal. The digital AGC is necessary for the proper operation of the digital FM demodulator.

4.3 Digitized Demodulator Output Testing

Testing of the digitized demodulator output can be performed by observing and recording the digitized demodulated spectrum or time domain output. The configuration of the AMPS receiver for the digitized demodulator output testing is shown in Figure 15. Testing at the digitized demodulator output includes only the demodulated desired signal spectrum test. The purpose of this test was primarily to demonstrate the capability of making the measurement at this output and to demonstrate that the FM modulated tone can be digitally demodulated correctly by the digital downconverter.

The demodulated desired signal output test uses the test setup as shown in Figure 15. Signal Generator #1 is set to a center frequency of 840 MHz and is frequency modulated with a 1-kHz tone at a peak deviation of ± 8 kHz. The demodulated signal output spectrum is observed and recorded for RF input levels of -15, -40, -60, and -110 dBm with the digital AGC of the digital downconverter enabled.

Figure 20 shows the demodulated signal output spectrum with the digital AGC enabled for all four RF input levels. Note that the signal level of the demodulated 1-kHz tone remains constant over the entire range of RF input signal levels from -15 dBm to -110 dBm. Also note that any harmonics, noise, or spurious responses are down a minimum of about 35 dB from the desired signal for the -110 dBm input and are even further below the desired signal for the other input signal levels.

4.4 Analog Audio Output Testing

Testing performed at the analog audio output of the AMPS receiver can follow traditional tests defined in the TIA/EIA-712 standard, "Recommended Minimum Standards for 800 MHz Cellular Base Stations" [9]. Three of the tests described in this document are highly relevant to electromagnetic compatibility (EMC) testing of the base station receiver: the adjacent and alternate channel desensitization test, the intermodulation spurious response attenuation test, and the protection against spurious-response interference test. The results of these tests are determined by using a radio test set to measure the SINAD at the analog audio output under various RF input conditions. For these tests the AMPS receiver is set up as shown in Figure 1. The tests are described in more detail below.

4.4.1 Adjacent and Alternate Channel Desensitization

This test is a measure of how well a receiver can detect an FM input signal at the desired frequency in the presence of an in-band, interfering, FM signal. The test is performed first with the interfering signal on an adjacent channel 30 kHz above the desired signal's channel and then 30 kHz below the desired signal's channel. Next, the test is performed with the interfering signal on an alternate channel 60 kHz above the desired signal's channel and then 60 kHz below the desired signal's channel. The test setup is shown in Figure 21. The basic testing procedure is now described and follows that given in Section 2.3.2.2 of [9].

The expander in the analog audio processor is enabled and the radio test set is configured to measure the SINAD using a C-message weighted filter. Signal Generator #1 is set to inject an 840-MHz desired RF input signal (with no interfering signal), frequency modulated with a 1-kHz sinusoidal tone at a ±8-kHz peak frequency deviation, into the AMPS receiver. The RF signal level is adjusted to obtain a 12-dB SINAD. The SINAD measurement is actually computed by taking an average of 10 SINAD readings from the radio test set, since there is some variation in SINAD from one reading to another. This RF signal level is then recorded and increased by 3 dB. Signal Generator #1 is then set to include an 840.03-MHz interfering signal along with the desired signal at the input to the AMPS receiver. The interfering signal is frequency modulated with a 400-Hz sinusoidal tone at a ±8-kHz peak frequency deviation.

The RF interfering signal level is then adjusted until the SINAD is reduced to 12 dB again. The level of the RF interfering signal is recorded and the difference between this interfering signal level and the previously recorded desired signal level is the selectivity. This test is repeated for RF interfering signal frequencies of 840.06, 839.97, and 839.94 MHz. The results of this test, the measured selectivity, are shown in Table 3.

Table 3. Adjacent and Alternate Channel Measured Selectivity

Channel	Interfering Signal Frequency (MHz)	Measured Selectivity (dB)	Minimum Selectivity Specification (dB)
Adjacent	840.03	66.0	16
Adjacent	839.97	65.5	16
Alternate	840.06	77.7	60
Alternate	839.94	77.0	60

As seen in Table 3, the measured selectivity for both the adjacent channel (30-kHz offset) and the alternate channel (60-kHz offset) far exceed the minimum selectivity specifications set forth in the TIA/EIA-712 standards document. This is a result of the digital channel filter attenuation being much better than the AMPS cellular channel bandwidth specifications.

4.4.2 Intermodulation Spurious Response Attenuation

This test is a measure of how well a receiver can detect an FM input signal at the desired frequency in the presence of two interfering continuous-wave (CW) signals that produce an intermodulation product that occurs at the same frequency as the desired input signal. The test is performed first with one interfering signal 60 kHz above and the other interfering signal 120 kHz above the desired input signal frequency. The test is then repeated with one interfering signal 60 kHz below and the other interfering signal 120 kHz below the desired input signal frequency. The same test setup shown in Figure 21 is used except that an additional RF signal generator (Signal Generator #3) is connected to the external RF input of Signal Generator #1. In this configuration, Signal Generator #3 serves as the desired RF signal while the two internal RF signal sources within Signal Generator #1 provide the interfering signals. Both Signal Generator #1 and Signal Generator #3 are phase-locked to the 10-MHz reference output of Signal Generator #2. The measurement procedure used follows that given in Section 2.3.3.2 of [9] and is described below.

For this test, the expander in the analog audio processor is bypassed. Again, the radio test set is configured to measure the SINAD using a C-message weighted filter. An 840-MHz desired RF input signal, frequency modulated with a 1-kHz sinusoidal tone at a $\pm$8-kHz peak frequency deviation, is generated by Signal Generator #3 and injected into the AMPS receiver. No interfering signal is present at this time. The RF signal level is adjusted to obtain a 12-dB SINAD. This RF signal level is recorded and then increased by 3 dB. The two internal RF signal sources within Signal Generator #1 are set to generate CW interfering signals of 840.06 and 840.12 MHz. The signal levels of both interfering signals are adjusted (maintaining equal signal levels) until the SINAD is reduced to 12 dB again. This value is recorded and the test is repeated for CW interfering signals of 839.94 and 839.88 MHz.

The intermodulation spurious response attenuation is determined by subtracting the signal level of the desired signal from the signal level of the interfering signals. The minimum measured intermodulation spurious response attenuation is 72.5 dB. This easily meets the required minimum of 65 dB set forth in the TIA/EIA-712 standard.

4.4.3 Protection Against Spurious-Response Interference

This test is a measure of how well the receiver can distinguish the desired input signal from an interfering FM signal that causes a response in the audio output of the receiver. For our implementation of the AMPS receiver, this interfering signal can be at any frequency other than the desired signal frequency from 0.68 to 2600 MHz. The procedure is generally based on that given in Section 2.3.4.2 of [9] and is detailed below. The measurement procedure is actually performed in two stages. In the first stage, the RF input frequencies of the interfering signal that cause a response in the audio output of the receiver are identified. In the second stage, for each of these frequencies, the RF input signal level of the interfering signal that causes a specified degradation in the SINAD is determined.

The procedure to determine the RF input frequencies that cause a response in the audio output of the receiver is now described. To accomplish this test, a desired RF signal and a high-power, RF interfering signal that is stepped in frequency from 0.68 to 2600 MHz are input into the AMPS receiver. The test is actually performed using three separate measurements with the interfering signal varying from 0.68 to 550 MHz, 550 to 1000 MHz, and 1000 to 2600 MHz. Figure 22 shows the test setup when the interfering signal ranging from 0.68 to 550 MHz is used. The same test setup is used when the interfering signal ranging from 550 to 1000 MHz is used, except that a 1000-MHz low-pass filter is used at the output of Signal Generator #3 instead of a 600-MHz low-pass filter. The test setup shown in Figure 23 is used when the interfering signal ranging from 1000 to 2600 MHz is used. Note that the only difference between the test setups in Figures 22 and 23 is how the desired signal and interfering signal are filtered and combined.

Regardless of the frequency range of the interfering signal, the measurement procedure follows a similar approach. The expander in the analog audio processor is bypassed. The radio test set is configured to measure the SINAD using a C-message weighted filter. An 840-MHz desired RF input signal, frequency modulated with a 1-kHz sinusoidal tone at a $\pm$8-kHz peak frequency deviation, is generated by Signal Generator #1 and injected into the AMPS receiver. With no interfering signal present, the RF signal level is adjusted to obtain a 12-dB SINAD. This RF signal level (-119 dBm) is recorded and then increased by 3 dB.

The interfering signal is generated by Signal Generator #3 and consists of an RF signal frequency modulated with a 400-Hz sinusoidal tone at a $\pm$8-kHz peak frequency deviation. The RF input signal level of this interfering signal is set to approximately -30 dBm. Using a personal computer and GPIB control, this interfering signal is then automatically stepped in frequency in 5-kHz increments over each of the three aforementioned frequency ranges. At each interfering signal frequency, the analog audio output of the AMPS receiver is monitored for a response. The spectrum analyzer, also under GPIB control, is used in zero-span mode to detect a response (the presence of the 400-Hz sinusoid) at each of the stepped frequency inputs. The zero-span mode on the spectrum analyzer is used instead of the SINAD mode on the radio test set, because the SINAD measurement takes too much time to settle to a value and would lead to an impractically long time to step through all of the frequencies. For each interfering signal frequency range, the frequencies where a response to the interfering signal is detected are recorded. Forty different interfering signal frequencies, ranging from around 420 to 1881 MHz, cause a response in the receiver. These frequencies are listed in Table 4.

For the second stage of testing, the basic test setup is shown in Figure 22 with three exceptions. The 13-dB attenuators are replaced with 10-dB attenuators, the radio test set is used instead of the spectrum analyzer, and the personal computer with the associated GPIB bus is removed. Measurements are made at the interfering signal frequencies that caused a response in the receiver during the first stage of testing (Table 4). The specific low-pass filter used for the testing depends on the frequency of the interfering signal. Table 5 lists the filter used for the interfering signals that occur within four different frequency ranges. (Recall that no interfering signals above 1900 MHz produce a response in the receiver.) The low-pass filter is used to reduce the signal level of harmonics that are present outside of the specific interfering signal frequency range.

As in the first stage of testing, the expander in the analog audio processor is bypassed. The radio test set is configured to measure the SINAD using a C-message weighted filter. An 840-MHz desired RF input signal, frequency modulated with a 1-kHz sinusoidal tone at a $\pm$8-kHz peak frequency deviation, is generated by Signal Generator #1 and injected into the AMPS receiver. With no interfering signal present, the RF signal level is adjusted to obtain a 12-dB SINAD. This RF signal level (-119 dBm) is recorded and then increased by 3 dB. The interfering signal is generated by Signal Generator #3 and consists of an RF signal frequency modulated with a 400-Hz sinusoidal tone at a $\pm$8-kHz peak frequency deviation. For each interfering signal frequency that causes a response in the receiver, the signal level of the interfering signal to degrade the SINAD to 12 dB is determined and recorded. The difference between this interfering signal level and the desired signal level, the spurious response attenuation, is calculated and is shown for each interfering signal frequency listed in Table 4. The spurious response attenuation is greater than

65.8 dB for all frequencies except at the image frequency of 974.400 MHz (where it is 57.8 dB). The specification set forth in the TIA/EIA-712 standard is at least 60 dB.

Table 4. Spurious Response Frequency and Attenuation

Spurious Response Frequency (MHz)	Spurious Response Attenuation (dB)
420.002	78.4
828.639	79.4
835.248	82.0
836.211	78.4
837.160	79.4
837.494	80.6
837.589	80.7
839.316	79.5
839.756	79.4
839.841	78.8
839.880	78.8
839.970	66.0
840.030	65.8
840.115	65.8
840.160	78.0
840.220	79.4
840.260	79.4
842.302	80.9
842.671	77.9
843.430	79.6

Spurious Response Frequency (MHz)	Spurious Response Attenuation (dB)
843.605	79.4
846.465	77.6
846.839	77.7
847.039	78.1
848.252	74.2
848.307	77.4
848.726	75.7
924.006	83.7
925.997	84.5
927.001	82.5
974.400	57.8
993.005	84.4
994.004	83.0
995.002	80.3
996.000	82.3
1679.970	75.6
1680.035	73.6
1680.000	73.6
1747.203	82.0
1881.602	78.9

Table 5. Filter Used for a Given Interfering Signal Frequency Range

Interfering Signal Frequency Range	Type of Filter
0.68 - 550 MHz	600-MHz Low Pass
550 - 1000 MHz	1000-MHz Low Pass
1000 - 1700 MHz	1700-MHz Low Pass
1700 - 1900 MHz	1900-MHz Low Pass

5. SUMMARY AND CONCLUSIONS

In this report we have described an example implementation of an SDR receiver. For this example, an AMPS cellular base station receiver was configured using SDR technology. The receiver is an actual current application of an SDR receiver. The architecture of our SDR receiver consists of four basic blocks: the WJ cellular B-band downconverter, the Sigtek ST-114 digital downconverter board that operates in a personal computer, an Analog Devices FIFO buffer memory board, and an analog audio processor.

A great advantage of the modular architecture that was used for our AMPS receiver is that it permits observation of the received signal at various stages of the processing. This provides the opportunity to gain insight into the performance of SDR receivers.

Signals may be observed at the digitized IF output, the digitally downconverted and filtered baseband output, the digital FM demodulator output (after the discriminator FIR filter), and the analog audio output. Testing was performed at all stages of the receiver where signals could be observed. While the capability of observing the IF signal before digitization would have provided additional insight into the behavior of SDR receivers, this capability was not available for this architecture.

Testing at the digitized IF output included a self-generated spurious response test, a desired input signal spectrum test, in-band and out-of-band aliasing tests, an image frequency test, and the small signal plus large signal (small desired signal in the presence of a large interfering signal) test. The digitized baseband output testing consisted of a channel filter test and a desired signal baseband spectrum test. The demodulated desired signal output test was performed at the digitized demodulator output. Finally, traditional analog testing was performed at the analog audio output of the receiver. This testing followed procedures outlined in the TIA/EIA-712 standard for the adjacent and alternate channel desensitization, intermodulation spurious response attenuation, and protection against spurious response interference tests.

The SDR AMPS receiver, while possessing the inherent flexibility advantages of SDR's, easily met the specifications for the analog audio output tests. The measured selectivity for both the adjacent channel (30-kHz offset) and the alternate channel (60-kHz offset) far exceed the minimum selectivity specifications set forth in the TIA/EIA-712 standards document. This is a result of the digital channel filter attenuation being much better than the AMPS cellular channel bandwidth specifications. The minimum measured intermodulation spurious response attenuation of 72.5 dB easily met the required minimum of 65 dB. The measured spurious response attenuation also readily met the required minimum of 60 dB for all frequencies except at the image frequency of 974.4 MHz (where it was 57.8 dB).

We showed measurements that produced aliasing in the AMPS receiver. This phenomenon does not occur in traditional analog receivers. While aliasing was shown to occur under certain frequency and signal level inputs, a good deal of filtering is present in the system to minimize the interfering effects of this aliasing. The behavior of a small desired signal in the presence of a large interfering signal was investigated. We showed that a strong RF in-band, interfering signal (of about -15 dBm) can render weak desired signals undetectable that are easily detectable with no large interfering signals present. Finally, we showed the effects of the digital AGC (located in the digital downconverter) on the digital baseband output signal. When using the digital AGC, for RF input levels into the AMPS receiver between -60 dBm and -110 dBm (where linearity in the cellular downconverter is ensured), the baseband signal level remained essentially constant. With the digital AGC disabled, for RF input levels between -60 dBm and -110 dBm, the baseband signal level changed by about 43 dB. The digital AGC is necessary for the proper operation of the digital FM demodulator.

Perhaps even more important than the specific results of the receiver testing, this report shows examples of testing at the various stages of processing in an SDR receiver. Since the signals at the outputs of processing stages in an SDR can be analog (such as at the analog IF or audio output) or digital (such as at the digitized IF or demodulated output), one must be able to analyze both analog and digital signals in an SDR receiver. When the output of a processing stage is an analog signal, a spectrum analyzer is used to display the frequency domain content (spectrum) of the signal, as in a traditional analog receiver. Analogously, when the output of a processing stage is a digital signal, the FFT is computed from the data and displayed to show the spectrum of the signal. The spectrum of the signal at the various processing stages in an SDR can be monitored to determine the receiver performance at each particular stage.

While the receiver described in this report is an AMPS cellular system, different cellular systems could be implemented in the future via software changes using the current hardware (the cellular B-band downconverter and the digital downconverter board) that we have selected. In the future, if the cellular downconverter is replaced with a wideband downconverter that has a very wide RF tuning range and if the DSP chip on the digital downconverter is used, an extremely versatile SDR receiver could be achieved. With this SDR receiver, many different types of receivers could be implemented strictly via software changes.

6. ACKNOWLEDGMENTS

The authors would like to thank several individuals for their contributions to this work. Lance Beard, formerly of the Watkins-Johnson Company, provided a tremendous amount of assistance in helping us use, understand, and interface to the WJ cellular B-band downconverter. Wayne

Barnes, of the Sigtek Corporation, provided detailed information about the Sigtek ST-114 digital downconverter board to help us both use the board and interface it to the WJ cellular B-band downconverter. Dave Damerow of the Harris Semiconductor Corporation provided technical assistance for configuring the Harris HSP50214 programmable downconverter IC used on the Sigtek ST-114. Many valuable comments to improve this report were provided by Robert Achatz of the Institute for Telecommunication Sciences. A special thanks goes to Yeh Lo of the Institute for Telecommunication Sciences who flawlessly performed the printed circuit board layout for the interface board between the WJ cellular B-band downconverter and the Sigtek ST-114 digital downconverter board. Without the assistance of these individuals, this work would not have been possible.

7. REFERENCES

[1] J. Mitola III, "The software radio architecture," *IEEE Communications Magazine*, Vol. 33, No. 5, pp. 26-38, May 1995.

[2] American National Standard T1.523-2001, *Telecom Glossary 2000*.

[3] J. Mitola III, "Wireless radio software architecture," in *The Froehlich/Kent Encyclopedia of Telecommunications*, Vol. 18, F.E. Froehlich and A. Kent, Eds., New York, NY: Marcel Dekker, Inc., 1999, pp. 105-156.

[4] J. Mitola III, "Software radios survey, critical evaluation and future directions," *IEEE AES Systems Magazine*, Vol. 8, No. 4, pp. 25-36, Apr. 1993.

[5] Sigtek, Inc., ST-114 HSP50214 Harris Downconverter Evaluation Board, Columbia, MD, Jun. 13, 1997.

[6] Harris Semiconductor Corporation, HSP50214 Programmable Downconverter, File Number 4266.1, May 1997.

[7] M.E. Frerking, *Digital Signal Processing in Communication Systems*, New York, NY: Chapman & Hall, 1994, pp. 199-202.

[8] Harris Semiconductor Corporation, *Digital Signal Processing Databook*, Melbourne, FL: Harris Semiconductor Corporation, 1994, p. 6-10.

[9] Telecommunications Industry Association, TIA/EIA-712 standard, "Recommended Minimum Standards for 800 MHz Cellular Base Stations," Arlington, VA, Jul. 1997.

[10] J.A. Wepman and J.R. Hoffman, "RF and IF digitization in radio receivers: Theory, concepts, and examples," NTIA Report 96-328, pp. 3-8, Mar. 1996.

[11] F.G. Stremler, *Introduction to Communication Systems*, Reading, MA: Addison-Wesley, Inc., 1979, p. 226.

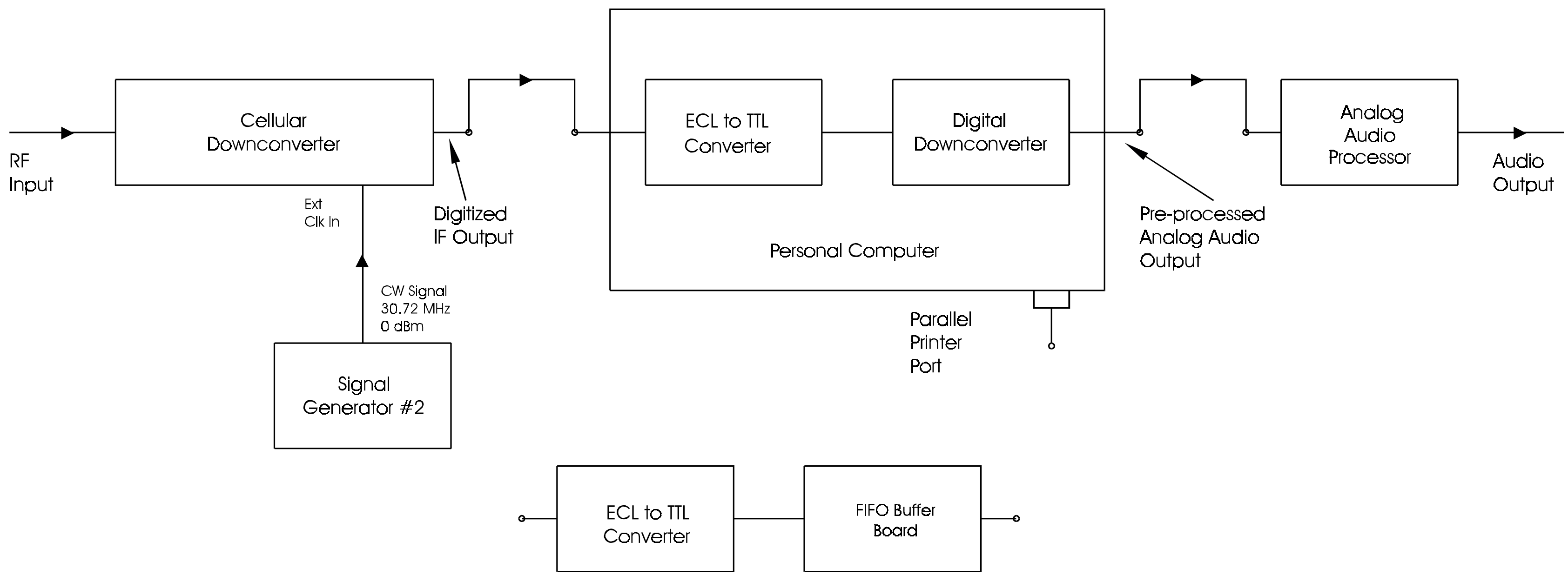


Figure 1. Architecture of the entire configuration of the cellular B-band receiver.

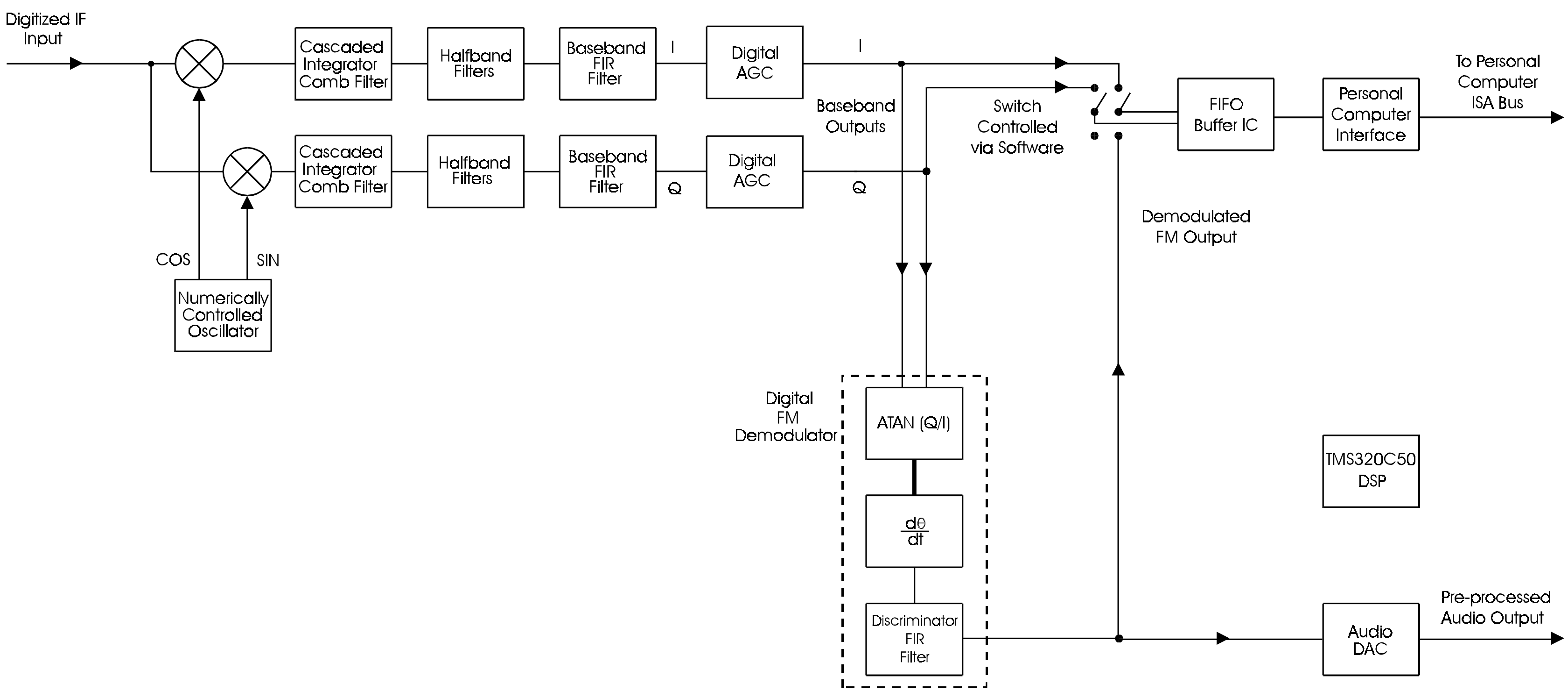


Figure 2. Processing performed by the digital downconverter.

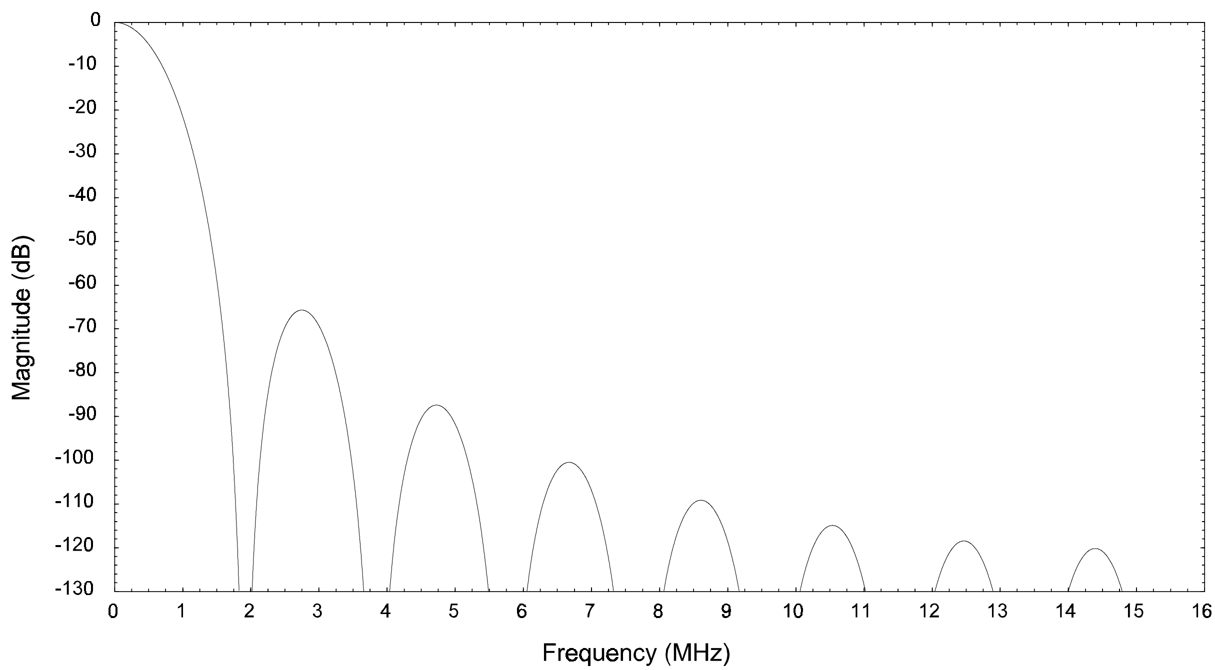
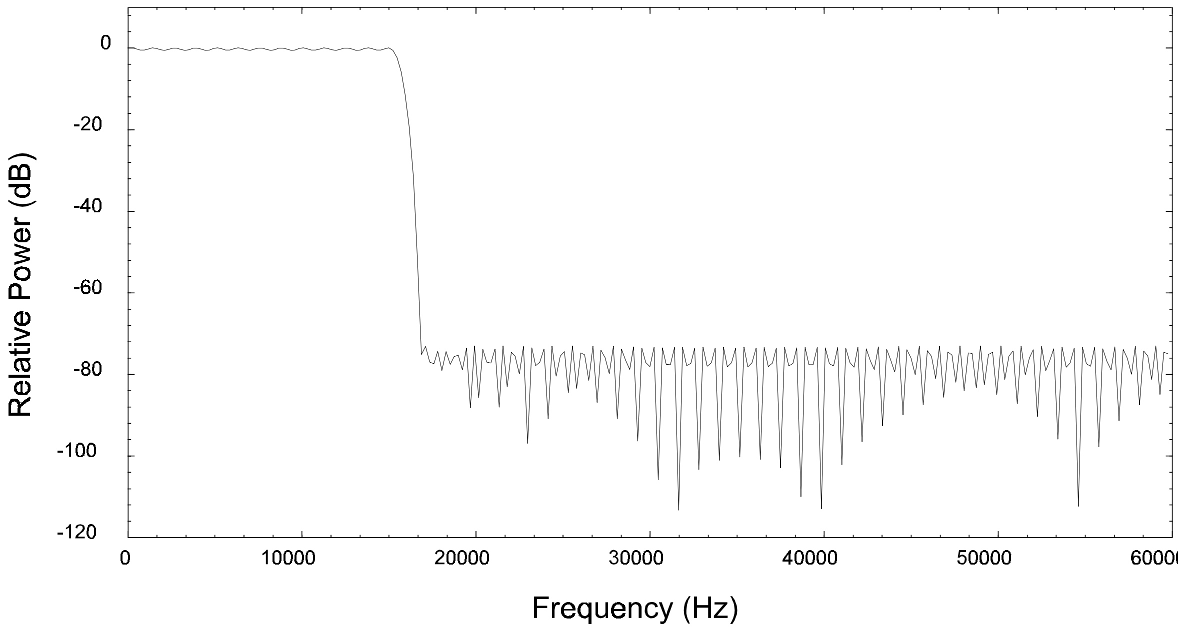
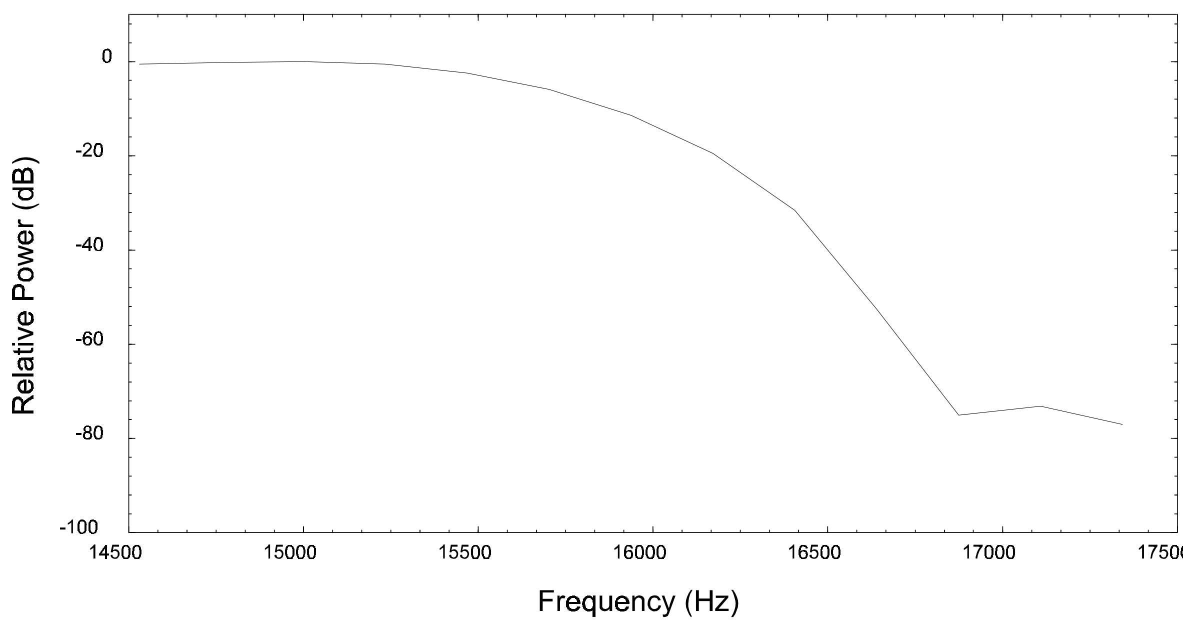


Figure 3. Magnitude response of the CIC filter.



(a)



(b)

Figure 4. Magnitude response of the baseband FIR filter showing the (a) passband and stopband and (b) transition band.

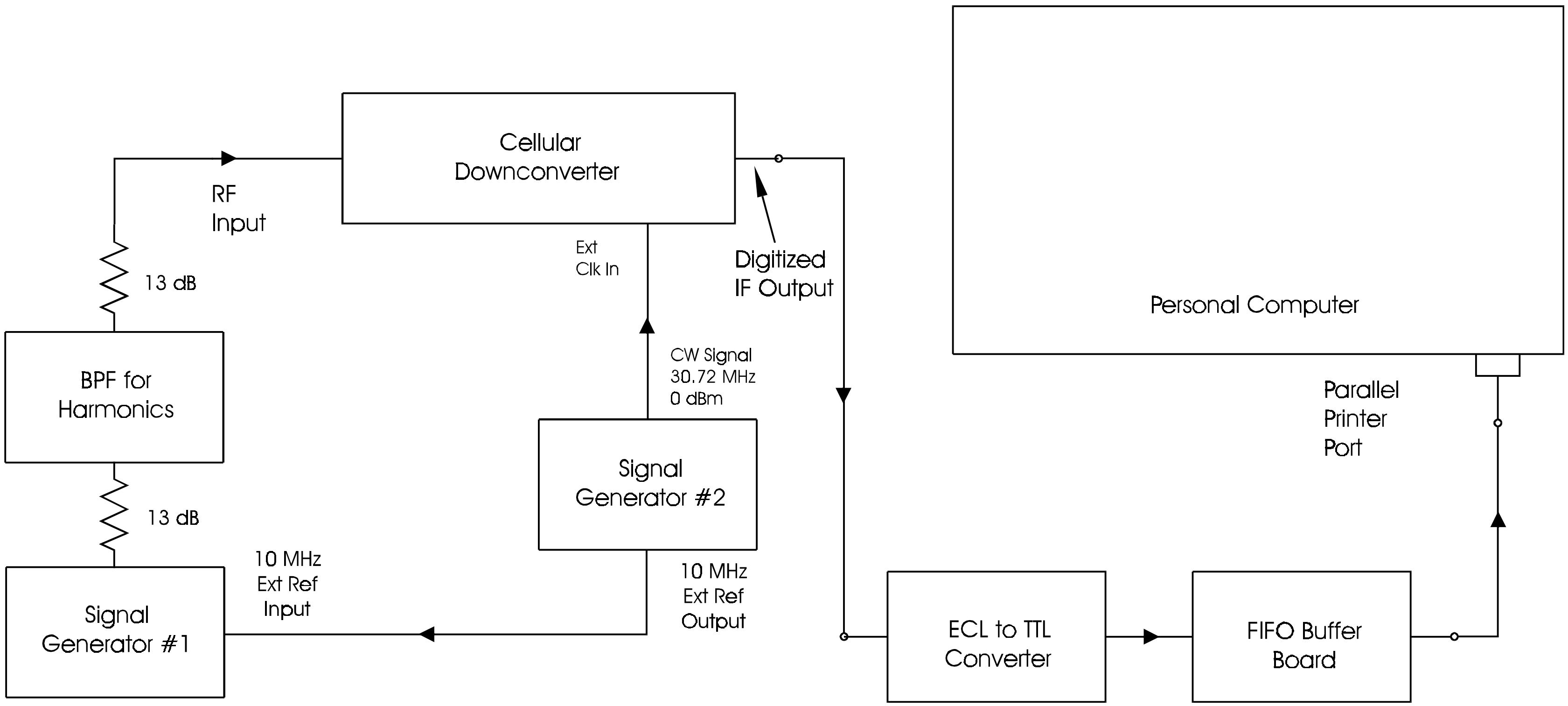


Figure 5. Test setup and receiver configuration to observe the digitized IF output.

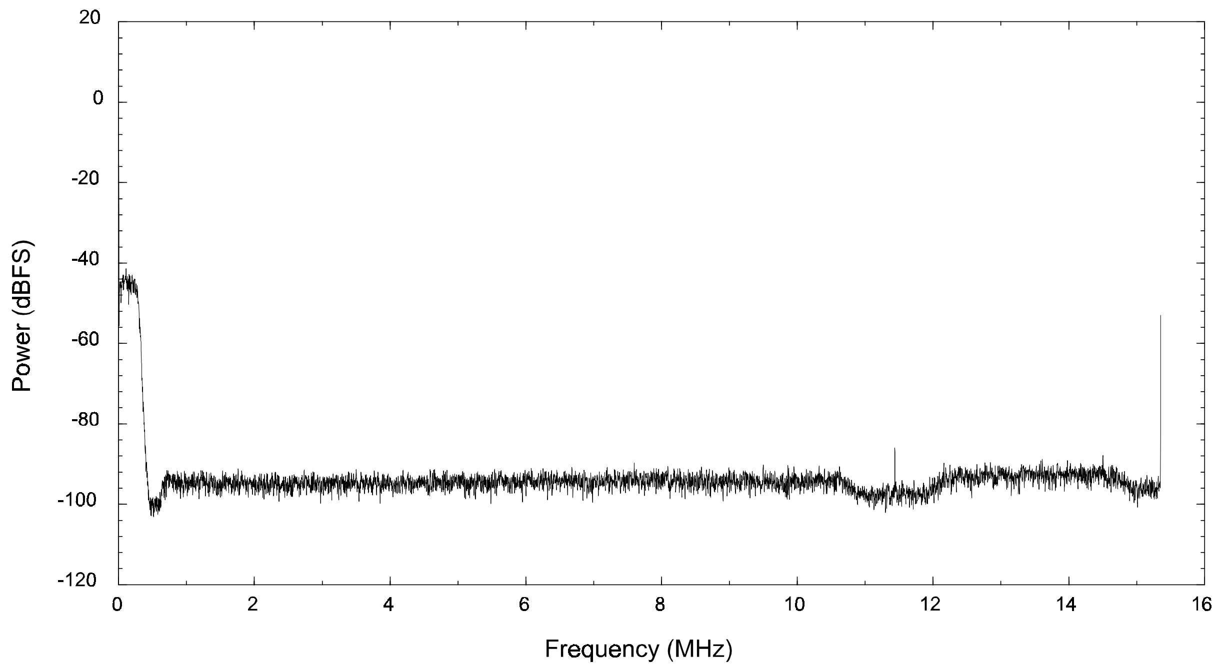


Figure 6. Self generated spurious response averaged power spectrum.

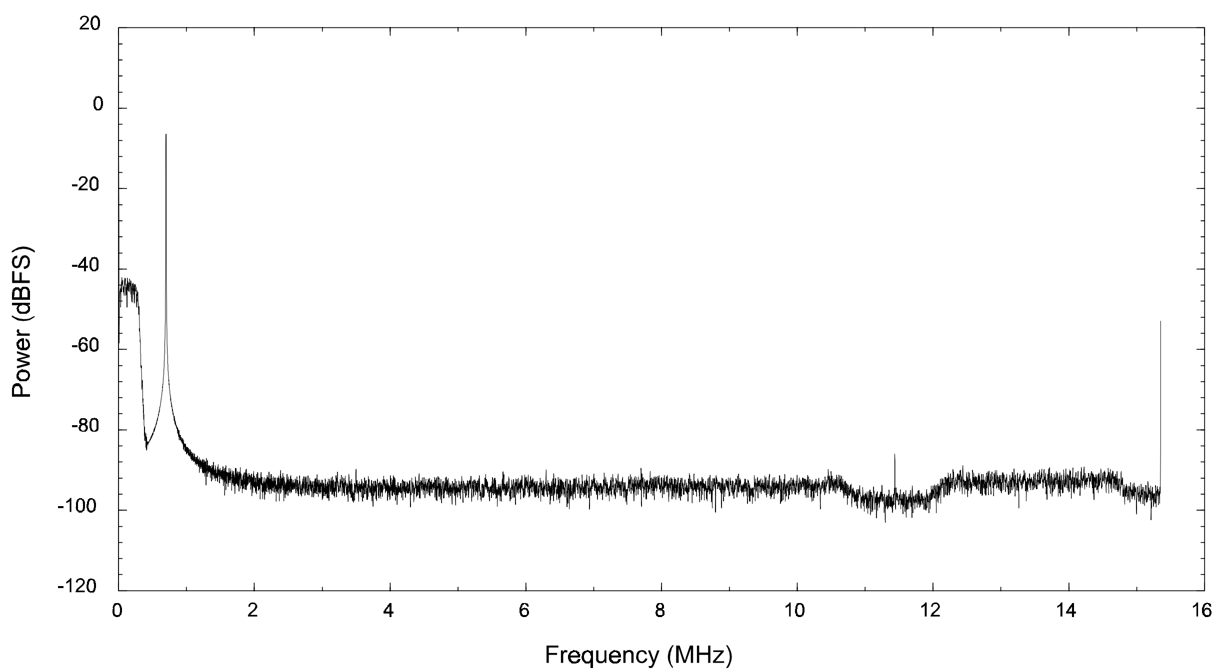


Figure 7. Averaged IF output power spectrum for an 835.02-MHz, -15 dBm RF input.

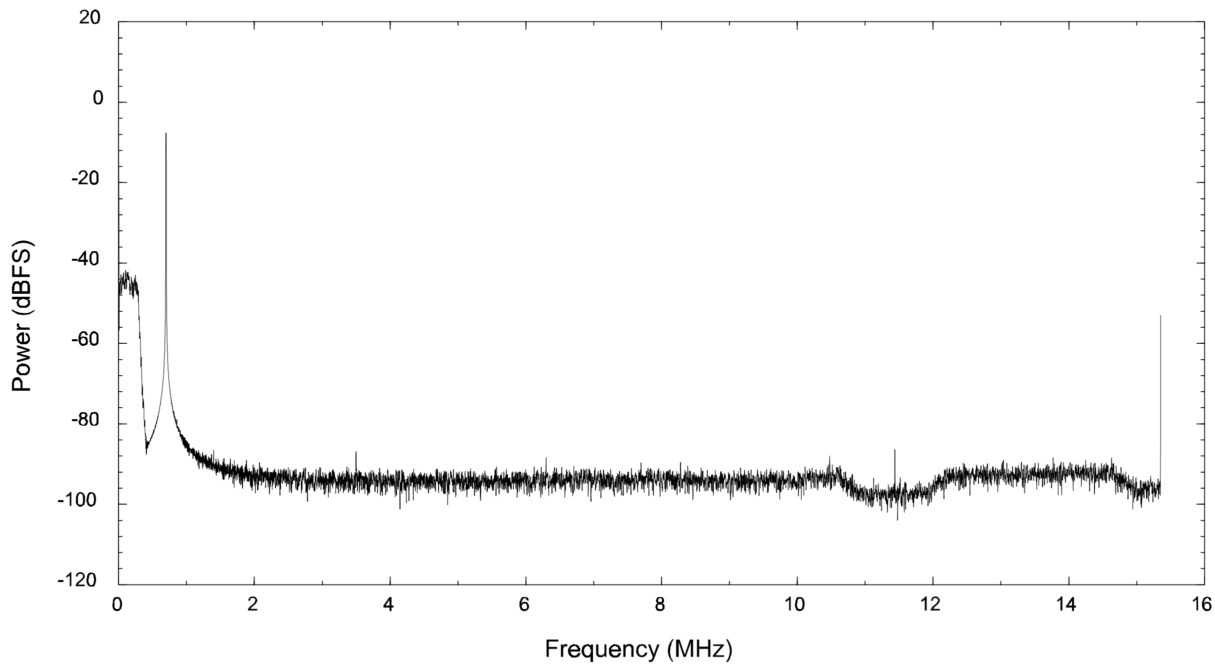


Figure 8. Averaged IF output power spectrum for an 835.02-MHz, -40 dBm RF input.

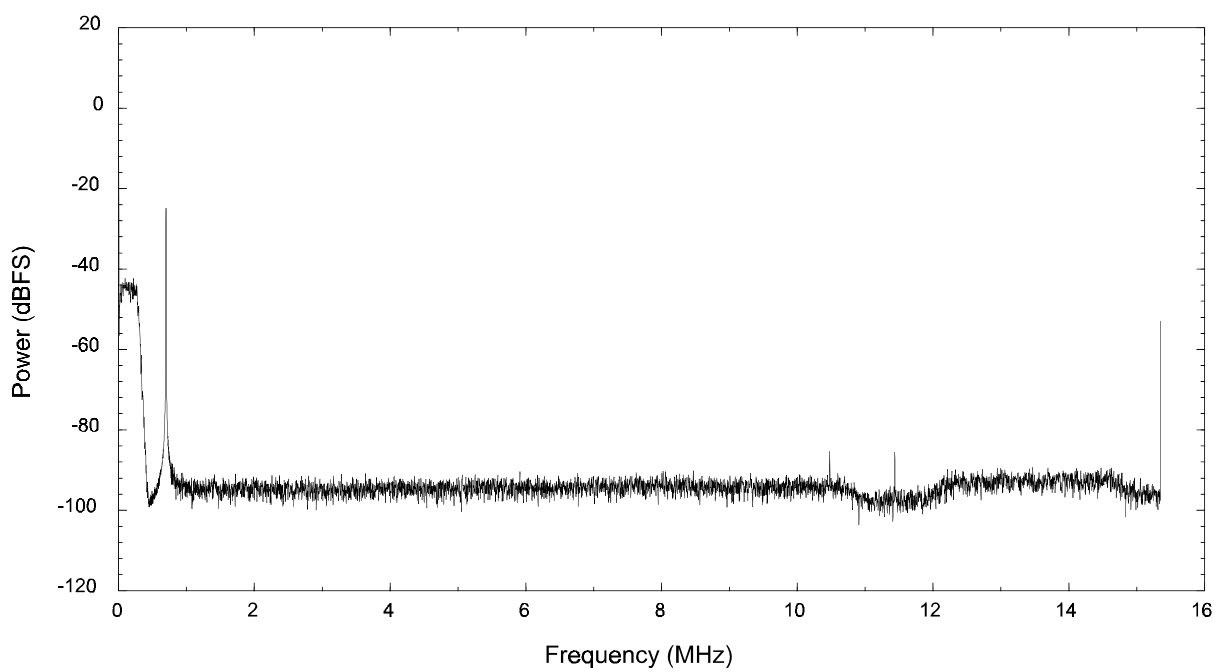


Figure 9. Averaged IF output power spectrum for an 835.02-MHz, -60 dBm RF input.

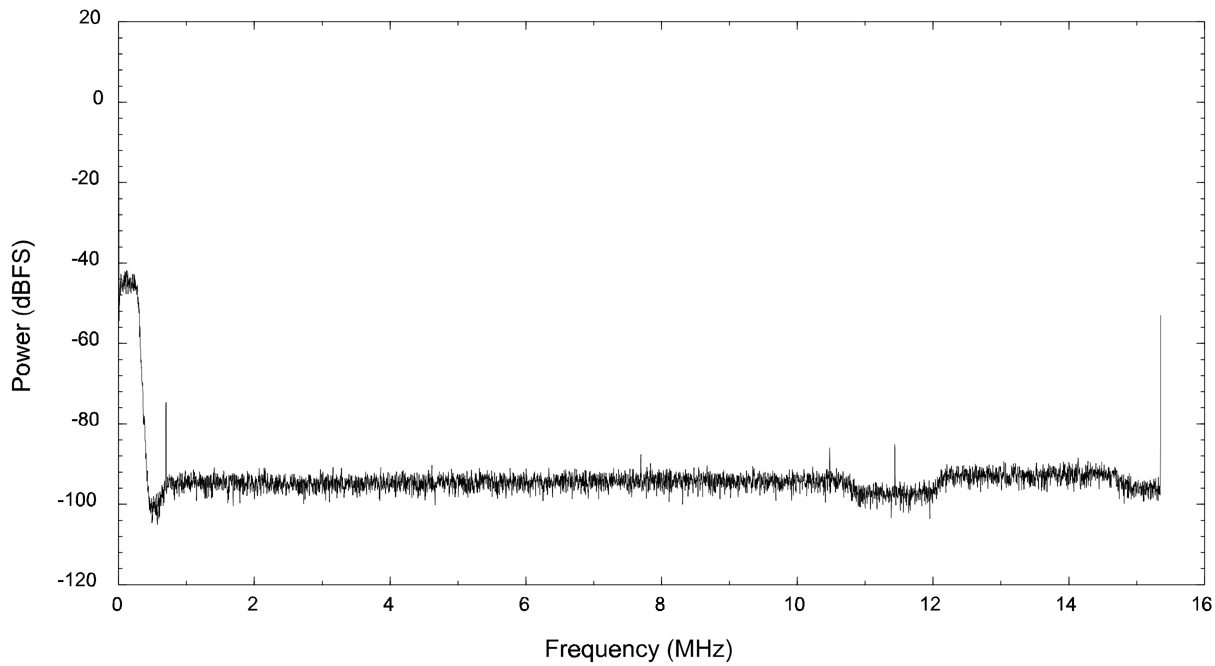


Figure 10. Averaged IF output power spectrum for an 835.02-MHz, -110 dBm RF input.

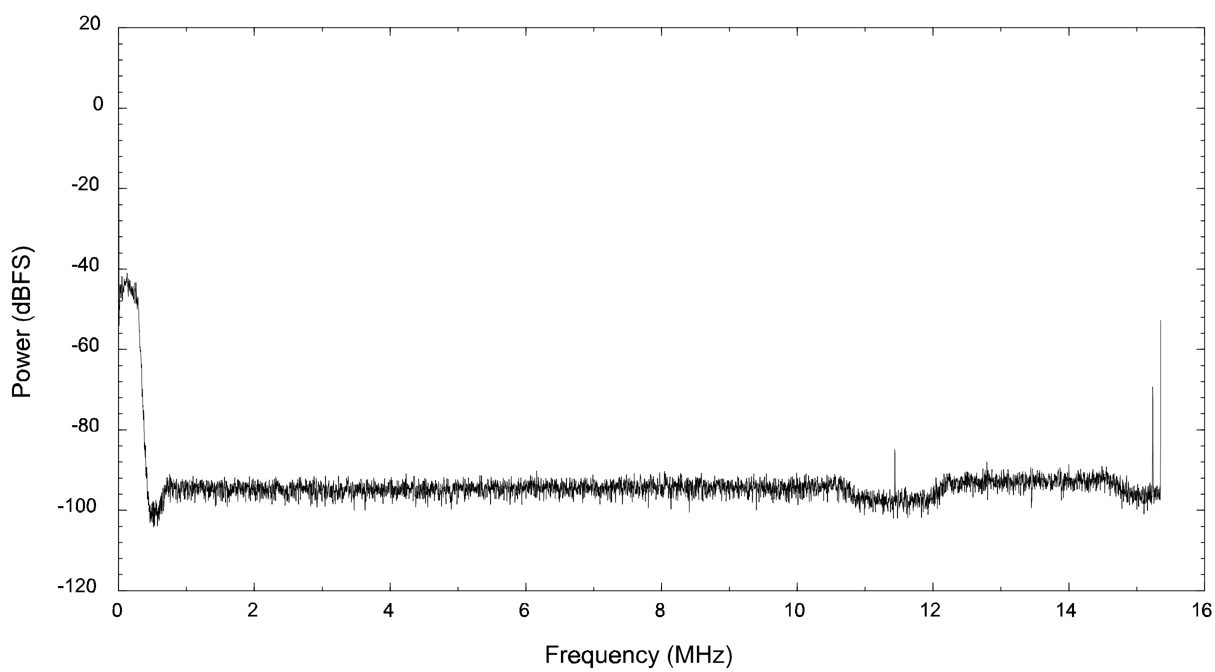


Figure 11. Averaged IF output power spectrum for the out-of-band aliasing test.

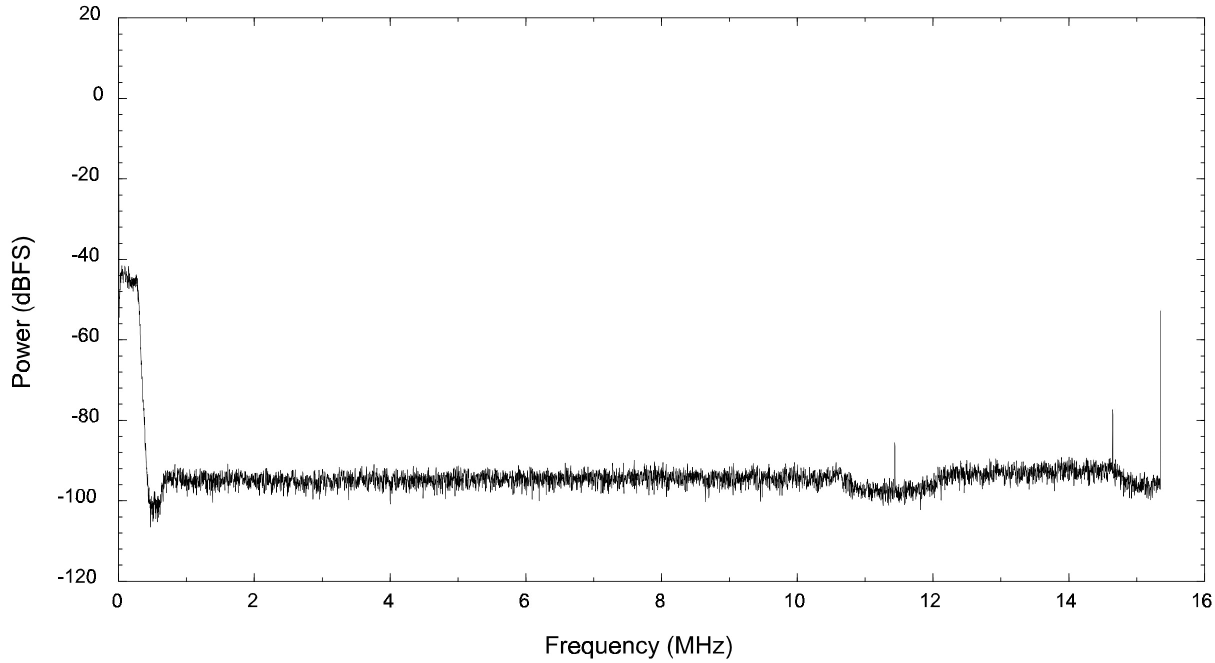


Figure 12. Averaged IF output power spectrum for the in-band aliasing test.

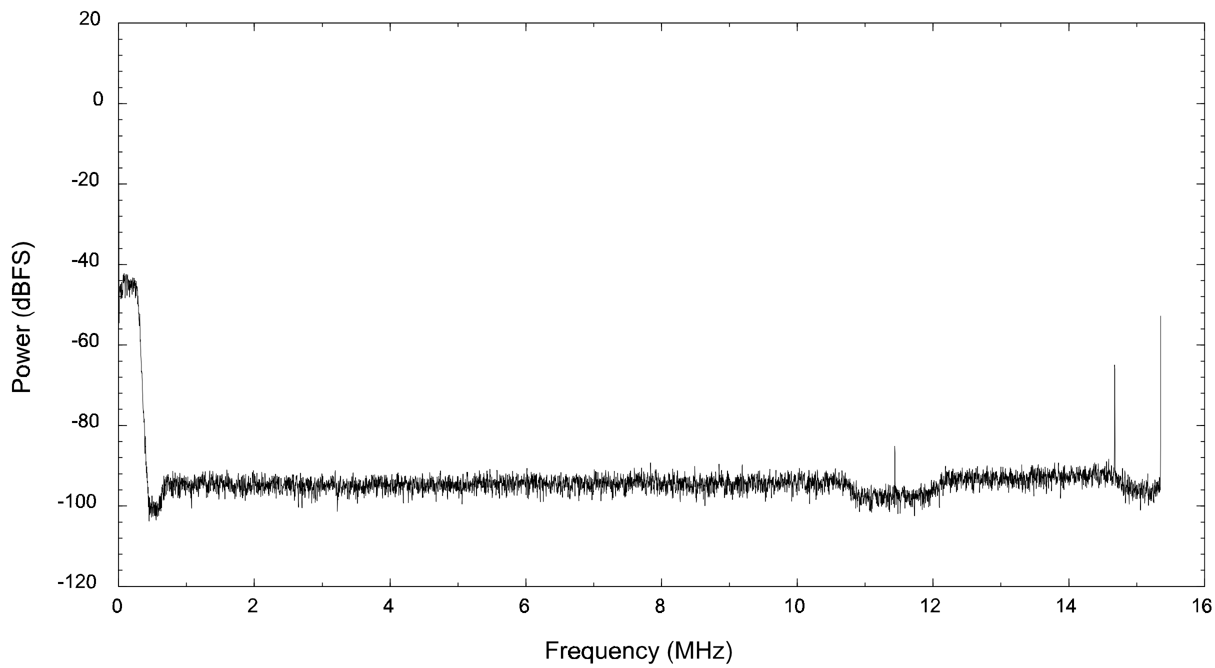
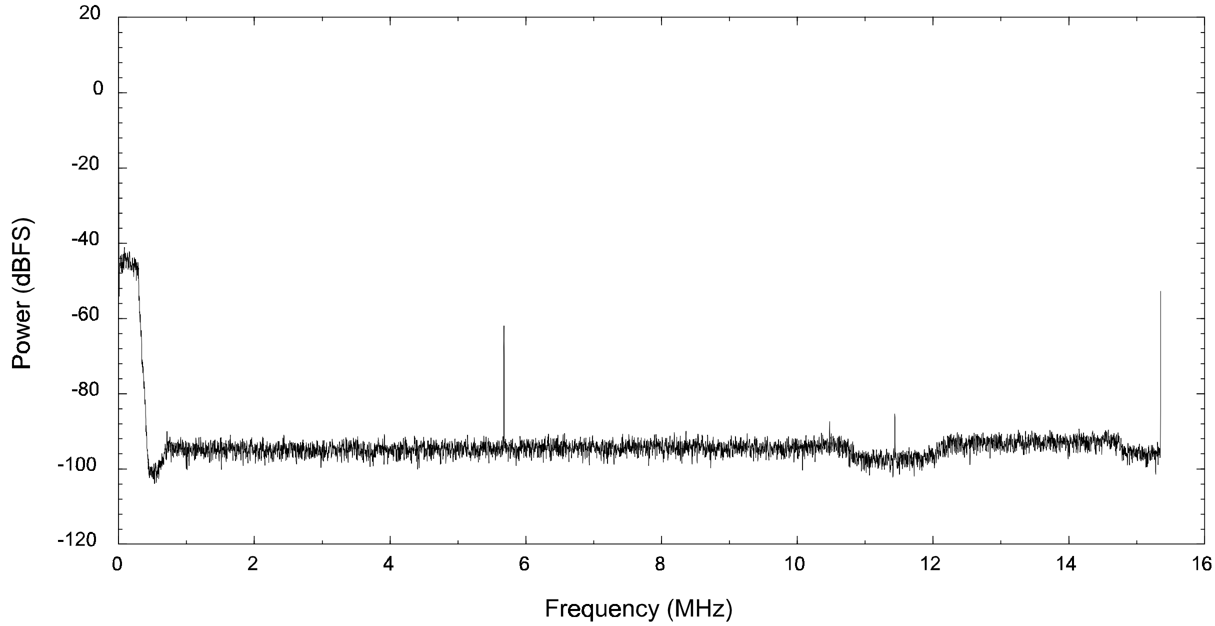
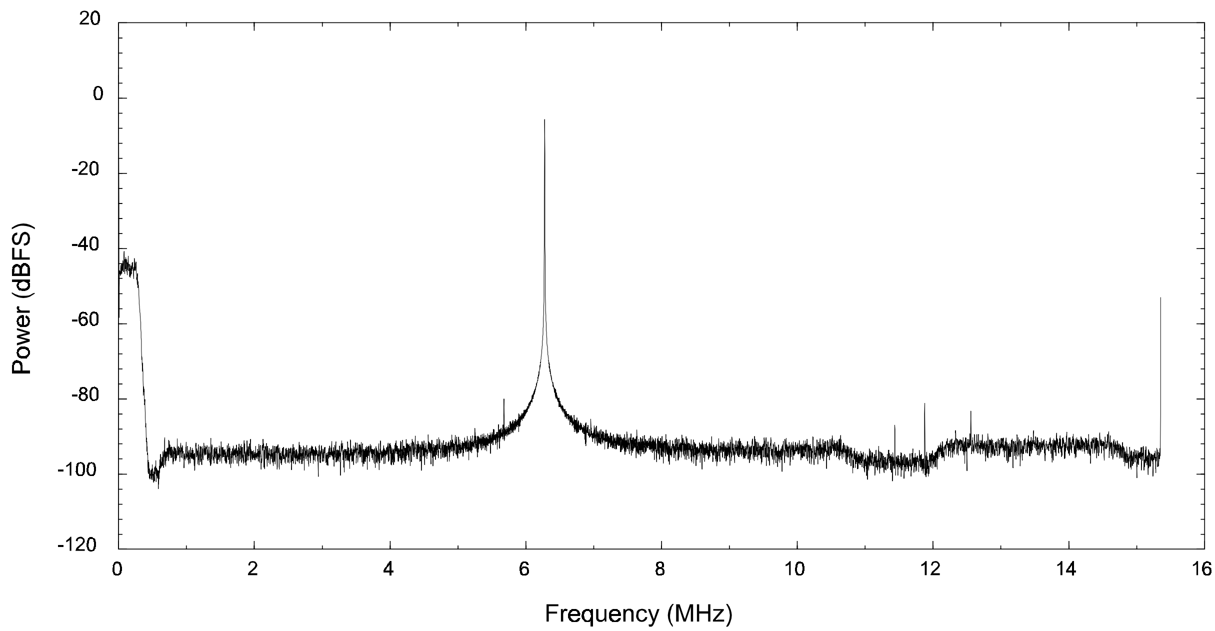


Figure 13. Averaged IF output power spectrum for the image frequency test.



(a)



(b)

Figure 14. Averaged IF output power spectrum showing a low-level desired signal in the presence of (a) no interferer and (b) a high-level (-15 dBm) interferer.

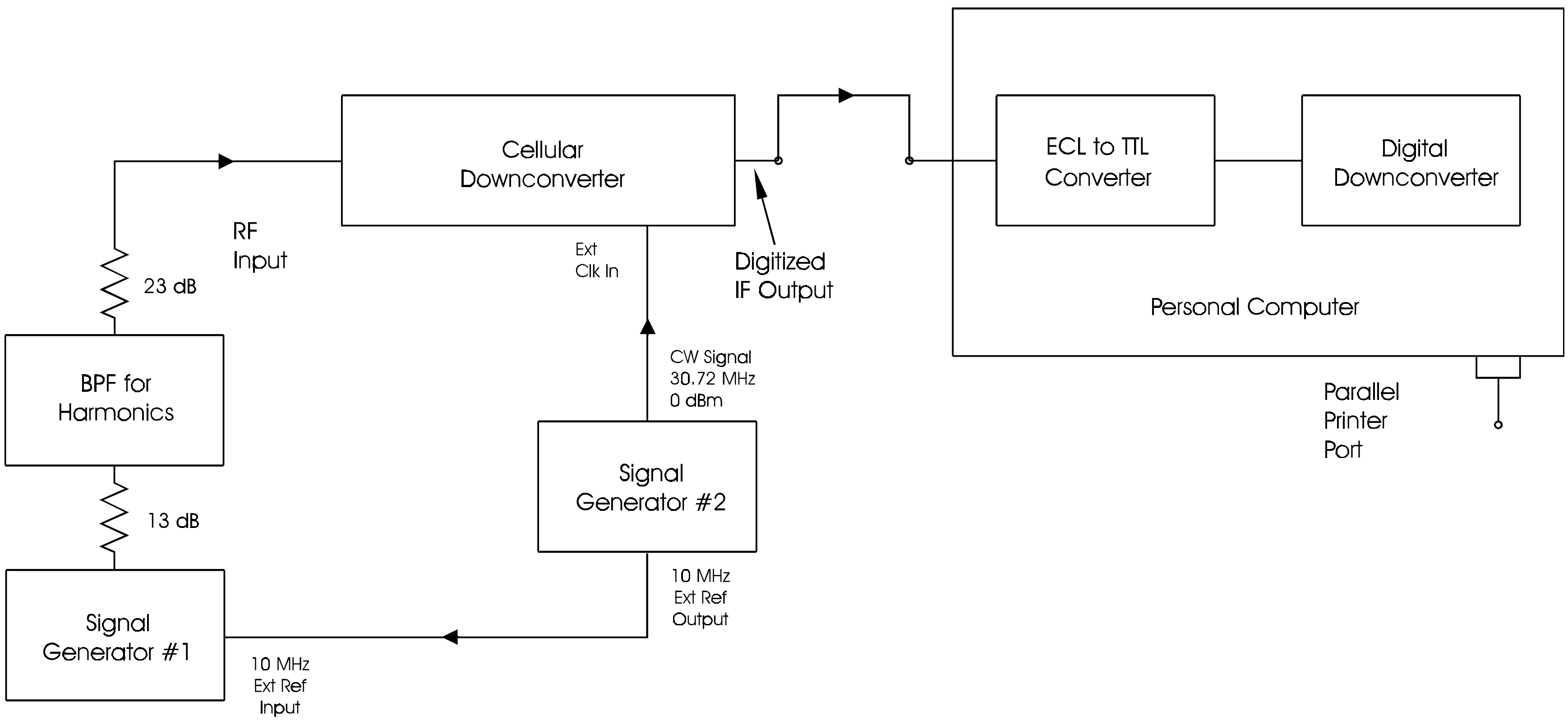


Figure 15. Test setup for observing the receiver baseband and demodulator outputs.

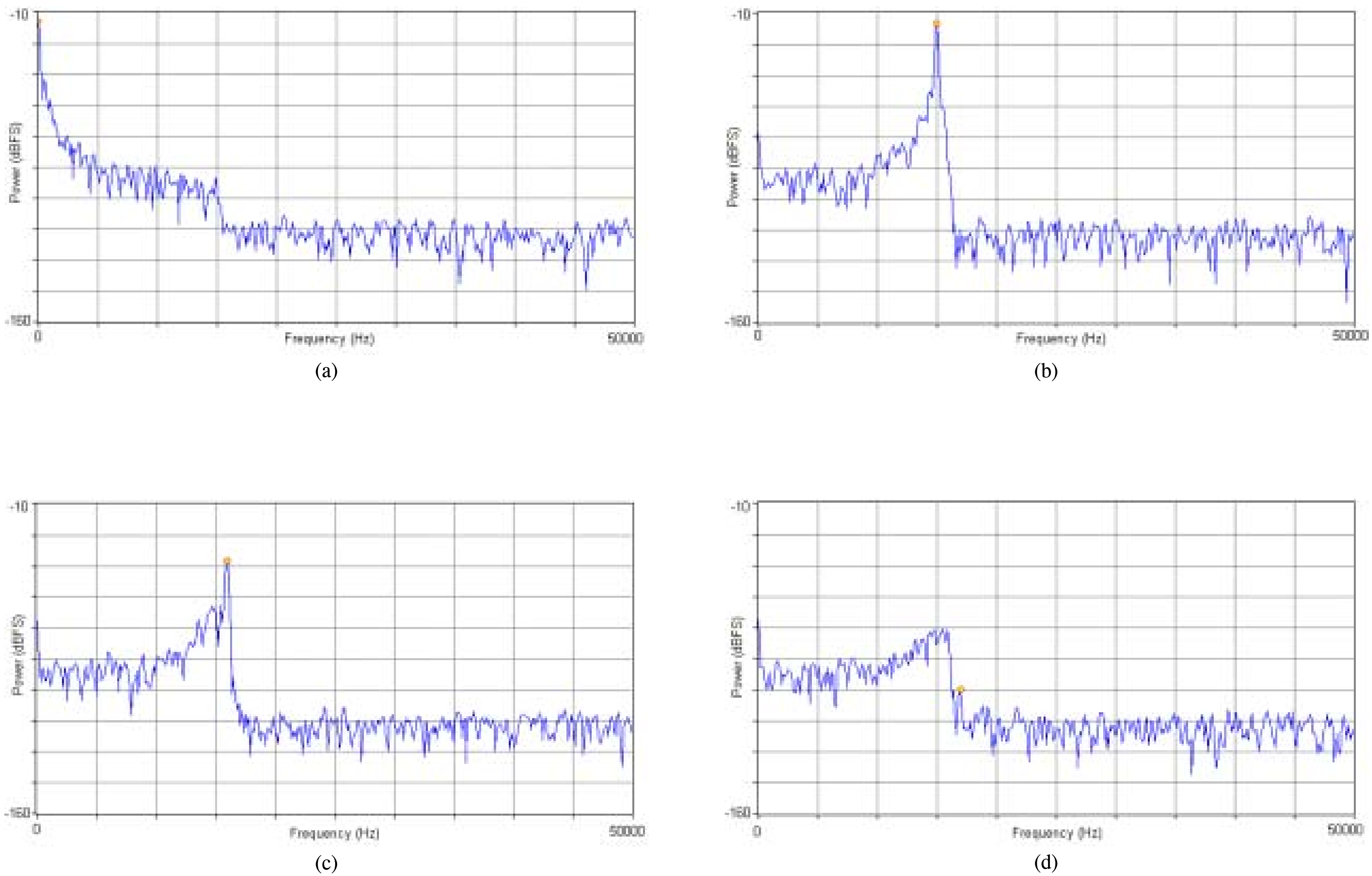
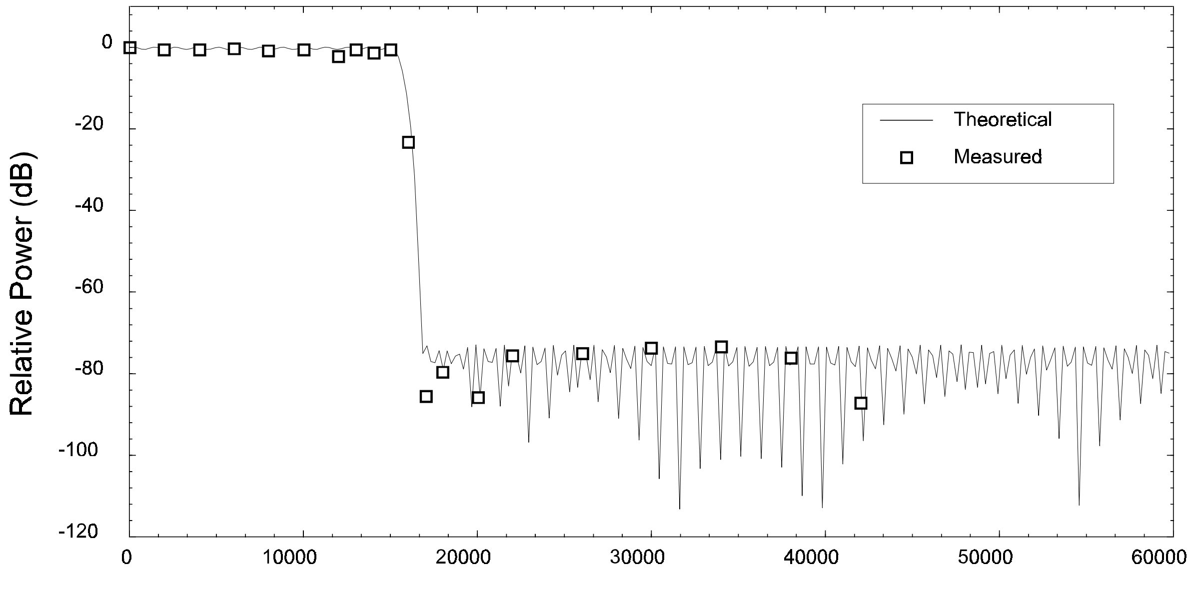
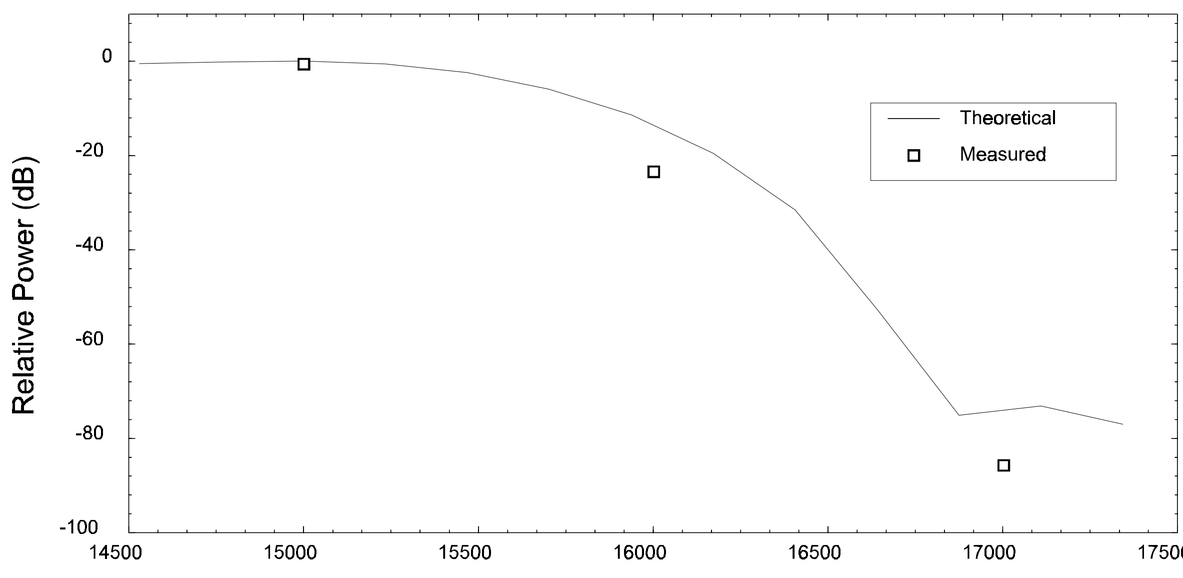


Figure 16. Example baseband output spectrum plots for determining the channel filter response at (a) 0 kHz, (b) 15 kHz, (c) 16 kHz, and (d) 17 kHz.



(a)



(b)

Figure 17. Measured and theoretical (a) passband and stopband and (b) transition band frequency response of the channel filter.

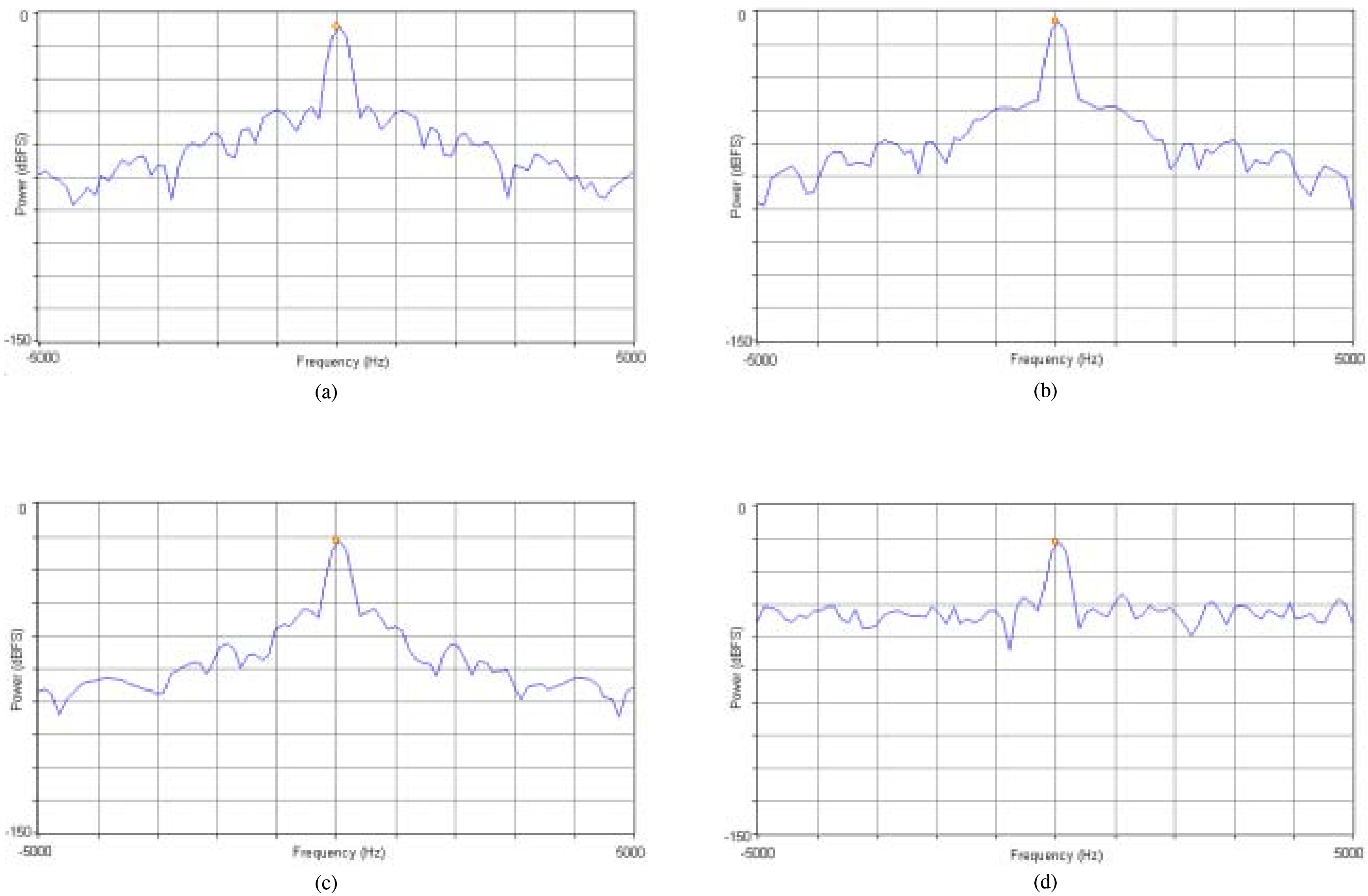
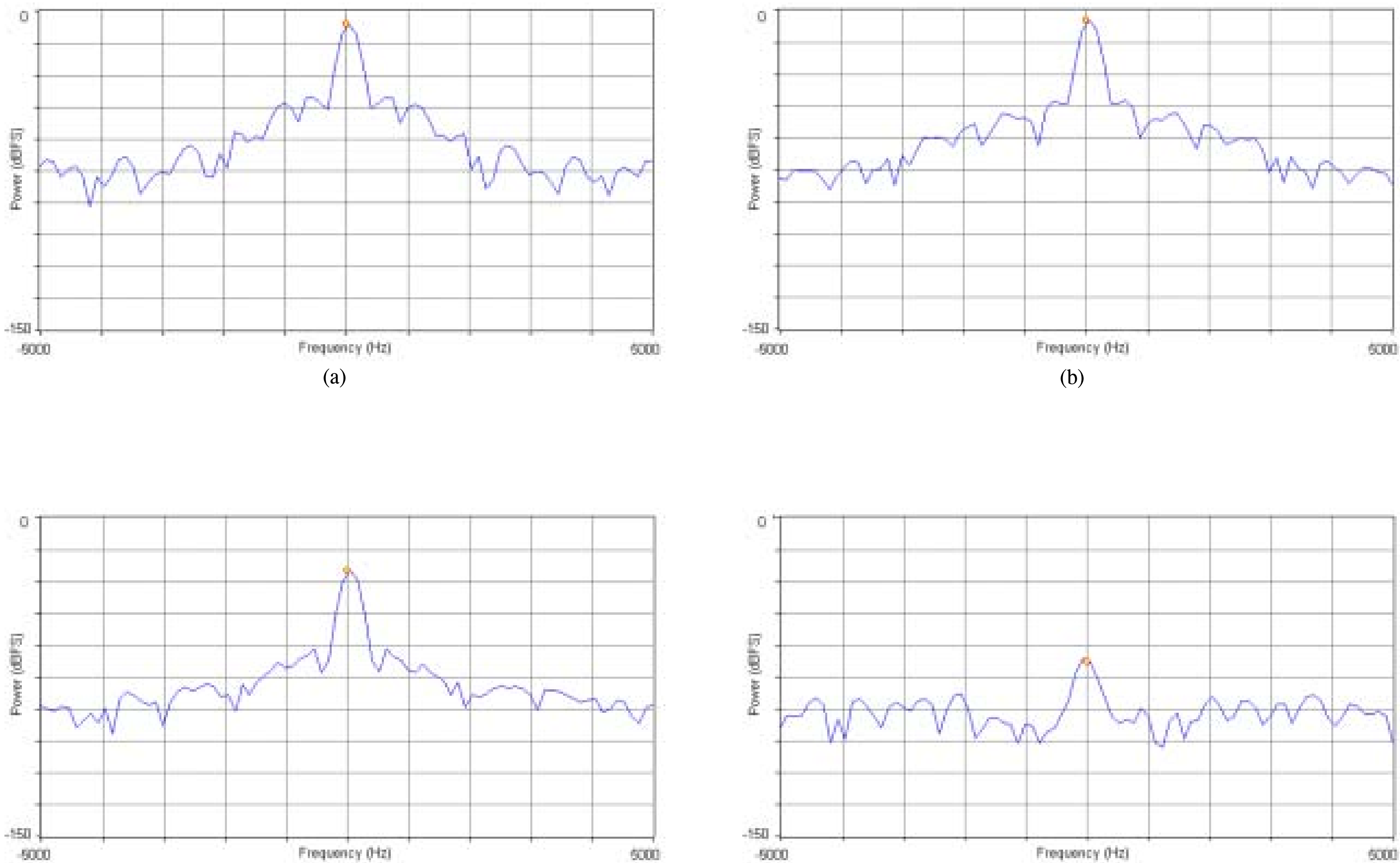
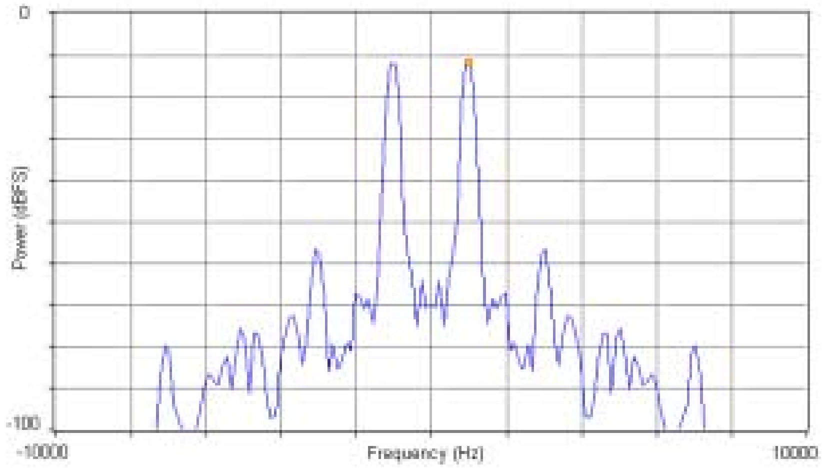


Figure 18. Output baseband spectrum with digital AGC enabled for 840-MHz RF input signal levels of (a) -15, (b) -40, (c) -60, and (d) -110 dBm.

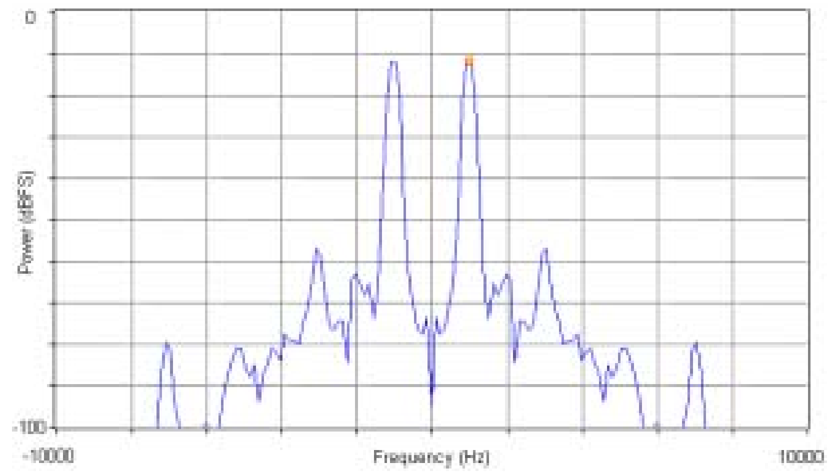


(a) (b) (c) (d)

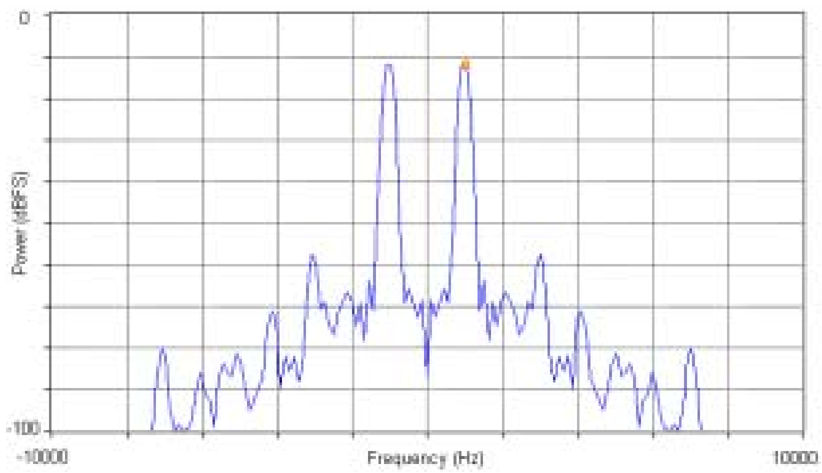
Figure 19. Output baseband spectrum with digital AGC disabled for 840-MHz RF input signal levels of (a) -15, (b) -40, (c) -60, and (d) -110 dBm.



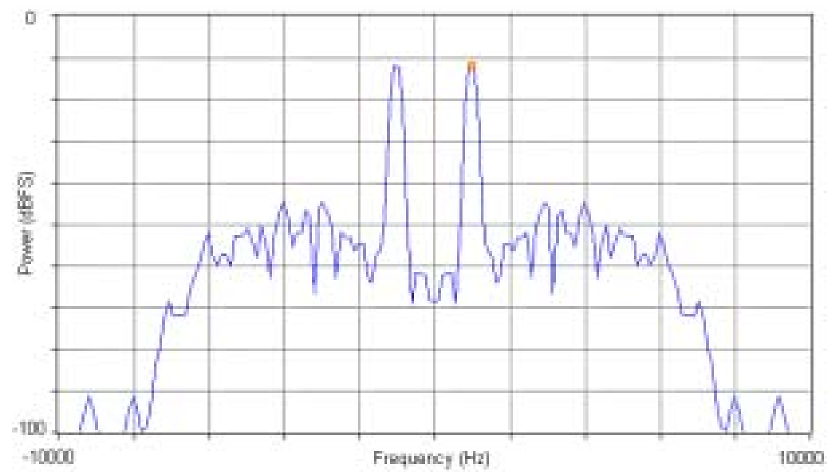
(a)



(b)



(c)



(d)

Figure 20. Demodulated output signal spectrum with digital AGC enabled for 840-MHz RF input signal levels of (a) -15, (b) -40, (c) -60, and (d) -110 dBm.

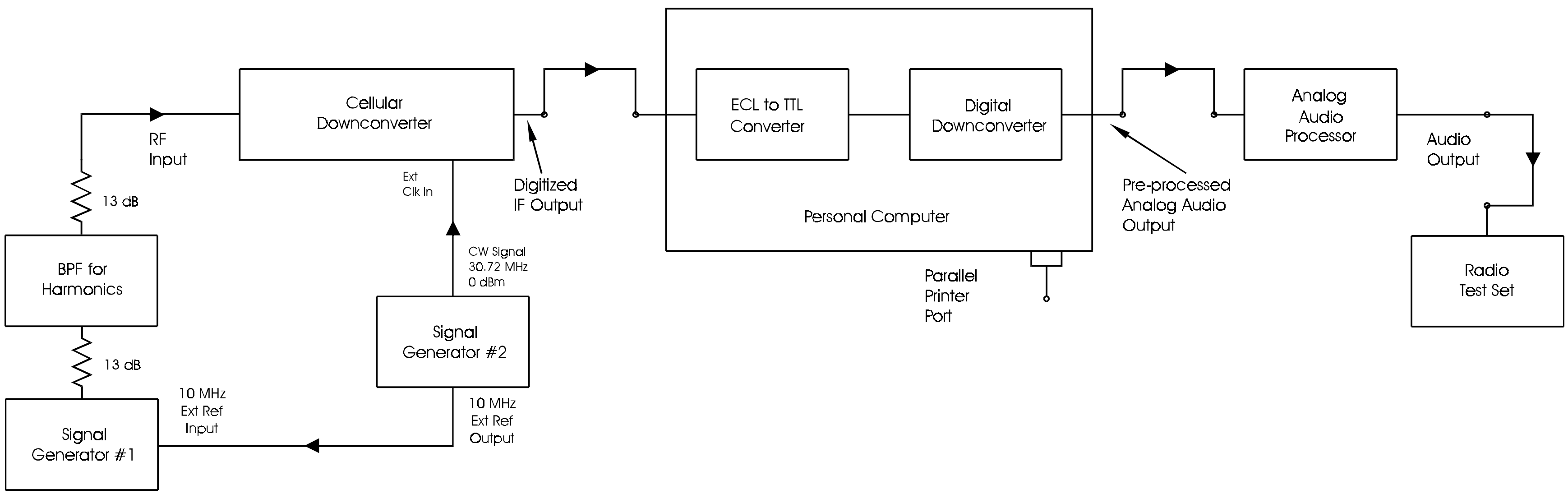


Figure 21. Test setup for the audio output channel desensitization test.

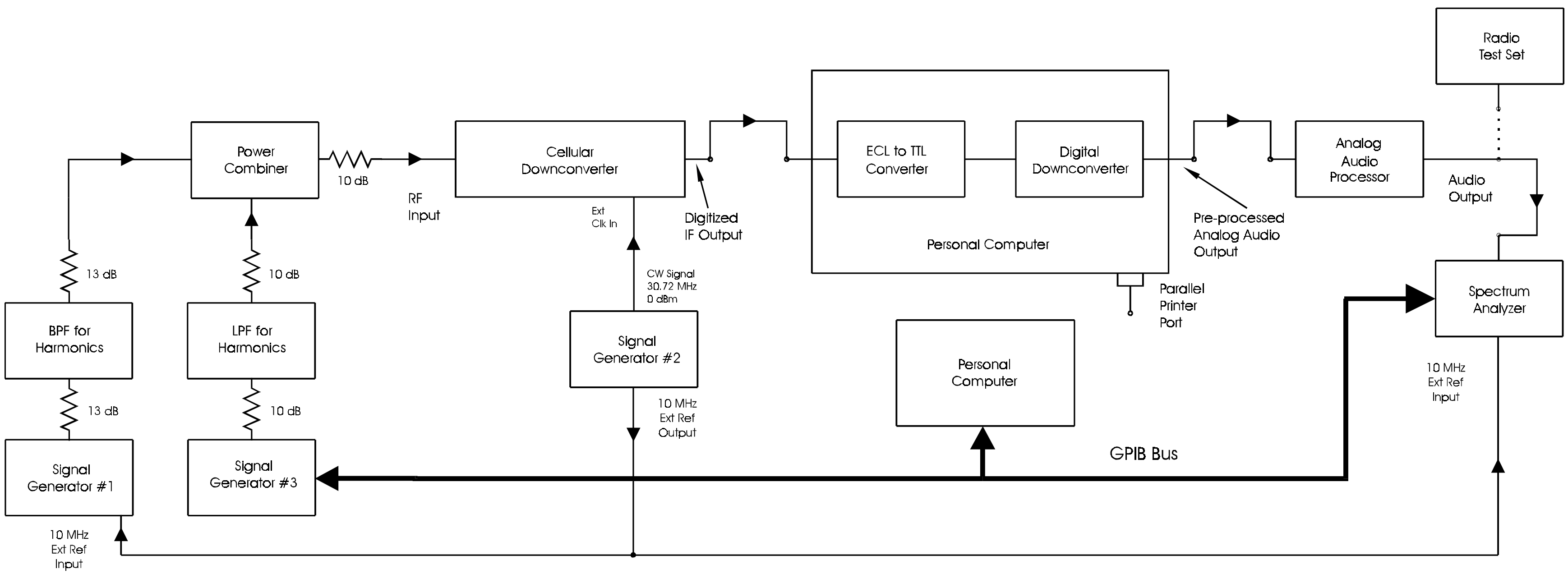


Figure 22. Test setup for the first stage of the spurious response interference test (for 0.68 - 550 MHz interfering signals).

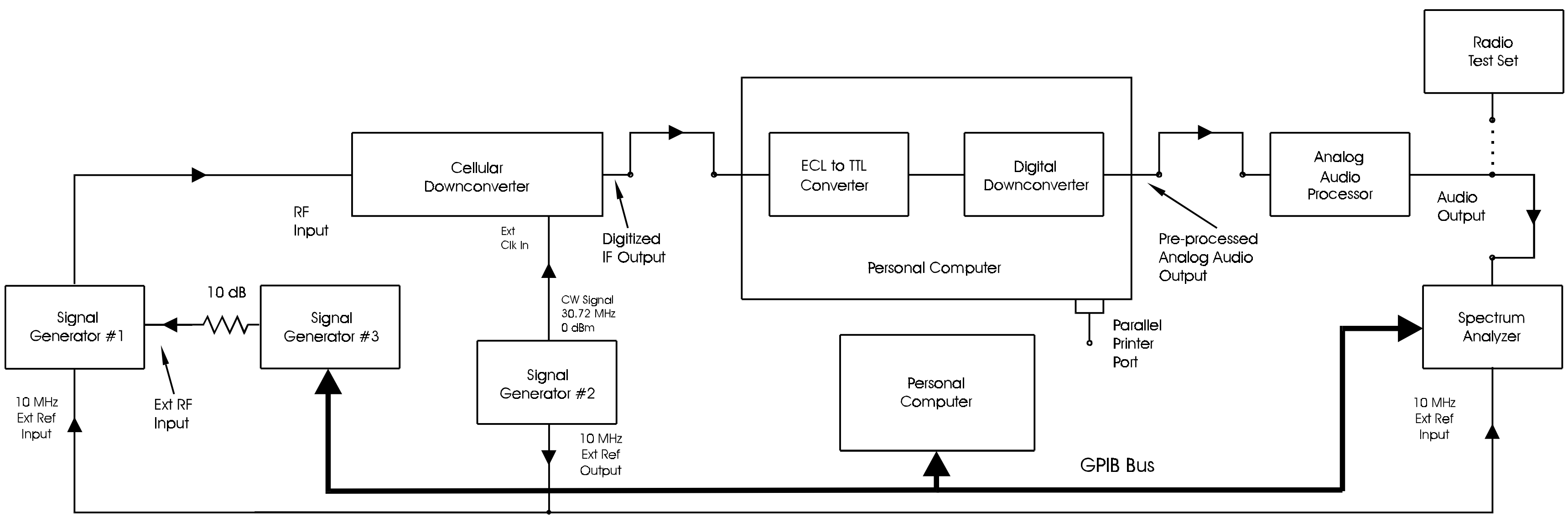


Figure 23. Test setup for the first stage of the spurious response interference test (for 1000 - 2600 MHz interfering signals).