TESTING DIGITAL RECEIVER PERFORMANCE THROUGH AN HF ENVIRONMENT SIMULATOR

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ABSTRACT

The work described in this thesis mainly consists of the development of a method for realistically simulating the HF environment and the testing of a particular digital receiver in this simulated environment. In particular, the HF environment was evaluated as to its effectiveness as a dither signal. The simulated environment was created from the limited sampling of a real HF spectrum database (the samples can be regarded as a distribution of carriers to which representative modulation needs to be added). This database was collected from an OTHR frequency management system and contains hourly samples of spectral data. The digital receiver was tested with two input signals added to representative simulated HF environments. The tests measured the IMD products and harmonics that were generated by the two input signals, with and without the HF environment present. These tests allowed the evaluation of the effect of HF environments upon digital receiver performance.

The existence of an HF environment simulator has allowed the development of a completely automatic testing system. It can perform two-tone testing in a recreated HF environment and achieves this using data from sparse samples derived from a suitable broadband spectrum monitor. The database used in the current work was derived from the Jindalee over the horizon radar frequency management system and was a good source of HF environmental data since it contains information covering several full sunspot cycles. As a result, a good set of tests can be performed using this database. If real testing in an HF environment were done it would take years to be completed since it would need to include a variety of times of day, times of the year, and different stages of the sunspot cycle. Spectrums were chosen from the database to be representative of the full range of ionospheric conditions of importance and two tone frequencies were chosen to be representative of the whole HF band of interest.

In the current research, only one digital receiver was tested in the HF environment simulator, this being the Echotek ECDR-GC214-PIC/TS. Tests were carried out to determine how the Echotek receiver operated in a variety of HF environments and to help determine strategies to operate the digital receiver in the HF environment. The environmental generator is a fairly general tool and can be used to test any sort of HF receiver. As a consequence, it could prove an important addition to the available testing facilities for HF communication and radar equipment.
STATEMENT OF ORIGINALITY

This thesis does not contain any material which has been accepted for the award of any degree or diploma in this university or other tertiary institution. Unless where stated or referenced, this work contains no material which has been previously published or written by other researchers.

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<table>
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<th>Description</th>
</tr>
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<tbody>
<tr>
<td>ADC</td>
<td>Analogue to digital converter</td>
</tr>
<tr>
<td>AM</td>
<td>Amplitude modulation</td>
</tr>
<tr>
<td>BW</td>
<td>Bandwidth</td>
</tr>
<tr>
<td>CFIR</td>
<td>Compensating finite impulse response</td>
</tr>
<tr>
<td>CIC</td>
<td>Cascade integrate comb</td>
</tr>
<tr>
<td>CW</td>
<td>Continuous Wave</td>
</tr>
<tr>
<td>DAC</td>
<td>Digital to analogue converter</td>
</tr>
<tr>
<td>DAB</td>
<td>Digital Audio Broadcasting</td>
</tr>
<tr>
<td>DC</td>
<td>Direct current</td>
</tr>
<tr>
<td>DDC</td>
<td>Digital down converter</td>
</tr>
<tr>
<td>DSBLC</td>
<td>Double sideband large carrier</td>
</tr>
<tr>
<td>DSBSC</td>
<td>Double sideband suppressed carrier</td>
</tr>
<tr>
<td>DSP</td>
<td>Digital signal processing</td>
</tr>
<tr>
<td>DSTO</td>
<td>Defence Science and Technology Organisation</td>
</tr>
<tr>
<td>FFT</td>
<td>Fast Fourier transform</td>
</tr>
<tr>
<td>FIFO</td>
<td>First in first out</td>
</tr>
<tr>
<td>FIR</td>
<td>Finite impulse response</td>
</tr>
<tr>
<td>FMS</td>
<td>Frequency management system</td>
</tr>
<tr>
<td>GPIB</td>
<td>General purpose interface bus</td>
</tr>
<tr>
<td>HF</td>
<td>High frequency</td>
</tr>
<tr>
<td>IF</td>
<td>Intermediate frequency</td>
</tr>
<tr>
<td>IIR</td>
<td>Infinite impulse response</td>
</tr>
<tr>
<td>IMD</td>
<td>Intermodulation distortion products</td>
</tr>
<tr>
<td>LSB</td>
<td>Lowest significant bit</td>
</tr>
<tr>
<td>LUT</td>
<td>Look up table</td>
</tr>
<tr>
<td>MSPS</td>
<td>Mega samples per second</td>
</tr>
<tr>
<td>NCO</td>
<td>Numerically controlled oscillator</td>
</tr>
<tr>
<td>OTHR</td>
<td>Over the horizon radar</td>
</tr>
<tr>
<td>PAD</td>
<td>Attenuator</td>
</tr>
<tr>
<td>PCI</td>
<td>Peripheral component interconnect</td>
</tr>
<tr>
<td>PFIR</td>
<td>Programmable finite impulse response</td>
</tr>
<tr>
<td>PLD</td>
<td>Programmable logic device</td>
</tr>
<tr>
<td>RTTY</td>
<td>Radio Teletypewriter</td>
</tr>
<tr>
<td>SFDR</td>
<td>Spurious free dynamic range</td>
</tr>
<tr>
<td>SINAD</td>
<td>Signal + noise + distortion to noise + distortion ratio</td>
</tr>
<tr>
<td>SNR</td>
<td>Signal to noise ratio</td>
</tr>
<tr>
<td>SSBC</td>
<td>Single sideband suppressed carrier</td>
</tr>
<tr>
<td>S/H</td>
<td>Sample and hold</td>
</tr>
<tr>
<td>VCO</td>
<td>Voltage controlled oscillator</td>
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1 Introduction

Up until now, only analogue receivers have been used in HF radar systems. With recent advances in digital technology, however, digital receivers are now an option. The performance of analogue to digital converters (ADC) and digital down converters (DDC) has shown continual improvement over the last two decades. Radar design engineers are on the verge of preferring digital receivers to the analogue variety since they are reprogrammable, deterministic, cheaper, require less maintenance and are easier to work with. This research explores some of the issues arising from the use of digital receivers in HF radar systems and develops techniques for measuring their performance in the HF spectrum.

The work described in this thesis mainly consists of the development of a method for realistically simulating the HF environment and the testing of a particular digital receiver in this simulated environment. In particular, the HF environment was evaluated as to its effectiveness as a dither signal. The simulated environment was created from the limited sampling of a real HF spectrum database (the samples can be regarded as a distribution of carriers to which representative modulation needs to be added). This database was collected from an OTHR frequency management system and contains hourly samples of spectral data. The digital receiver was tested with two input signals added to representative simulated HF environments. The tests measured the IMD products and harmonics that were generated by the two input signals, with and without the HF environment present. These tests allowed the evaluation of the effect of HF environments upon digital receiver performance.

The existence of an HF environment simulator has allowed the development of a completely automatic testing system. It can perform two-tone testing in a recreated HF environment and achieves this using data from sparse samples derived from a suitable broadband spectrum monitor. The database used in the current work was derived from the Jindalee over the horizon radar frequency management system and was a good source of HF environmental data since it contains information covering several full sunspot cycles. As a result, a good set of tests can be performed using this database. If real testing in an HF environment were done it would take years to be completed since it would need to include a variety of times of day, times of the year, and different stages of the sunspot cycle. Spectrums were chosen from the database to be representative of the full range of ionospheric conditions of importance and two tone frequencies were chosen to be representative of the whole HF band of interest.

In the current research, only one digital receiver was tested in the HF environment simulator, this being the Echotek ECDR-GC214-PIC/TS. Tests were carried out to determine how the Echotek receiver operated in a variety of HF environments and to help determine strategies to operate the digital receiver in the HF environment. The environmental generator is a fairly general tool and can be used to test any sort of HF receiver. As a consequence, it could prove an important addition to the available testing facilities for HF communication and radar equipment.
1.1 Literature Review

In the literature there is a lot written about dither and its different forms, how it affects the ADC and how the ADC operates. Different forms of dither can be injected into the ADC and studied. In [1], Carbone and Petri study the performance of two types of dither, namely stochastic and deterministic. They conclude that superior performance can be obtained by deterministic dither in terms of system resolution and accuracy at the expense of worse spectral characteristics. Gray [2] goes into further details with regard to the mathematical equations of dithered quantizers and by deriving new theorems, although he does not support his theorems with experimental results. These papers study dithered quantizers in particular but do not study how it effects ADCs. It also doesn’t study how the HF environment acts as a dithered signal.

Other papers have studied how dither and different forms of dither affect ADCs. The deviation of the ADC characteristics from the ideal straight line was evaluated for analogue and digital dither in [3]. The effect of dither peak-to-peak values and the number of PDF impulses were investigated. The papers objective was to show that digital dither can replace analogue dither. The main conclusion drawn was that for an n-bit ADC, an (n+5)-bit DAC was required. Wagdy in another paper [4] goes on to do some simulations for two dithering techniques, namely additive and subtractive types. He looks at ADC’s with no, single and multi-bit errors. His main finding was that subtractive dither out performs additive dither especially for large amplitude dither. This conclusion can be helpful in further study on implementing additional dithering techniques for this masters.

Harmonic and IMD performance of ADCs with multibit errors and additive errors were studied in [5]. Its focus was on the mathematical modelling of ADC with multibit errors and dither. The three forms of dither which it focused on were Rectangular probability density functions (PDF), Triangular PDF and Gaussian PDF. Using the model (or mathematical equations), expressions were obtained for the harmonic and IMD performance of the ADC. He produces an example using his model in which he injects a two tone half scale input into a 5-bit ADC. One of his main findings which draws particular interest is where he states, “These results clearly show that characterizing ADCs, especially the modern ADCs characterized by high speed, and high resolution, using the two-tone test, may not be reliable unless the dither in the test setup is controlled.” This statement confirms the finding in this masters, that the uncontrolled HF environment does act as a suitable dither signal although more dither needs to be added to the ADC front end to get the performance published in the ADC datasheet.

One of the several papers which does real ADC performance testing and does a comparative analysis between results with and without dither is [6]. Babu performs tests of an ADC with a single sin wave input which was combined with a pseudorandom dither source. The dither was adjusted so that the peak-to-peak amplitude was 10-45% of the full scale of the ADC input. Therefore the combined signal was operating just under the full scale of the ADC. He performs tests to a 12-bit, 5MHz and a 14 to 15-bit, 10MHz ADC. The findings of the paper was that dither improved the performance of the ADC by between 10-20dB. It appeared as though during that period everyone was testing ADCs for their dithered performance.
Two other researchers, Kikkert and Bigdeli, produced the best and most understandable paper on a performance comparison of an ADC with and without dither. Reference [7] uses a 10-bit 40MHz ADC, with a two tone input combined with a pseudorandom noise generator for the dither. The main conclusion was that additive dither makes the ADC behave much more like a conventional analogue component, such that as the input level was reduced, the harmonics also reduce. The paper was very similar to the tests which were performed in this masters, instead I used the HF environment as the dither source and I carried out extensive testing which cycled through many more combinations of two tone signal frequencies.

Kikkert and Bigdeli also produced a paper on frequency shift dither for ADCs[8]. This technique looks at comparing the performance of additive and FS dither and then both together. FS dither is not out of band dither but it’s the act of shifting the whole input signal in frequency and then digitizing, after which it is shifted back. It shows that the combination of additive and FS dither technique works extremely well, although present hardware limitations of the VCO and DAC prevent this from being used in real systems.

An application note [9] written by Brannon from analogue devices, the manufacturer of ADCs, is a fantastic source of information on how dither affects ADCs. The application note focused on a 12-bit, 41MSPS ADC, the first converter designed with a wideband, high SFDR front end. It explains the two types of distortion in depth, namely static and dynamic. Static distortion refers to the characteristics of its transfer function. Dynamic distortions are SINAD, SFDR and other forms of noise and harmonic distortion. It explains two forms of dither, namely subtractive wideband dither and out of band dither, and how it can help in reducing these errors. The application note can be useful for further investigation into including out of band dither which can be combined with the simulated HF environment input.

Mathematical modelling of the two tone testing of an ADC is shown in [10]. It sets up equations for harmonic and IMD distortion for a two tone sine wave input from a signal generator. It then compares these against two tone equations and creates equations for the SNR of a two tone input. After which the paper investigated the effective number of bits and compares these equations against equations for a single tone input. It concludes by running tests which show that the effective number of bits was a lot higher with a dual tone test, which matches the theoretical value. They make the final statement that “high precision generators are not necessary to characterize the nonlinearity of high resolution ADCs”. Here they have not considered how dither affects the ADC and what effect it has on the equations which have been created.

In [11], Vozzo uses a very similar test setup to characterize the performance of analogue receivers. Vozzo assembled the test system and ran the tests at DSTO in the group that I am currently employed. The system uses a lot of out of date technology to perform these tests. From the test system, I have only used the BPFs for my automatic test system. I also use the latest technology, in particular a leading edge digital receiver was used. Vozzo’s research focused on noise figure, third order intercept point and third order IMD product results, to characterize analogue receiver
performances. He did not investigate how dither affects the ADC, especially not how the HF environment acts as a dither source.

Through these papers they have investigated dither sources but not how the HF environment acts as a dither source. They also don’t investigate how the HF environment affects the digital receiver performance. These are the areas of research which have been covered in this research masters. Further references to related topics may be found in [12] and [13]

1.2 Thesis Structure

In the next section digital receivers will be described in detail. Firstly, digital receiver theory will be explained which includes the complex translation process, after which different analogue and digital receiver architectures will be described. The bulk of section 2 is taken up by describing the digital receiver architecture in fine detail, which includes the ADC and DDC. The ADC performance in terms of SFDR and SNR is explained first. Following this, the DDC components of the digital receiver, such as the NCO, CIC and FIR filters are described. The final part of section 2 informs the reader of what the limitations of digital receivers are. After reading section 2, the reader should understand clearly what digital receivers are, what limitations they have and how they compare to analogue receivers.

Section 3 describes the test system that was created for this research masters. Firstly, each individual component such as the combiners, attenuators, signal generators, BPF, digital receiver, and the controlling PC are explained. After this, the testing methodology is discussed. Section 4 then explains how the simulated HF environment is created.

The test results are discussed in section 5. This section compares the results of two tone testing with and without the simulated HF environment. It also explains the results that were gathered for all the different HF environments which were used in the testing. After this, section 6 concludes the body of work and explains future work for the project.
2 Digital Receivers

This chapter will inform the reader about the most important aspects of digital receivers. It will also briefly explore the conventional analogue receiver architecture and compare this to digital receiver architecture. Digital receiver components as well as the theoretical aspects will be explained in detail. Finally the positives and negatives about operating digital receivers within the HF environment will be highlighted.

2.1 Introduction

In the past analogue receivers have ruled the RF world, but since the digital revolution, digital receivers are starting to be seriously considered for receiver systems, especially HF radar systems. The performance of analogue to digital converters (ADC) and digital down converters (DDC) have been continually improving. Radar design engineers now prefer digital receivers over analogue receivers as they are reprogrammable, deterministic, cheaper, require less maintenance and are easier to work with. Since the costs of a digital receiver are so low, it will make the task of designing a huge receiver array with a digital receiver per channel feasible.

2.1.1 Digital Receiver Theory

Receivers, both analogue and digital, select a band of interest out of the signal environment. The band of interest is filtered from the rest of the signals, then converted down to bass band by the DDC using a digital mixer. The signal is then digitally processed further to obtain the desired output. An example of extracting a 6kHz band of interest centred at 20MHz is shown in Figure 1.

![Figure 1 - DDC of a 6kHz band centred at 20MHz](image)
2.1.1.1 Complex Translation

Complex translation is performed particularly well in digital receivers because the mathematics is simple, predictable and accurate. It is done by translating all analytic complex sinusoids by a frequency, resulting in the shifting of the whole spectrum by that frequency.

Every real signal (e.g. $f(t) = \sin(w_0 t)$) can be represented by two vectors rotating (with a frequency $w_0$) in opposite directions in the complex plane. Therefore two symmetric frequencies will occur in the frequency domain, one at $-w_0$ and the other at $w_0$.

Consider that $\hat{f}(t)$ is $f(t)$ shifted by 90 degrees. Then $f(t) + j \hat{f}(t)$ will cause the negative component at $-w_0$ to disappear and the component at $w_0$ to reinforce. Similarly for $f(t) - j \hat{f}(t)$, the positive component at $w_0$ will disappear and the component at $-w_0$ will reinforce.
Now consider an example where the in phase component $I$ is $f(t) = \cos(w_0 t)$ and the 90 degrees out of phase component $Q$ is $\hat{f}(t) = \sin(w_0 t)$. Therefore from the Euler identity we know that $e^{jw_0 t} = I + jQ = \cos(w_0 t) + j\sin(w_0 t)$ and $e^{-jw_0 t} = I + jQ = \cos(w_0 t) - j\sin(w_0 t)$ [16].

Now let's look at how up and down conversion works. If the signal $x(t)$, represented in the frequency domain as $X(w)$, is multiplied by an analytic signal $e^{jw_0 t}$, then the output will be $e^{jw_0 t} x(t)$ and is represented in the frequency domain as $X(w - w_0)$.

Therefore the spectrum of $x(t)$ will be shifted up by $w_0$. Similarly if $x(t)$ is multiplied by $e^{-jw_0 t}$ then the spectrum of $x(t)$ will be shifted down by $w_0$.
After down conversion the spectrum is shifted down to DC as shown in the Figure 11.
The above considerations form the foundation to the theory of the digital down conversion process.

2.1.2 Analogue Receivers Architecture

Analogue receivers have been used for nearly a century, as a result they have been so widely researched and tweaked that they are well mature in their development. Figure 12 shows a superheterodyne configuration that is commonly used, which will be explained here in more detail. It consists of an antenna which receives signals from the atmosphere, followed by a filter and low noise amplifier, first local oscillator and mixer, IF amplifier and filter, second local oscillator and mixer, filter and amplifier feeding an ADC following by digital signal processing (DSP).

![Figure 12 - Superheterodyne analogue receiver](image)

The analogue receiver system can be described by the following. The HF signal is initially conditioned by a band selection filter. This filters out anything other than the band of interest from the atmosphere. Secondly some gain may be added to the filtered signal, although not much is added otherwise signal distortion and mixer overload can result. The signal is then mixed with an analogue local oscillator to translate the frequency up/down to an intermediate frequency (IF). After this, it is filtered again to provide better selectivity and the bulk of the gain is also added via an amplifier. It is passed through the second mixer to translate the signal down to basband so that a slower ADC can be used. Further gain is then added so that the
signal at the input to the ADC is at the full ADC scale. Following this the required signal processing is done in the digital domain.

As it can be seen, analogue filters are mainly used to provide the selectivity of the signal of interest. These analogue filters require continuous tuning, are costly, bulky, heavy, and have fixed cut off frequencies. These are the main downfalls of analogue receivers.

### 2.1.3 Digital Receiver Architecture

The digital receiver architecture can be different depending on the design requirements, although the simple system in Figure 14 will be described first.

![Figure 14 - Direct digital HF receiver](image)

Analogue filtering occurs after the antenna and then the signal is amplified. The analogue filter must be highly tuneable and requires a high out of band rejection to prevent aliasing. Therefore the filter needs to be continually tweaked to get the best performance. All the gain of the system is provided at the ADC front end to utilize the ADC’s dynamic range. Because of this, both the filter and the amplifier need to be highly linear and have low noise figures.

After the analogue signal conditioning, an ADC then digitises the signal. The ADC must have a large enough analogue bandwidth and fast enough sample and hold circuitry.

The signal is then mixed with two outputs from a LO, one precisely offset by 90 degrees of phase from the other, creating sine and cosine signals. After this a low pass decimating FIR filter is used to remove any unwanted signals. At its output you can select either I and Q (complex) values or just real values, depending on the system requirements. Finally the required DSP is performed in the DSP block.
Testing Digital Receiver Performance through an HF Environment Simulator

Figure 15 - Digital Receiver

The other alternative is for the ADC to digitise the whole HF spectrum without using any analogue signal conditioning. Following the ADC a digital down converter (DDC) can be used to perform band selection all in the digital domain. This reduces the complexity of continuously adjusting analogue filters and also removes the problem of linearity and noise on the input signal. The DDC will be described further in the following sections.

### 2.1.3.1 Analogue to Digital Converter (ADC)

ADC’s along with the digital down converter (DDC) form the backbone of any digital receiver as shown in Figure 15. The ADC digitises the analogue signal which is then fed into the DDC for band selection. State of the art ADC’s typically have 14-bit resolutions and operate up to 100MSPS, making them ideal for capturing the entire HF band. They also have up to 100dB multitone spurious free dynamic range (SFDR) and 250MHz of input bandwidth[17]. A functional block diagram of an ADC is shown in Figure 16.

![Figure 16 - ADC functional block diagram[17]](image)

**2.1.3.1.1 ADC Performance**

**2.1.3.1.1 SFDR**

One of the best ways to view the ADC’s performance is to look at the SFDR. Figure 17 shows the spectrum of a 14-bit AD6644 ADC sampling at 65MHz with an input signal of 15.5MHz.
Figure 17 and Figure 18 show that when pure sinusoids are injected into the ADC, quantisation spurs will result. These occur because the frequency distribution of the quantisation noise is highly correlated with the input signal and sampling rate. The quantisation spurs are related to the input and sampling frequency by the formula:

\[ f_{spur} = \pm k f_m \pm n f_s \]  

These spurs can be reduced by adding dither (random noise) to the input signal as shown in Figure 19, thus causing the input voltage to be random. The dither can then
be removed in processing or added in a band limited fashion in an unused part of the spectrum. Figure 21 and Figure 20 shows the improvement in the output spectrum when adding dither to the input signal.

Figure 19 - Adding out of band dither[17]

Figure 20 - SFDR with dither[17]
Another limiting factor is the production of nonlinearities by components that do not behave in the same way as conventional linear devices, such as amplifiers. These occur in the front end, converter transfer function and are produced in the encoding process.

Also ADC performance is restricted by the failure of the track and hold circuitry, (or input comparators) to exhibit adequate slew rate to keep up with rapidly changing analogue inputs, which further limits the SFDR.

### 2.1.3.1.1.2 SNR

The (signal to noise ratio) SNR of the ADC can be described by the following equation:

\[
SNR(dB) = 6.02N + 1.76 [15]
\]

Where N is the number of bits of the ADC.

The noise is distributed over the entire Nyquist bandwidth from DC to \( f_s/2 \) (\( f_s \) is the sampling frequency). Therefore if the bandwidth of interest is only a fraction of the Nyquist bandwidth, then the SNR can be represented by the formula:

\[
SNR(dB) = 6.02N + 1.76 + 10\log\left(\frac{f_s}{2 \times BW}\right) [15]
\]

If a FFT of length \( M \) is being used to view the spectrum, then the frequency resolution is \( f_s/M \). Therefore the SNR will be given by:
\[ \text{SNR}(dB) = 6.02N + 1.76 + 10 \log \left( \frac{f_s \times M}{2 \times f_s} \right) = 6.02N + 1.76 + 10 \log \left( \frac{M}{2} \right) \] [15]

Where \(10 \log \left( \frac{M}{2} \right)\) is known as the processing gain, therefore the SNR can be increased by increasing the length of the FFT, but only if the SNR levels are above the LSB of the ADC. Figure 22 shows the noise floor of the ADC which can be worked out by the equation described above. Other factors contribute to the noise performance of the ADC, these include thermal noise, aperture uncertainty/jitter and comparator ambiguity.

2.1.3.2 Digital Down Converter (DDC)

The other way to view the digital receiver architecture is to view the DDC as one of the main components of the whole system.

The DDC consists of an NCO which mixes the signal down to baseband, followed by a N stage Cascade Integrate Comb (CIC) filter and two stages of decimate by two.
filtering, to remove everything else except the desired signal. At the output, a 
resampler is used to increase/decrease the number of samples to match the user’s 
rates.

The block diagram of a commonly used DDC architecture will be described.

![Figure 24 - DDC architecture][18]

Firstly the Zero Pad allows the user to clock the chip at higher rates than the input 
sample rate. The NCO mixes the signal down to bassband, where the signal is 
centred at DC. Following bassband conversion, the five stage CIC filter[18] reduces 
the sampling rate down by a programmable value nominally ranging from 8 to 
4096[18]. Some course gain can be added to boost weak signal levels before being 
filtered by a decimate by two low pass compensating finite impulse response filter 
(CFIR). The CFIR is a 21 tap[18] symmetrical filter with programmable tap weights. 
The next stage is matched filtering using a programmable finite impulse response 
filter (PFIR), a 63 tap[18] symmetrical filter. It can also convert complex output data 
to real. The final stage is the resampler which filters the PFIR output to generate new 
sample points in between the PFIR output samples. It is programmed to generate new 
samples at \( R \) times the PFIR output sample rate.

2.1.3.2.1 Zero Pad

The input samples are clocked in at the sampling clock rate. The zero pad allows 
samples to be clocked in at lower rates with respect to the sampling clock. It works 
by inserting zeros between samples. For example, if the input data rate is 20MSPS 
and the system has a sampling clock of 40MHz, then the zero pad can insert a zero in 
between samples thus increasing the input data rate up to 40MSPS.

![Figure 25 - Zero padding data points][18]

2.1.3.2.2 Numerically Controlled Oscillator

Figure 26 - NCO architecture[18]

Figure 26 shows the typical NCO used in digital receiver DDC. The tuning frequency is a 32-bit word and the phase offset is a 16-bit word[18]. $FREQ$, the tuning frequency can be set using the formula:

$$FREQ = 2^{32} \frac{F}{F_{CK}}$$

where $F = \text{desired tuning frequency}$

$$F_{CK} = \text{chip's clock rate}$$

The phase offset can be set using the formula:

$$PHASE = 2^{16} \frac{P}{2\pi}$$

where $P = \text{desired phase in radians between 0 and } 2\pi$ [18]

A positive tuning frequency should be used to down convert the signal, and a negative frequency used to up convert the signal.

Dithering on the phase input reduces NCO spur levels. Figure 27 shows the worst case spur of $–105\text{dB}$ without dither and $–116\text{dB}$ with dither[18]. As you can see an improvement of $11\text{dB}$ can result from using dither[18].

The two worse case spurs in Figure 27(b) are due to frequencies that are related to the sampling frequency by multiples of $F_{CK}/96$ and $F_{CK}/124$[18]. In this situation the rounding errors in the look up table repeat in a regular fashion, therefore concentrating the power at one frequency. Thus the spur energy is not spread across a broad range of frequencies. If these frequencies are not used, then worst case spurs will be below $–115\text{dB}$ for all frequencies[18].

The NCO peak spur levels can be viewed in Figure 28. Here the tuning frequency is scanned across a frequency range with the peak hold function turned on. This once again shows the improvement in the NCO output by using dither, as the peak spur level is reduced from $–107\text{dB}$ to $–121\text{dB}$.
2.1.3.2.3 Five Stage CIC Filter

Figure 29 - Five stage CIC decimate by N filter[18]

Figure 30 - Three stage decimating CIC filter[19]
Figure 29 shows a pictorial representation of a five stage CIC filter. The two basic building blocks to the CIC filter are an integrator and comb. Figure 30 shows a three stage CIC filter in integrator and comb blocks. An integrator is a single-pole infinite impulse response (IIR) filter with a unity feedback coefficient. It is also known as an accumulator. The power response of the integrator is a low-pass filter with a $-20\text{dB}$ per decade roll off with infinite gain at DC[20].

A comb is an odd symmetric FIR filter running at a sampling rate, $f_s$, with a rate of change $R$. $M$ in Figure 32 is called the differential delay and is usually limited to 1 or 2[18].

The output of the CIC filter is decimated by a factor $N$ with respect to the input. $N$ nominally ranges between 8 and 4096[18]. This allows the output bandwidth of the CIC filter to range from 16kHz to over 12MHz when the input rate is 100MHz[18].

The gain from the CIC filter must be compensated for in the CIC\_SCALE value. Also bit growth and rounding both need to be considered in the design of a CIC filter.
2.1.3.2.4 Course Channel Gain

Course gain can be added to boost weak signal levels before being filtered by a decimate by two low pass CFIR. The signal levels can be boosted by shifting the output of the CIC filter up by a certain number of bits. Therefore the course gain can be determined by the following equation:

\[
\text{COURSE \ GAIN} = 2^{\text{NO. OF SHIFTED BITS}} \quad [18]
\]

2.1.3.2.5 Finite Impulse Response (FIR) Filter Design in logic

The CFIR and PFIR filters are based upon basic FIR filter designs. It can take many forms depending upon what resources are available in the PLD. From these design constraints a CFIR can be designed in logic.

2.1.3.2.5.1 Parallel FIR Filters

The conventional parallel filter can be seen in Figure 33. Here 8-bit registers are arranged in a shift register configuration to provide an 8 tap FIR filter with a width \( w \).

The output can be written as the following, where \( n \) is the tap number:

\[
y(n) = \sum_{n=1}^{8} x(n)h(n) \quad [21]
\]

If the filter coefficients are symmetric around the centre value, half the number of multipliers can be used, thus using less resources in the PLD as shown in Figure 34.
Furthermore the parallel vector multiplier in Figure 34 can be optimised using look-up tables (LUTs). The parallel vector multiplier can be replaced by Figure 35. These are further discussed in [21].

After the multipliers have been replaced by LUTs the resource usage of the FIR filter in the PLD has been greatly reduced.

*This multiplier performs the function \([x(0) \times h(0)] + [x(3) \times h(3)] + [x(2) \times h(2)] + [x(1) \times h(1)]\). Both LUTs consist of 4 FPGA LEs; \(\sim 1\) LUTs.*

---

**Figure 34 - Symmetric parallel FIR filter[21]**

**Figure 35 - Multiplier using LUTs[21]**
2.1.3.2.5.2 Serial FIR Filters

So far fully parallel FIR filter types have been discussed. They are designed for maximum speed and size. However size (in the PLD) can be reduced even more by using serial FIR filters, although speed is a trade off. A comparison can be made between parallel and serial FIR filters designed in FLEX 8000A Devices in Table 1.

<table>
<thead>
<tr>
<th>Filter Name</th>
<th>Input Precision (Bits)</th>
<th>Taps</th>
<th>Size (Logic Cells)</th>
<th>Device</th>
<th>Clock Rate (MHz)</th>
<th>Clock Cycles per Result</th>
<th>Speed (MSPS)</th>
<th>MIPS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parallel</td>
<td>8</td>
<td>16</td>
<td>488</td>
<td>EPF8820A</td>
<td>101</td>
<td>1</td>
<td>101</td>
<td>1.616</td>
</tr>
<tr>
<td>Serial</td>
<td>8</td>
<td>16</td>
<td>272</td>
<td>EPF6452A</td>
<td>63</td>
<td>9</td>
<td>7.0</td>
<td>112</td>
</tr>
</tbody>
</table>

Table 1 - Comparison of FIR filter architectures in FLEX 8000A devices[21]

Serial FIR filters are very similar to parallel FIR filters, although serial FIR filters only process one bit at a time. Also they reuse the same LUT rather than using extra circuitry, therefore it can only contain one set of data. These are further discussed in detail in [21].

Figure 36 - Fully serial symmetric FIR filter[21]
2.1.3.2.5.3 Scaling FIR Filters

Larger tap size filters can be created by implementing a series of smaller filters which have been described in sections 2.1.3.2.5.1 and 2.1.3.2.5.2.

To add more bits of precision to the input, additional LUTs are added to each block. For serial designs each computation will take one more clock cycle. In parallel designs, each extra bit of precision requires one additional LUT.

![16 tap parallel FIR filter](image1)

![32 tap serial FIR filter](image2)

2.1.3.2.5.4 Decimation in FIR Filters

You can create a decimating filter by discarding any unwanted samples from the FIR filter. Therefore the filter only computes every \( n \)th result, where \( n \) is the decimation factor.

In the decimate by two filter in Figure 39, the filter runs at the output rate rather than the input rate, saving roughly 50% of the power consumed by the full speed filter. An example is shown in Figure 39.
2.1.3.2.6 The First Decimate By Two Filter (CFIR)

Following the CIC filter, the data is filtered by two stages, each decimating by two. In this section, the first stage of filtering is discussed, namely the CFIR filter. Nominally it is a 21 tap decimate by two symmetric filter with programmable 16-bit coefficients[18]. Because the filter decimates by two, a stop band must be placed in the portion of the spectrum that would alias into the signal of interest. This filter has very wide transition band specifications, therefore a 21 tap filter is good enough to provide anti-aliasing stop band rejection. It also helps provide compensation for the droop in the CIC filter’s passband and provides additional stopband rejection for the second stage PFIR filter.
Some gain will be applied to the signal by the CFIR. The $CFIR\_SUM$ in the $CFIR\_GAIN$ formula is the sum of the 21 coefficients.

$$CFIR\_GAIN = \frac{CFIR\_SUM}{65536}$$ \[18\]

### 2.1.3.2.7 The Second Decimate By Two Filter (PFIR)

The second stage of filtering is provided by a 63 tap decimate by two symmetric PFIR filter with programmable 16-bit coefficients\[18\]. Once again a stopband is placed in the area of the spectrum that would alias into the signal of interest. The PFIR filter pass band must be flat in the region of the signal of interest to leave the desired signal almost untouched. Figure 41 illustrates the pass and stop band requirements of the filter.

![PFIR filter characteristics](image)

**Figure 41 - PFIR filter characteristics** \[18\]

Gain is introduced by the filter. This can be described in the formula below, where $PFIR\_SUM$ is equal to the sum of the 21 coefficients.

$$PFIR\_GAIN = \frac{PFIR\_SUM}{65536}$$ \[18\]

Some gain is also added to the signal after filtering before being fed into the resampler. This “fine gain” is nominally a positive 14-bit integer ranging from 0 to 16383\[18\]. The fine gain is set by the formula:

$$FINE\_GAIN = \frac{FINE}{1024}$$ \[18\]

### 2.1.3.2.7.1 Complex to Real Conversion

The PFIR can be used to convert from the complex format to a scalar format. A low pass filter is used by the PFIR so that the filtered signal resides from $-F_{PFIR}/4$ to $F_{PFIR}/4$, where $F_{PFIR}$ is the sample rate of the data at the filter input. Although in this mode the filter does not decimate by two, therefore the input sample rate is the output sample rate of the filter. The signal is then up converted by $F_{PFIR}/4$ and thus it resides from 0 to $F_{PFIR}/2$, and the imaginary part is discarded.
2.1.3.2.8 Resampler

The resampler block diagram is shown in Figure 42. It consists of an input buffer, an interpolation or resampling filter, followed by a final shift block.

\[ N_{DEC} \] is the decimation factor and \( N_{DELAY} \) is the interpolation factor. The ratio of the two factors (\( \frac{N_{DELAY}}{N_{DEC}} \)) sets the resampler’s sampling rate change[18]. The input buffer accepts data from all the different channels (if multiple channels are used) and adds them as necessary. It also serves as a FIFO between the channels and the resampler, and acts as a delay line for the interpolation filter. The input buffer resources can be configured into different segments depending upon how many channels are used.

The interpolation filter firstly pads the data with zeros by a factor of \( N_{DELAY} \) and then filters (\( QTAP \) is the filter length) the zero padded data. After this, the signal is then decimated by a factor of \( N_{DEC} \). The resampling ratio is determined by the following formula.

\[
RATIO = 2^{26} \left( \frac{N_{DEC}}{N_{DELAY}} \right) = 2^{26} \left( \frac{INPUT \ SAMPLE \ RATE}{OUTPUT \ SAMPLE \ RATE} \right) [18]
\]

Figure 43 shows the three spectral plots for the steps required to resample the data. The first plot shows the data after it has been zero padded. \( F_s \) is the sample rate into the resampler and \( N_{DELAY} \times F_s \) is the sample rate after zero padding. The second spectrum shows the signal after the \( QTAP \) filter has been applied to it. On the same plot the \( QTAP \) frequency response is shown. The last spectrum shows the final result after decimating by \( N_{DEC} \).
2.1.4 Digital Receiver Limitations

It is hard to compare a digital receiver to an analogue receiver because it really depends upon the design requirements of the system. Therefore only in broad terms will the comparison be made between the two variants of receivers. As a result, exact performance figures will not be mentioned for analogue and digital receivers.

Band selection is extremely good in most analogue receivers and is provided by high quality analogue filters. Such analogue filters are also required in digital receivers for environmental filtering to protect the ADC front end and to prevent aliasing. Digital filters cannot be used for these purposes. The S/H and DDC process can be performed in analogue or digital. Certainly digitally it is easier because digital components don’t need to be regularly tuned unlike analogue components and the values throughout the digital process are also deterministic. What limits digital DDC is the PLD sizes and the cost of these chips, although these are both improving with time.

The input signal BW is a limiting factor for current digital receiver technology. This is due to the sample and hold circuitry on the ADC. State of the art analogue receivers out perform digital receivers in this area. SFDR is also better for analogue receivers, although BW is a trade off.

Figure 43 - Resampler's spectral response[18]
3 Design of the Digital Receiver Test System

It is impossible to test the performance of a direct digital high frequency (HF) receiver in all possible environments since these take place over an eleven year cycle. It is possible, however, to test in simulated HF environments. This allows for a comprehensive test of the effectiveness of the HF environment as a dither signal. The simulated environments are created from data derived from a real HF spectrum database. This database was collected using the Frequency Management System of an over the horizon radar (OTHR) and contains hourly samples of spectral data stretching over several sunspot cycles.

The HF spectrum has changed in the past thirty years from predominantly being constructed from AM, RTTY and CW signals. In today’s environment the spectrum consists of mainly SSB, digital and DAB signals. Since the simulated HF environment was constructed using AM techniques, an area of further study could be reconstructing the spectrum using current broadcasting techniques (i.e. a lot of DAB in the broadcast bands and more SSB and digital links). The methodology I have adopted allows for a change in the types modulation, but assumes the power distribution in the spectrum remains roughly the same in a future sunspot cycle.

The digital receiver was tested with two input signals added to several simulated HF environments. This permitted the measurement of intermodulation distortion (IMD) products and harmonics that were generated by the two input signals, with and without the HF environment present. From this we determine the effect of the different HF environments upon the digital receiver performance.

3.1 System Description

![Figure 44 - Test signal setup](image-url)
The test system consisted of a digital receiver capturing the intermodulation distortion (IMD) products of two input signals added to a simulated HF environment, as seen in Figure 44.

The two input signals were filtered through a band pass filter (BPF) to suppress any harmonics that were generated by the signal generators. After the BPF’s, the signal was attenuated (by 17dB) to prevent any IMD products being created by the signals’ interaction with each other in the signal generators. They were then combined using a resistive combiner. This composite signal was then resistively summed with the simulated HF environment which was fed through a 20dB attenuator to reduce IMD products. These are potentially created through interaction with the two tone signal in the signal generator front end. Although there is a potential in the environmental generator to cause artificial spectrum through the low level of harmonic suppression (only 30dB), the higher signal levels of the fundamentals will be representative of reality and the harmonics will be no more than the level of variability that could be expected in normal conditions. Consequently, the harmonics will not significantly alter the expected results. The methodology is still valid and future improvements in signal generator technology will lead to improvement in the effectiveness of the approach.

3.1.1 Resistive Combiners

The combiners were designed so that they would match the impedance of 50 ohms at the three ports. A 6dB loss results from the use of these combiners.

![Figure 45 - Resistive Combiner](image-url)
3.1.2 Attenuator Properties

The attenuator suppresses distortion products by the multiple of its order. For example, second order distortion will be suppressed by twice as much as the attenuator value. It is similar for third order distortions, where the suppression will be three times the attenuation. This is shown in Figure 46.

![10dB Attenuator Characteristics](image)

**Figure 46 – 10dB Attenuator Characteristics**

3.1.3 Signal Generators

The two sources which provide the test signals for the two tones are both Agilent E4423B type signal generators. The most important signal specifications are listed in Table 2. A more comprehensive list is given in the datasheet for the E4423B. The E4438C which is very similar to the E4423B, provides I and Q generation which is needed to create the HF environments.

<table>
<thead>
<tr>
<th>Specification</th>
<th>E4423B Signal Specifications[22]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Attenuator hold level range</td>
<td>23dB</td>
</tr>
<tr>
<td>Level accuracy</td>
<td>±0.5dB</td>
</tr>
<tr>
<td>Harmonics</td>
<td>-30dBc</td>
</tr>
</tbody>
</table>
3.1.4 Band Pass Filters

From section 3.1.3 it is evident that the signal generators have harmonics at 30dB under the main signal. This is a problem when trying to perform two tone testing because ultimately only the main signal with no harmonics is wanted. Therefore band pass filters are used to suppress the unwanted harmonics.

The band pass filters used for this project are controllable via GPIB. The GPIB allows the user to switch between different filters depending upon the input
frequency. The different band pass filters are listed in Table 3. Each of the filters has an out of band rejection better than 60dB as shown in Figure 49, Figure 50, Figure 51 and Figure 52. The band pass filters were chosen over low pass filters and the simpler polynomial variant because the hardware was already available from a previous two tone testing system, and that they are switchable via GPIB which is essential for the automatic test system. The filter further suppresses the signal generator harmonics (at -30dBc) down below 90dB. At least an extra 10dB suppression would have ideal as the ADC has a SFDR with dither of about -100dBc. Certainly for future work I would suggest building better band pass filters which can be controllable over GPIB, so that the suppression is far greater than 100dB and that the filter remains fully automatic.

### Table 3 - Band pass filter properties

<table>
<thead>
<tr>
<th>Filter Number</th>
<th>Frequency Range (MHz)</th>
<th>Out of band rejection (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4-7</td>
<td>61</td>
</tr>
<tr>
<td>2</td>
<td>6.5-13</td>
<td>61</td>
</tr>
<tr>
<td>3</td>
<td>12-24</td>
<td>61</td>
</tr>
<tr>
<td>4</td>
<td>23-45</td>
<td>61</td>
</tr>
</tbody>
</table>

*Figure 49 - BPF Number One Frequency Response (4-7MHz)*
Figure 50 - BPF Number Two Frequency Response (6.5-13MHz)

Figure 51 - BPF Number Three Frequency Response (12-24MHz)
3.1.5 Controlling PC

To perform efficient multiple two tone testing with a simulated HF environment, an automatic system was designed. The system consisted of a PC which communicates with the Digital Rx PC via an Ethernet cable, and the signal generators setup via GPIB as shown in Figure 53.

![Figure 53 - Test System Setup](image)

The controlling PC performs the initialisation of the signal generators and Digital Rx PC. It then sets up the first round of signals on the signal generators, after which it controls the digital receiver PC to capture the data at the two tone, IMD and harmonic frequencies. This process continues until all the required tests have been completed.
3.1.6 Digital Receiver Card

The digital receiver card used in this project was Echotek Corporation’s ECDR-GC214-PCI/TS, part number 12-0043/CC398. It incorporates two channels with a 14 bit 65MHz A/D converter (AD66440) on each. For this project only one channel was required. The ADC’s typically have SFDR’s in excess of 90 dBFS, as shown in the digital receiver tests in Figure 57 and Figure 58.

After the ADC process, the signal is down converted using Graychip’s GC4016. This chip does the necessary filtering and decimation using CIC, CFIR and PFIR filters which are described in section 2.1.3.2.

The features of the Echotek card are listed below. For further information the reader should consult the datasheet[24].

- Four digital receiver channels on a PCI short card.
- Two analogue inputs at IF’s greater than 200MHz. Uses AD6644 (14 bit, 60MHz) ADC’s.
- Receiver channels can be combined for wider bandwidth.
- Synchronization control of multiple receiver and transmitter boards.
- PCI short cards.
- PCI bus revision 2.1 compliant.
- External clock input and optional on board oscillator.
- FIFO depth selectable from 4k complex samples to 128k complex samples per receiver channel.
Testing Digital Receiver Performance through an HF Environment Simulator

- Decimation range:
  - 32 to 16384 individual channel mode.
  - 16 to 8192 paired channel mode.
  - 8 to 4096 quad channel mode.
- On board resampler and,
- 16 or 20 bit output modes.

Figure 55 - ECDR-GC214-PCI/TS Block Diagram[24]

Figure 56 - ECDR-GC214-PCI/TS Functional Description[24]
A/D Sample Rate = 69.333 MHz
Down-Convert Center Frequency = 12.8 MHz
Output Sample Rate = 8.66625 MHz
Input Signal: 12.89645 MHz @ + 2 dBm
Data: 16 Bit Complex
Filtering: CFIR & PIIR 80% BW. No Resampler.

Figure 57 - ECDR-GC214-PCI/TS Dynamic Performance Data 1[25]

A/D Sample Rate = 69.333 MHz
Down-Convert Center Frequency = 12.8 MHz
Output Sample Rate: 4.333 MHz
Input Signal: 12.89645 MHz @ + 2 dBm
Data: 16 Bit Complex
Filtering: CFIR & PIIR 80% BW. No Resampler.

Figure 58 - ECDR-GC214-PCI/TS Dynamic Performance Data 2[25]
3.2 Testing Methodology

3.2.1 Two Tone Tests

One of the most common ways to test the performance of any nonlinear device is via two tone testing. Two tone testing works by inputting two signals at known frequencies and amplitudes, and measuring their interaction with each other. This interaction causes intermodulation distortion (IMD) products. The signal harmonics were also measured. By examining the results of the two tone testing, the user can determine what impact the signal interaction has on the equipment.

The IMD and harmonic products that were measured for these two tones are those that are typically most significant (highest magnitude). The frequency of these are shown below:

\[
\begin{align*}
2 \times f_1 & \quad \text{(2nd harmonic)} \\
2 \times f_2 & \quad \text{(2nd harmonic)} \\
3 \times f_1 & \quad \text{(3rd harmonic)} \\
3 \times f_2 & \quad \text{(3rd harmonic)}
\end{align*}
\]

When \( f_2 > f_1 \):

\[
\begin{align*}
|f_1 - f_2| & \quad \text{(2nd order IMD)} \\
f_1 + f_2 & \quad \text{(2nd order IMD)} \\
|2 \times f_1 - f_2| & \quad \text{(3rd order IMD)} \\
2 \times f_2 - f_1 & \quad \text{(3rd order IMD)} \\
2 \times f_1 + f_2 & \quad \text{(3rd order IMD)} \\
2 \times f_2 + f_1 & \quad \text{(3rd order IMD)}
\end{align*}
\]

The interaction with the clock harmonics could have been investigated and can be done in future work. The harmonic frequencies due to the 65MHz clock are 130, 195, 260, 325, 390, 455, 520MHz and higher.

Two tone frequencies were chosen to best represent a complete test. The first tone was held at a fixed frequency and the second tone stepped on a logarithmic scale either side (eg \( \pm 100\text{Hz}, \pm 1k\text{Hz}, \pm 10k\text{Hz}, \pm 100k\text{Hz}, \pm 1\text{MHz}, \pm 10\text{MHz} \)). Once the IMD and harmonic products were measured for these combinations, the first tone was moved by roughly 1MHz and the test repeated. The first tone frequencies were generated by adding a randomly chosen decimal fraction to each integer MHz as seen in Table 4. The full set of frequencies that were selected are shown in Appendix H.

<table>
<thead>
<tr>
<th>Main Freq (MHz)</th>
<th>Random No</th>
<th>Test Signal Freq (MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>0.665718685</td>
<td>5.665719</td>
</tr>
<tr>
<td>6</td>
<td>0.597728208</td>
<td>6.597728</td>
</tr>
</tbody>
</table>
3.2.2 Two Tone Tests within a simulated HF environment

The two tone input frequencies are shown in Appendix H. The frequency resolution of the HF environment depends on the sample length and replay frequency. To increase the readability of the IMD and harmonic products, the spectrum was reduced to thermal noise at and around these frequencies in order to ensure the readability of the desired signal. The filtering was done after the HF environment creation process in the frequency domain, using MATLAB, before the HF spectrum was loaded into the signal generator. This process is described in more detail in section 4.1.

3.2.3 Comparing Two Tone Tests with and without a simulated HF environment

Once the data for all the two tone frequency pairs was gathered, it was compared against data with only the two tones present, without the HF environment. This shows the improvement or degradation of the performance of a digital receiver, in particular its performance against a realistic HF environment. The results are discussed in detail in section 5.
4  HF Environment Creation

4.1  Simulated HF Environment Creation Process

The Jindalee OTHR facility located at Alice Springs measures the HF environment at every hour of the day with a 2kHz frequency resolution.

The data shows that the HF environment changes greatly by the time of day and by the season of the year. As a consequence, the tests used simulated HF environments for a number of times of the day and different seasons of the year. It is also known that the HF environment changes properties from year to year in response to the number of sunspots that form on the sun[26] as shown in Figure 60. As a consequence, high and low sunspot years were chosen, those being 1997 and 2001. The full list of HF environment data times that were used for this test is shown Table 5. All eight days which were chosen showed no flares or distortions and therefore its spectrum represented an average day.

Table 5 - HF Environments that were used

<table>
<thead>
<tr>
<th>Date</th>
<th>Local Time in 24hrs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>High Sunspot Year (2001)</td>
<td></td>
</tr>
<tr>
<td>15-Jan</td>
<td>0200 0500 0900 1200 1600 1900 2200</td>
</tr>
<tr>
<td>15-Apr</td>
<td>0200 0500 0900 1200 1600 1900 2200</td>
</tr>
<tr>
<td>15-Jul</td>
<td>0200 0500 0900 1200 1600 1900 2200</td>
</tr>
<tr>
<td>15-Oct</td>
<td>0200 0500 0900 1200 1600 1900 2200</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Date</th>
<th>Local Time in 24hrs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Low Sunspot Year (1996 or 1997)</td>
<td></td>
</tr>
<tr>
<td>15-Jan</td>
<td>0200 0500 0900 1200 1600 1900 2200</td>
</tr>
<tr>
<td>15-Apr</td>
<td>0200 0500 0900 1200 1600 1900 2200</td>
</tr>
<tr>
<td>15-Jul</td>
<td>0200 0500 0900 1200 1600 1900 2200</td>
</tr>
<tr>
<td>15-Oct</td>
<td>0200 0500 0900 1200 1600 1900 2200</td>
</tr>
</tbody>
</table>
Before the HF environment data was used, the gain differences associated with the capturing system for the two years 1997 and 2001, were removed. Great care was needed in translating the signal back to that seen at the antenna base rather than at the receiver input. This process involved taking the raw data from the HF environment database (in dB), subtracting the preamp gain and adding the splitter loss. After this the cable loss at each frequency is added using the cable loss equation, where the cable constant is specified by the cable manufacturer. The detailed matlab scripts are in Appendix G. The receiver system used for each year is shown in Figure 61 and Figure 62. Examples of spectrums before and after the gain removal for each year are shown in Figure 63, Figure 64, Figure 65 and Figure 66.
Figure 63 - Spectrum before gain removal (1997 15 January 2am)

Figure 64 - Spectrum after gain removal (1997 15 January 2am)
Figure 65 - Spectrum before gain removal (2001 15 January 2am)

Figure 66 - Spectrum after gain removal (2001 15 January 2am)
Testing Digital Receiver Performance through an HF Environment Simulator

Note – The x axis in the above plots and all associated plots are in terms of dBm.

The simulated HF environment was created from the HF environment database (scaled to the antenna base). Since the database only has limited frequency precision (2kHz), it can only be regarded as the distribution of carrier signals. As consequence, the spectrum needed to be filled out with modulation in order to attain a representation of the finer frequency spectrum. This is essential if we are to produce a simulated signal that is anything like the real signal at the antenna base.

Firstly, every second 2kHz sample was removed to provide some thinning thus reducing the sample resolution to 4kHz. After this decimation, the 4kHz samples were regarded as carriers and were amplitude modulated with a random signals \( s(t) \), resulting in a 100Hz spectrum resolution. The type of modulation was also varied using a mixture of double sideband suppressed carrier (DSBSC), double sideband large carrier (DSBLC) and single sideband suppressed carrier (SSBC) modulation techniques which are shown in Figure 67. In future work I would suggest reducing the sample resolution to 6kHz and mainly use SSB amplitude modulation, because most signals broadcasted in the HF band have 6kHz BW and are SSB amplitude modulated. Two examples of the results of this process are shown in Figure 68 and Figure 69. As part of recreating the HF environment, 20dB gain was added to the signal. This accounted for the 20dB attenuator used on the output of the signal generator in the test system, described in section 3.1.

During the recreation process a “peak hold” wasn’t used, therefore some of the signals have been suppressed during the recreation of the spectrum. This can be seen on Figure 68 and Figure 69 in the 18MHz region. If these tests were to be repeated a peak hold approach would be used.

---

**Figure 67 - AM Techniques[28]**
Figure 68 - Spectrum after gain removal and before recreation process (2001 15 January 2am)

Figure 69 - Spectrum after gain removal and after recreation process (2001 15 January 2am)
The spectrum also required modification for each first tone listed in Table 4 and all its second tones (Note: Tone two was stepped on a logarithmic scale either side of tone one, ie ±100Hz, ±1kHz, ±10kHz, ±100kHz, ±1MHz, ±10MHz). The reason for doing this was to increase the measurability of the IMD and harmonic products. To do this, the spectrum was reduced to thermal noise at and around the IMD product and harmonic frequencies. Without this, the background signal strength would be too strong for the measurement of product signals. Therefore for each simulated HF environment time, another 25 spectrums were created, one for each tone 1 frequency and all its tone 2 frequencies. The filtering was done after the HF environment creation process, in the frequency domain, using MATLAB.

Two examples of this process are shown in Figure 70 and Figure 71. Here tone one was 16.463716MHz and tone two was 17.463716MHz. Therefore, one of the 3rd order IMD products will be 15.463716MHz. This was the frequency where the spectrum was reduced to thermal noise, so that measuring the IMD product at that frequency would not be corrupted by any other signals.

After the spectrum was reduced to thermal noise at the IMD and harmonic frequencies, a random phase was added to the spectrum and the results saved to a data file which was then loaded into the E4438C signal generator. Once all the spectrums were loaded they were played back one at a time when commanded via the GPIB.
4.2 Simulated HF Environment Creation Validation

Tests were carried out to validate the process of recreating a spectrum from the HF environment database to determine how realistic the process was. A real HF spectrum of Adelaide was recorded with a 100Hz frequency resolution. Its mean and standard deviation for both the time and frequency domains were calculated and are shown in Table 6. The Adelaide spectrum was recorded because of the cost and logistics involved in recording a spectrum in Alice Springs.

Table 6 - Statistics of a real Adelaide HF spectrum with a frequency resolution of 100Hz

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time Domain</td>
<td>0.00</td>
<td>0.23</td>
</tr>
<tr>
<td>Frequency Domain</td>
<td>115.93</td>
<td>7.40</td>
</tr>
</tbody>
</table>

A number of tests were conducted, as a part of the research masters, to compare the results of Table 6 against those obtained using simulated data (derived by creating a spectrum through sub-sampling the above data). Different amplitude modulation techniques were investigated to see how they affected the output of the simulation process. Simulated signals were created by modulating with a variety of combinations of the modulation types SSBSC, DSBSC and DSBLC.

The effect of removing (before the simulation process) every n-th frequency sample was also tested. The reason for removing every n-th frequency sample was that the HF spectrum generally has an average of 4kHz channel spacing.
Be aware that the spectrum in Adelaide is dominated by local signals and power line noise. On the other hand the spectrum in Alice Springs is dominated by mainly skywave signals, that’s why it was chosen for the OTHR. The Adelaide tests only provide a means for doing a check for the recreation process.

Six different combinations of the above variations were tried.
1. No frequency samples were removed and SSBSC, DSBSC, and DSBLC were used for amplitude modulation
2. No frequency samples were removed and DSBSC, and DSBLC were used for amplitude modulation
3. Every second frequency sample was removed and SSBSC, DSBSC, and DSBLC were used for amplitude modulation
4. Every second frequency sample was removed and DSBSC, and DSBLC were used for amplitude modulation
5. Every third frequency sample was removed and SSBSC, DSBSC, and DSBLC were used for amplitude modulation
6. Every third frequency sample was removed and DSBSC, and DSBLC were used for amplitude modulation

Table 7 - Statistics of simulated HF spectrums in the frequency domain

<table>
<thead>
<tr>
<th>Case</th>
<th>Mean</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>One</td>
<td>128.33</td>
<td>35.80</td>
</tr>
<tr>
<td>Two</td>
<td>138.60</td>
<td>12.64</td>
</tr>
<tr>
<td>Three</td>
<td>123.98</td>
<td>41.16</td>
</tr>
<tr>
<td>Four</td>
<td>138.26</td>
<td>12.67</td>
</tr>
<tr>
<td>Five</td>
<td>122.11</td>
<td>43.49</td>
</tr>
<tr>
<td>Six</td>
<td>138.23</td>
<td>12.67</td>
</tr>
</tbody>
</table>

Table 8 - Statistics of simulated HF spectrums in the frequency domain limited to 0-120dBm

<table>
<thead>
<tr>
<th>Case</th>
<th>Mean</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>One</td>
<td>135.62</td>
<td>16.90</td>
</tr>
<tr>
<td>Two</td>
<td>138.66</td>
<td>12.43</td>
</tr>
<tr>
<td>Three</td>
<td>134.17</td>
<td>17.78</td>
</tr>
<tr>
<td>Four</td>
<td>138.33</td>
<td>12.40</td>
</tr>
<tr>
<td>Five</td>
<td>133.64</td>
<td>18.19</td>
</tr>
<tr>
<td>Six</td>
<td>138.29</td>
<td>12.42</td>
</tr>
</tbody>
</table>

Table 9 - Statistics of simulated HF spectrums in the time domain

<table>
<thead>
<tr>
<th>Case</th>
<th>Mean</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>One</td>
<td>0.00</td>
<td>0.27</td>
</tr>
<tr>
<td>Two</td>
<td>0.00</td>
<td>0.28</td>
</tr>
<tr>
<td>Three</td>
<td>0.00</td>
<td>0.28</td>
</tr>
<tr>
<td>Four</td>
<td>0.00</td>
<td>0.28</td>
</tr>
<tr>
<td>Five</td>
<td>0.00</td>
<td>0.26</td>
</tr>
<tr>
<td>Six</td>
<td>0.00</td>
<td>0.28</td>
</tr>
</tbody>
</table>
Table 7, Table 8 and Table 9 show the results of the average of ten simulated spectrums for each of the six cases in the respective domain. To make the test results clearer, the frequency domain test data was restricted to be between 0 and 120dBm. After the simulation process, many samples in the frequency domain lay under the noise floor of the hardware and could therefore be ignored. By doing so, the results in Table 8 were produced.

The best case which was closest to the mean of the real spectrum, was case number five. This was expected because every third frequency sample was removed and SSBSC was not used in the modulation process. Case four produced the closest variance and standard deviation to the real spectrum. In the time domain, case five produced the closest mean and standard deviation.

Case four had overall best statistics in the frequency domain, but I chose to use case three, since it would be unrealistic to ignore SSBSC amplitude modulation. All the results for the time domain were so close that there could be little differentiation between the options.

From this investigation it can be concluded that the simulated HF environment provides (in terms of overall statistics) a good enough representation of the corresponding real spectrum. This aspect, however, might be worth further development if the simulator is to be used for more modulation sensitive applications, rather than the SFDR measurements of the current thesis. More work does need to be done on the verification of the simulated environment, but this in itself would constitute an extensive research project.
5 Test Results and their Interpretation

5.1 HF Environment Differences

There are differences in HF environment spectrums at different times of the day and year. This is particularly evident by examining how the spectrum changes during the day. In general, the spectrum for the times of 2am, 5am and 10pm are less noisier (have less signals) than 9am, 12noon, 4pm and 7pm. This is especially prevalent in the upper HF band (15-30MHz), because there are more signals in the upper HF band during the day and the ionosphere is thicker due to the sun keeping it alive. A good example of this is the 15 July 2001 HF environment spectrums, as shown in Figure 72. The HF environment changes seasonally because of the different sunrise and sunset times, and partly due to lightning during the monsoon period.
It was also evident that, in general, a high sunspot year (2001) contained more noise in its HF environment than that of a low sunspot year (1997). The reason for this is improved global propagation at high sunspot number periods. Consequently, it is highly likely that the dither provided by the environment will change with year, time and frequency.

5.2 Individual Spurious Results

5.2.1 Two Tone Testing with Simulated HF Environments

Signal levels of the individual harmonics and IMD products were measured only if they fell in the HF band of interest (5-30MHz). The results were plotted for each individual spur listed below:

\[ 2 \times f_1 \quad \text{(2nd harmonic)} \]
\[ 2 \times f_2 \quad \text{(2nd harmonic)} \]
\[ 3 \times f_1 \quad \text{(3rd harmonic)} \]
\[ 3 \times f_2 \quad \text{(3rd harmonic)} \]

when \( f_2 > f_1 \)

\[ |f_1 - f_2| \quad \text{(2nd order IMD)} \]
\[ f_1 + f_2 \quad \text{(2nd order IMD)} \]
\[ |2 \times f_1 - f_2| \quad \text{(3rd order IMD)} \]
\[ 2 \times f_2 - f_1 \quad \text{(3rd order IMD)} \]
\[ 2 \times f_1 + f_2 \quad \text{(3rd order IMD)} \]
\[ 2 \times f_2 + f_1 \quad \text{(3rd order IMD)} \]

It should be noted that the above measurements need to be expanded in a future system by including the possibility of aliased 2nd harmonics. This is unnecessary for frequencies below 15MHz, but becomes an issue for signals above 15MHz.
Each two tone signal level was placed 6dBm under the ADC overload point. This ensured that the maximum input level of the two tone signal combined with the simulated HF environment was achieved on the ADC input.

The digital receiver was setup with the following parameters:

- \( BW = 10\text{kHz} \)
- \( \text{Sample Period} = 16.64\text{kHz} \)
- \( \text{Number of Samples} = 20\ 800 \)
- \( \text{Attenuation} = 0\text{dB} \)

The x-axis plots of Figure 73 show tone one frequency increasing in value (the tone which was held fixed while tone two was moved on a logarithmic basis either side of it, after which tone one was moved by approximately 1MHz, and the process was repeated). The exact set of frequencies for the x axis is shown in Appendix D. Only one set of plots for one day have been shown, due to the similarity between days (all plots are shown in Appendix C). The plots also include the difference between signal levels with respect to the spurious signal levels of two tone testing without an HF environment present (a positive value means an improvement).
Testing Digital Receiver Performance through an HF Environment Simulator
The second order IMD is showing the lowest value of SFDR, therefore in future work sub octave filtering could be implemented to further suppress this IMD product. Also third order, in band IMD products, are very difficult to filter as they are close to the main signals.
Over most of these plots it is evident to some extent that the 2am, 5am and 10pm times have a better SFDR for most of the spurs. This is also true for all the spectrums tested (the four days for both years, 1997 and 2001). Each pair of spurious plots in Figure 73 is explained in detail below.

2 × \( f_1 \) (2nd harmonic): The SFDR over the whole frequency range was greater than 80dB except in one region where it reached down to 72dB. Compared to two tones with no HF environment, tone one’s frequency between 5 and 6MHz showed a difference of between \( \pm 5 \)dB, otherwise it showed a performance greater than 5dB and up to 30dB, except in one small region where it was 0dB.

2 × \( f_2 \) (2nd harmonic): Overall, the SFDR was greater than 75dB, except at the higher tone one frequency where it was 70dB. Compared to two tones with no HF environment, the lower end of tone one’s frequency between 5 and 7MHz and showed a difference between \( \pm 10 \)dB. Otherwise it showed a performance greater than 0dB and up to 30dB, except in one small region where it was \( \pm 5 \)dB.

3 × \( f_1 \) (3rd harmonic): 80dB of SFDR was achieved with this 3rd harmonic. The improvement, with respect to two tones with no spectrum, was between 10 and 30dB. The cause of the 10-15dB swing every 400kHz has not, as yet, been ascertained and needs further investigation.

3 × \( f_2 \) (3rd harmonic): 80dB of SFDR was achieved with this 3rd harmonic. The improvement, with respect to two tones with no spectrum, was between 10 and 30dB. The worst tone one frequency range was between 10 and 19MHz, which is the higher end of the x axis. The cause of the 10-15dB swing every 400kHz has not, as yet, been ascertained and needs further investigation.

\[ |f_1 - f_2| \] (2nd order IMD): This 2nd order IMD product was one of the lowest SFDR out of all the spurs with it being greater than 68dB. Out of all the test signals, only 30 had this IMD product fall in the HF region. It appears that when the frequency of tone one was increased the SFDR decreased. This was also the case in the comparison between two tones with no HF environment. The improvement in SFDR ranges from 2 to 8dB.

\[ f_1 + f_2 \] (2nd order IMD): This 2nd order IMD product has the lowest SFDR of all the spurs with it being greater than 65dB. Of all the test signals, 110 had this IMD product fall in the HF region. Compared with the two tones with no HF environment, tone one’s frequency up to 12MHz
showed an improvement of between 3.5 and 7dB. Although over 12MHz the improvement was only between 1.5 to 4.5dB.

\[ |2 \times f_1 - f_2| \quad (3\text{rd order IMD}) \]  
|2 \times f_2 - f_1| \quad (3\text{rd order IMD}) : The SFDR over the whole frequency range was greater than 78dB, except with a few spikes dropping as low as 69dB. Compared to two tones with no HF environment, tone one’s frequency showed a degradation of up to –30dB. Although at about 22MHz (tone one frequency) there was an improvement of between 10 to 40dB.

\[ 2 \times f_1 + f_2 \quad (3\text{rd order IMD}) \] : As above

\[ 2 \times f_2 + f_1 \quad (3\text{rd order IMD}) : \] As above

Lack of experience meant that the echotek receiver had not been set up for optimal performance before the measurements and future tests will need to include a receiver optimisation procedure.

5.2.2 Two Tone Testing without an HF Environment

The tests were also carried out without adding in the HF environment and the harmonics and IMD products were measured. The graphs in Figure 74 show the results for each spurious value. These results were used to determine the level of improvement in performance, compared with two tone testing with various simulated HF environments, as done in section 5.2.1. They have very similar patterns to those in Figure 73, although in general have less noise on the plots.
Figure 74 - Harmonic and IMD Product Plots for no HF Environment
5.3 Worst Case SFDR

Figure 75 shows the worst case SFDR for all the tests conducted in one day. Only January 2001 is shown because very similar results were obtained for all the days tested. By taking the average SFDR of the spectrums it can be concluded that the times of 2am, 5am and 10pm performed the best by having slightly better SFDR as seen in Table 10.

Table 10 - Average worst case SFDR, and average difference in worst case SFDR between tests without a HF environment present, for each time of day

<table>
<thead>
<tr>
<th>Units in (dB)</th>
<th>2am</th>
<th>5am</th>
<th>9am</th>
<th>12noon</th>
<th>4pm</th>
<th>7pm</th>
<th>10pm</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>January</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1997</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>77.738</td>
<td>3.072</td>
<td>77.598</td>
<td>2.967</td>
<td>76.417</td>
<td>1.786</td>
<td>75.996</td>
<td>1.365</td>
</tr>
<tr>
<td><strong>April</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>77.009</td>
<td>2.377</td>
<td>78.415</td>
<td>3.783</td>
<td>76.180</td>
<td>1.549</td>
<td>76.059</td>
<td>1.428</td>
</tr>
<tr>
<td><strong>July</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>76.833</td>
<td>2.202</td>
<td>77.188</td>
<td>2.557</td>
<td>76.861</td>
<td>2.230</td>
<td>76.379</td>
<td>1.748</td>
</tr>
<tr>
<td><strong>October</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>77.517</td>
<td>2.886</td>
<td>77.139</td>
<td>2.508</td>
<td>76.215</td>
<td>1.584</td>
<td>75.719</td>
<td>1.088</td>
</tr>
<tr>
<td><strong>2001</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>76.715</td>
<td>2.084</td>
<td>77.681</td>
<td>3.049</td>
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Figure 75 - Worst case SFDR for January 2001 compared to Two Tones with no HF Environment
From Table 10, it is clear that with the HF environment present, the SFDR performance of the digital receiver was improved on average by 2dB. A 5dB improvement for tone one frequencies between 5 and 15MHz can be achieved as seen in Figure 75. The AD6644 datasheet[17] shows a performance increase of about 10dB by adding dither to the input signal as seen in Figure 76 and Figure 77. The 8dB difference in performance (by dither introduction) between the AD6644 and the results in this report may be a result of the different kind of dither signal which was used. For the tests conducted in the AD6644 datasheet, it was a deterministic dither signal with a magnitude of –19dBm. On the other hand, the environmental dither of the current considerations has a varying signal level that is not deterministic.
6 Conclusion and Future Work

The purpose of this work was to develop an HF environmental simulator that could be used to test the performance of a direct digital HF receiver and to evaluate the effectiveness of the HF environment as a dither signal. The digital receiver was tested with two input signals added to several simulated HF environments. The tests measured the IMD products and harmonics that were generated by the two input signals, with and without the HF environment present. These tests allowed the evaluation of the effect of HF environments upon digital receiver performance.

A major part of this work involved the development of the HF environment simulator. The simulated HF environment was coupled with a two tone test system in order to produce an automated testing environment that could measure the SFDR of a digital receiver over a variety of conditions. The importance of the environment simulator was that it could produce environments over the vast range of conditions that occur in the HF spectrum. These conditions vary diurnally, with frequency and with year (over an 11 year cycle). The simulator, however, has access to a database for this range of variations (collected over a 25 year period) and so can produce representative variations over the full range. If testing in an HF environment were to be done it would take years to complete, especially if sunspot variations are important to the tests. With the simulated environment, comprehensive testing could be done in a matter of days.

The above HF test system is completely automatic and has applications well beyond the current considerations. Any device (whether a digital receiver, amplifier, combiner, splitter or filter) can be tested for its performance in an HF environment. Testing is extremely important, especially if a device has not been used in the HF environment before. This kind of testing can determine any deficiencies in the device, before it is used in the field. It can also shed some light on ways to overcome problems or determine methods of operating more effectively.

Future improvements to the HF environment simulator will include real time signal processing in order to show, for example, the SFDR of the current signal of interest. It could also have a running logger which plots the worst case SFDR for the harmonics and IMD products for each two tones of a particular HF spectrum. Currently all the signal processing is done after the tests have finished. The simulator could also include some adjustable input gain with feedback to ensure that the input signal to the ADC is just under the ADC full scale dynamic range. This would allow testing over the maximum possible range. Currently, all the gains are set by the user before the automatic testing occurs.

In this research, only one digital receiver was tested, this being the Echotek ECDR-GC214-PIC/TS. The unit under test was integrated into the HF environment simulator so that it could be controlled automatically. The two tone testing at the frequencies in Appendix H were carried out on all the spectrums in Table 5. This represents a complete test, in a lab environment, over a fully representative range of conditions. These tests were carried out to determine how the Echotek digital receiver operated in the HF environment and to help determine strategies to operate the digital receiver in the HF environment or to find out if the digital receiver had any other associated problems.
From the testing of the Echotek digital receiver, it can be concluded that the HF environment improves the SFDR by at least 2dB. In addition, the HF environments between 10pm and 5am perform, on average, better than those during the day and early evening, but only by a small margin (as seen in Table 10). There is no evidence, however, that the diurnal, seasonal or sunspot variation in HF environments significantly effect the digital receiver performance. This is surprising since considering the large variations in the characteristics of the environmental dither. In particular, main band of dither is located at specific frequency ranges, and there are frequency ranges in which there is no dither. These ranges change for the different time of day, time of year, and different years. For all these HF environments, the dither was sub-optimal and a better dither signal could be generated artificially as shown in the AD6644 datasheet[17].

At the receiver input, the dither could be augmented by artificial dither to increase the SFDR of the digital receiver up to the levels shown in the ADC datasheet. There are many methods of doing this, but, depending upon how much noise is injected, the SNR of the ADC may be decreased[9].

There are two methods to overcome the problem of dither decreasing SNR. First, the dither can be generated using a pseudo random digital number generator. This digital signal is converted to an analogue signal and added to the analogue input of the ADC. After digital conversion the pseudo random digital number is subtracted. In this way the SNR is not affected by the dither.

![Subtractive Wideband Dither](image)

The second method is to generate the noise in a similar fashion, although make it lie out of the band of interest. This can be anywhere in the HF environment which is of no interest to the user (there are always regions of the HF band with little or no

*Figure 78 - Subtractive Wideband Dither*[9]
activity and these shift around depending upon the time of day). A simple circuit containing a noise diode can be used as a noise source for dither. Noise levels out of the diode are quite small and therefore some form of gain must be applied. As an example, the circuit in Figure 80 provides 80dB of noise adjustment range with a 1 volt control signal.

The HF environment is a sufficient dither signal, although it could be improved. Its spectrum is broadband although the main signals are located within certain bands. The major component that the HF environment lacks as a dither signal is a deterministic input level. This can be rectified by introducing extra dither by one of the two methods described above, which has a deterministic level, thus ensuring good
dither all the time. More research needs to be done on implementing dithering techniques which can be used with the HF environment.

There are other ways to improve the digital receiver performance overall, especially it’s SFDR. This can be achieved by redesigning the NCO, CIC filter, CFIR filter and PFIR filter, by adding more stages, more bits and/or more taps. Even if these improvements could be made to a digital receiver, the limiting factor is still the ADC performance. Only after this performance is improved by the manufactures will we see SFDR higher than currently offered. Until then, more research needs to be done to improve the resolution of current ADC’s.
Testing Digital Receiver Performance through an HF Environment Simulator

BIBLIOGRAPHY


Appendix A – HF Environments from Database (at the antenna base)
Testing Digital Receiver Performance through an HF Environment Simulator

Spectrum after gain removal (1997 15 January 9am)

Spectrum after gain removal (1997 15 January 12noon)
Testing Digital Receiver Performance through an HF Environment Simulator

Spectrum after gain removal (1997 15 July 10pm)

Spectrum after gain removal (1997 15 October 2am)
Testing Digital Receiver Performance through an HF Environment Simulator

Spectrum after gain removal (1997 15 October 5am)

Spectrum after gain removal (1997 15 October 9am)
Testing Digital Receiver Performance through an HF Environment Simulator

Spectrum after gain removal (2001 15 January 9am)

Spectrum after gain removal (2001 15 January 12noon)
Testing Digital Receiver Performance through an HF Environment Simulator

Spectrum after gain removal (2001 15 January 4pm)

Spectrum after gain removal (2001 15 January 7pm)
Testing Digital Receiver Performance through an HF Environment Simulator

Spectrum after gain removal (2001 15 January 10pm)

Spectrum after gain removal (2001 15 April 2am)
Testing Digital Receiver Performance through an HF Environment Simulator

Spectrum after gain removal (2001 15 April 12noon)

Spectrum after gain removal (2001 15 April 4pm)
Testing Digital Receiver Performance through an HF Environment Simulator
Testing Digital Receiver Performance through an HF Environment Simulator

Spectrum after gain removal (2001 15 July 2am)

Spectrum after gain removal (2001 15 July 5am)
Testing Digital Receiver Performance through an HF Environment Simulator

Spectrum after gain removal (2001 15 July 4pm)

Spectrum after gain removal (2001 15 July 7pm)
Testing Digital Receiver Performance through an HF Environment Simulator

Spectrum after gain removal (2001 15 October 12noon)

Spectrum after gain removal (2001 15 October 4pm)
Testing Digital Receiver Performance through an HF Environment Simulator

Spectrum after gain removal (2001 15 October 7pm)

Spectrum after gain removal (2001 15 October 10pm)
Appendix B – Recreated HF Environments Using AM Techniques

Spectrum after gain removal and HF recreation (1997 15 January 2am)

Spectrum after gain removal and HF recreation (1997 15 January 5am)
Testing Digital Receiver Performance through an HF Environment Simulator

Spectrum after gain removal and HF recreation (1997 15 January 4pm)

Spectrum after gain removal and HF recreation (1997 15 January 7pm)
Testing Digital Receiver Performance through an HF Environment Simulator

Spectrum after gain removal and HF recreation (1997 15 January 10pm)

Spectrum after gain removal and HF recreation (1997 15 April 2am)
Testing Digital Receiver Performance through an HF Environment Simulator

Spectrum after gain removal and HF recreation (1997 15 April 12noon)

Spectrum after gain removal and HF recreation (1997 15 April 4pm)
Testing Digital Receiver Performance through an HF Environment Simulator

Spectrum after gain removal and HF recreation (1997 15 April 7pm)

Spectrum after gain removal and HF recreation (1997 15 April 10pm)
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Spectrum after gain removal and HF recreation (1997 15 July 2am)

Spectrum after gain removal and HF recreation (1997 15 July 5am)
Testing Digital Receiver Performance through an HF Environment Simulator
Testing Digital Receiver Performance through an HF Environment Simulator

Spectrum after gain removal and HF recreation (2001 15 January 2am)

Spectrum after gain removal and HF recreation (2001 15 January 5am)
Testing Digital Receiver Performance through an HF Environment Simulator

Graph 1: Spectrum after gain removal and HF recreation (2001 15 January 4pm)

Graph 2: Spectrum after gain removal and HF recreation (2001 15 January 7pm)
Testing Digital Receiver Performance through an HF Environment Simulator

Spectrum after gain removal and HF recreation (2001 15 July 2am)

Spectrum after gain removal and HF recreation (2001 15 July 5am)
Testing Digital Receiver Performance through an HF Environment Simulator

Spectrum after gain removal and HF recreation (2001 15 July 10pm)

Spectrum after gain removal and HF recreation (2001 15 October 2am)
Testing Digital Receiver Performance through an HF Environment Simulator
Appendix C – Harmonics and IMD Product Plots

2*fl, 2nd harmonic (SFDR), two tones only

2*n2, 2nd harmonic (SFDR), two tones only
Testing Digital Receiver Performance through an HF Environment Simulator

3rd, 3rd harmonic (SFDR), two tones only

3rd, 3rd harmonic (SFDR), two tones only
Testing Digital Receiver Performance through an HF Environment Simulator

$2\times f_1 + f_2$, 3rd order IMD (SFDR), two tones only

$2\times f_2 + f_1$, 3rd order IMD (SFDR), two tones only
Testing Digital Receiver Performance through an HF Environment Simulator
Testing Digital Receiver Performance through an HF Environment Simulator

2^{nd}, 2nd harmonic (SFDR) 1997 January

2^{nd}, 2nd harmonic (Difference between harmonic with HFE and harmonic with no HFE) 1997 January
Testing Digital Receiver Performance through an HF Environment Simulator

**First Figure:**
- Title: f1+f2, 2nd order IMD (SFDR) 1997 January
- Graph showing dB vs. Tone 1 Frequency (MHz)
- Legend: 2am, 5am, 9am, 12noon, 4pm, 7pm, 10pm

**Second Figure:**
- Title: f1+f2, 2nd order IMD (Difference between harmonic with HFE and harmonic with no HFE) 1997 January
- Graph showing dB vs. Tone 1 Frequency (MHz)
- Legend: 2am, 5am, 9am, 12noon, 4pm, 7pm, 10pm
Testing Digital Receiver Performance through an HF Environment Simulator

2^1+2, 3rd order IMD (SFDR) 1997 January

2^1-2, 3rd order IMD (Difference between harmonic with HF E and harmonic with no HF E) 1997 January
Testing Digital Receiver Performance through an HF Environment Simulator

3rd harmonic (SFDR) 1997 January

3rd harmonic (Difference between harmonic with HFE and harmonic with no HFE) 1997 January
Testing Digital Receiver Performance through an HF Environment Simulator

2^m+n^2, 3rd order IMD (SFDR) 1997 January

2^m+n^2, 3rd order IMD (Difference between harmonic with HFE and harmonic with no HFE) 1997 January
Testing Digital Receiver Performance through an HF Environment Simulator

2\textsuperscript{nd} 2\textsuperscript{nd} harmonic (SFDR) 1997 April

2\textsuperscript{nd} 2\textsuperscript{nd} harmonic (Difference between harmonic with HFE and harmonic with no HFE) 1997 April
Testing Digital Receiver Performance through an HF Environment Simulator
Testing Digital Receiver Performance through an HF Environment Simulator

2^4-1-2, 3rd order IMD (SFDR) 1997 April

2^4-1-2, 3rd order IMD (Difference between harmonic with HFE and harmonic with no HFE) 1997 April
Testing Digital Receiver Performance through an HF Environment Simulator

2$\times$2-f1, 3rd order IMD (SFDR) 1997 April

2$\times$2-f1, 3rd order IMD (Difference between harmonic with HFE and harmonic with no HFE) 1997 April
Testing Digital Receiver Performance through an HF Environment Simulator

3rd, 3rd harmonic (SFDR) 1997 April

3rd, 3rd harmonic (Difference between harmonic with HFE and harmonic with no HFE) 1997 April
Testing Digital Receiver Performance through an HF Environment Simulator

![Graph 1](image1)

![Graph 2](image2)
Testing Digital Receiver Performance through an HF Environment Simulator

\[ 2^{45} + f_1, \text{3rd order IMD (SFDI)} \] 1997 April

\[ 2^{45} + f_1, \text{3rd order IMD (Difference between harmonic with HFE and harmonic with no HFE)} \] 1997 April
Testing Digital Receiver Performance through an HF Environment Simulator

2nd harmonic (SFDR) 1997 July

2nd harmonic (Difference between harmonic with HFE and harmonic with no HFE) 1997 July
Testing Digital Receiver Performance through an HF Environment Simulator

2^nd, 2nd harmonic (SFDR) 1997 July

2^nd, 2nd harmonic (Difference between harmonic with HFE and harmonic with no HFE) 1997 July
Testing Digital Receiver Performance through an HF Environment Simulator

2*ff1-f2, 3rd order IMD (SFDR) 1997 July

![Graph 1](image1)

2*ff1-f2, 3rd order IMD (Difference between harmonic with HFE and harmonic with no HFE) 1997 July

![Graph 2](image2)
Testing Digital Receiver Performance through an HF Environment Simulator

2nd, 3rd order IMD (SFDR) 1997 July

3rd order IMD (Difference between harmonic with HFE and harmonic with no HFE) 1997 July
Testing Digital Receiver Performance through an HF Environment Simulator

3rd, 3rd harmonic (SFDR) 1997 July

3rd, 3rd harmonic (Difference between harmonic with HFE and harmonic with no HFE) 1997 July
Testing Digital Receiver Performance through an HF Environment Simulator

1. 3rd harmonic (SFDR) 1997 July

2. 3rd harmonic (Difference between harmonic with HFE and harmonic with no HFE) 1997 July
Testing Digital Receiver Performance through an HF Environment Simulator

2^m+1, 3rd order IMD (SFDR) 1997 July

2^m+1, 3rd order IMD (Difference between harmonic with HFE and harmonic with no HFE) 1997 July
Testing Digital Receiver Performance through an HF Environment Simulator

**2*2+1, 3rd order IMD (SFDR) 1997 July**

![Graph 1](image1)

**2*2+1, 3rd order IMD (Difference between harmonic with HFE and harmonic with no HFE) 1997 July**

![Graph 2](image2)
Testing Digital Receiver Performance through an HF Environment Simulator

2^n, 2nd harmonic (SFDR) 1997 October

2^n, 2nd harmonic (Difference between harmonic with HFE and harmonic with no HFE) 1997 October
Testing Digital Receiver Performance through an HF Environment Simulator
Testing Digital Receiver Performance through an HF Environment Simulator

![Graph 1](image1)

![Graph 2](image2)
Testing Digital Receiver Performance through an HF Environment Simulator
Testing Digital Receiver Performance through an HF Environment Simulator

2*1-1/2, 3rd order IMD (SFDR) 1997 October

2*1-1/2, 3rd order IMD (Difference between harmonic with HFE and harmonic with no HFE) 1997 October
Testing Digital Receiver Performance through an HF Environment Simulator

3rd, 3rd harmonic (SFDR) 1997 October

3rd, 3rd harmonic (Difference between harmonic with HFE and harmonic with no HFE) 1997 October
Testing Digital Receiver Performance through an HF Environment Simulator

2\(n+1\) \& 2, 3rd order IMD (SFDR) 1997 October

[dB vs. Tone 1 Frequency (MHz)]

2\(n+1\) \& 2, 3rd order IMD (Difference between harmonic with HFE and harmonic with no HFE) 1997 October

[dB vs. Tone 1 Frequency (MHz)]
Testing Digital Receiver Performance through an HF Environment Simulator

2^n2+n1, 3rd order IMD (SFDR) 1997 October

2^n2+n1, 3rd order IMD (Difference between harmonic with HFE and harmonic with no HFE) 1997 October
Testing Digital Receiver Performance through an HF Environment Simulator

2nd harmonic (SFDR) 2001 January

2nd harmonic (Difference between harmonic with HFE and harmonic with no HFE) 2001 January
Testing Digital Receiver Performance through an HF Environment Simulator

2^nd Harmonic (SFDP) 2001 January

2^nd Harmonic (Difference between harmonic with HFE and harmonic with no HFE) 2001 January
Testing Digital Receiver Performance through an HF Environment Simulator

![Graph 1: f1-f2, 2nd order IMD (SFDR) 2001 January](image1)

![Graph 2: f1-f2, 2nd order IMD (Difference between harmonic with HFE and harmonic with no HFE) 2001 January](image2)
Testing Digital Receiver Performance through an HF Environment Simulator

\[ f_{1+2}, \text{ 2nd order IMD (SFDR) 2001 January} \]

- 2am
- 5am
- 9am
- 12noon
- 4pm
- 7pm
- 10pm

\[ f_{1+2}, \text{ 2nd order IMD (Difference between harmonic with HFE and harmonic with no HFE) 2001 January} \]

- 2am
- 5am
- 9am
- 12noon
- 4pm
- 7pm
- 10pm
Testing Digital Receiver Performance through an HF Environment Simulator

**Figure 1**: 2ⁿ1/2, 3rd order IMD (SFDR) 2001 January

**Figure 2**: 2ⁿ1/2, 3rd order IMD (Difference between harmonic with HFE and harmonic with no HFE) 2001 January
Testing Digital Receiver Performance through an HF Environment Simulator

**Figure 1:** 2\*f2-f1, 3rd order IMD (SFDR) 2001 January

**Figure 2:** 2\*f2-f1, 3rd order IMD (Difference between harmonic with HFE and harmonic with no HFE) 2001 January
Testing Digital Receiver Performance through an HF Environment Simulator

3rd harmonic (SFDR) 2001 January

3rd harmonic (Difference between harmonic with HFE and harmonic with no HFE) 2001 January
Testing Digital Receiver Performance through an HF Environment Simulator

2**1+2, 3rd order IMD (SFDR) 2001 January

[Graph showing dB vs. Tone 1 Frequency (MHz) for different times of the day.]

2**1+2, 3rd order IMD (Difference between harmonic with HFE and harmonic with no HFE) 2001 January

[Graph showing dB vs. Tone 1 Frequency (MHz) for different times of the day, showing the difference between harmonic with and without HFE.]
Testing Digital Receiver Performance through an HF Environment Simulator

2^2+N+1, 3rd order IMD (SFDR) 2001 January

2^2+N+1, 3rd order IMD (Difference between harmonic with HFE and harmonic with no HFE) 2001 January
Testing Digital Receiver Performance through an HF Environment Simulator

2nd harmonic (SFDR) 2001 April

2nd harmonic (Difference between harmonic with HFE and harmonic with no HFE) 2001 April
Testing Digital Receiver Performance through an HF Environment Simulator

**2\textsuperscript{nd} harmonic (SFDR) 2001 April**

**2\textsuperscript{nd} harmonic (Difference between harmonic with HFE and harmonic with no HFE) 2001 April**
Testing Digital Receiver Performance through an HF Environment Simulator
Testing Digital Receiver Performance through an HF Environment Simulator

**f1+2, 2nd order IMD (SFDR) 2001 April**

- 2am
- 5am
- 9am
- 12noon
- 4pm
- 7pm
- 10pm

**f1+2, 2nd order IMD (Difference between harmonic with HFE and harmonic with no HFE) 2001 April**

- 2am
- 5am
- 9am
- 12noon
- 4pm
- 7pm
- 10pm
Testing Digital Receiver Performance through an HF Environment Simulator

2*F1-F2, 3rd order IMD (SFDR) 2001 April

2*F1-F2, 3rd order IMD (Difference between harmonic with HFE and harmonic with no HFE) 2001 April
Testing Digital Receiver Performance through an HF Environment Simulator

2^3-1, 3rd order IMD (SFDR) 2001 April

2^3-1, 3rd order IMD (Difference between harmonic with HFE and harmonic with no HFE) 2001 April
Testing Digital Receiver Performance through an HF Environment Simulator

3rd, 3rd harmonic (SFDR) 2001 April

3rd, 3rd harmonic (Difference between harmonic with HFE and harmonic with no HFE) 2001 April
Testing Digital Receiver Performance through an HF Environment Simulator

**3^rd, 3rd harmonic (SFDR) 2001 April**

- 2am
- 5am
- 9am
- 12noon
- 4pm
- 7pm
- 10pm

**3^rd, 3rd harmonic (Difference between harmonic with HFE and harmonic with no HFE) 2001 April**

- 2am
- 5am
- 9am
- 12noon
- 4pm
- 7pm
- 10pm
Testing Digital Receiver Performance through an HF Environment Simulator

2*f1 + f2, 3rd order IMD (SFDR) 2001 April

\[ \text{dB} \]

Tone 1 Frequency (MHz)

2*f1 + f2, 3rd order IMD (Difference between harmonic with HFE and harmonic with no HFE) 2001 April

\[ \text{dB} \]

Tone 1 Frequency (MHz)
Testing Digital Receiver Performance through an HF Environment Simulator

![Chart 1: 2*f2+f1, 3rd order IMD (SFDR) 2001 April](image)

![Chart 2: 2*f2+f1, 3rd order IMD (Difference between harmonic with HFE and harmonic with no HFE) 2001 April](image)
Testing Digital Receiver Performance through an HF Environment Simulator

![2nd harmonic (SFDR) 2001 July](image1)

![2nd harmonic (Difference between harmonic with HFE and harmonic with no HFE) 2001 July](image2)
Testing Digital Receiver Performance through an HF Environment Simulator

2nd harmonic (SFDR) 2001 July

2nd harmonic (Difference between harmonic with HFE and harmonic with no HFE) 2001 July
Testing Digital Receiver Performance through an HF Environment Simulator

**Figure 1:**
- **f1-f2, 2nd order IMD (SFDR) 2001 July**
- Graph shows the 2nd order intermodulation distortion (IMD) level for different hours of the day (2am, 5am, 9am, 12noon, 4pm, 7pm, 10pm) across a frequency range of 5 MHz to 30 MHz.

**Figure 2:**
- **f1-f2, 2nd order IMD (Difference between harmonic with HFE and harmonic with no HFE) 2001 July**
- Graph indicates the difference in IMD levels with and without high-frequency environmental (HFE) conditions for the same frequency range and time slots.
Testing Digital Receiver Performance through an HF Environment Simulator

2*1-12, 3rd order IMD (SFDR) 2001 July

2*1-12, 3rd order IMD (Difference between harmonic with HFE and harmonic with no HFE) 2001 July
Testing Digital Receiver Performance through an HF Environment Simulator

2^nd-1, 3rd order IMD (SFCDR) 2001 July

2^nd-1, 3rd order IMD (Difference between harmonic with HF and harmonic with no HF) 2001 July
Testing Digital Receiver Performance through an HF Environment Simulator
Testing Digital Receiver Performance through an HF Environment Simulator

3rd harmonic (SFDR) 2001 July

3rd harmonic (Difference between harmonic with HFE and harmonic with no HFE) 2001 July
Testing Digital Receiver Performance through an HF Environment Simulator

2^n+2+fl, 3rd order IMD (SFDR) 2001 July

2^n+2+fl, 3rd order IMD (Difference between harmonic with HFE and harmonic with no HFE) 2001 July
Testing Digital Receiver Performance through an HF Environment Simulator

2nd Harmonic (SFDR) 2001 October

2nd Harmonic (Difference between harmonic with HFE and harmonic with no HFE) 2001 October
Testing Digital Receiver Performance through an HF Environment Simulator

2^nd, 2nd harmonic (SFDR) 2001 October

2^nd, 2nd harmonic (Difference between harmonic with HFE and harmonic with no HFE) 2001 October

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Testing Digital Receiver Performance through an HF Environment Simulator

**f1-f2, 2nd order IMD (SFDR) 2001 October**

- 2am
- 5am
- 9am
- 12noon
- 4pm
- 7pm
- 10pm

**f1-f2, 2nd order IMD (Difference between harmonic with HFE and harmonic with no HFE) 2001 October**

- 2am
- 5am
- 9am
- 12noon
- 4pm
- 7pm
- 10pm
Testing Digital Receiver Performance through an HF Environment Simulator

![Graph 1: 1+2, 2nd order IMD (SFDR) 2001 October](image1)

![Graph 2: 1+2, 2nd order IMD (Difference between harmonic with HFE and harmonic with no HFE) 2001 October](image2)
Testing Digital Receiver Performance through an HF Environment Simulator

2^m1-2, 3rd order IMD (SFDR) 2001 October

2^m1-2, 3rd order IMD (Difference between harmonic with HFE and harmonic with no HFE) 2001 October
Testing Digital Receiver Performance through an HF Environment Simulator

2*2-f1, 3rd order IMD (SFDR) 2001 October

dB

Tone 1 Frequency (MHz)

2*2-f1, 3rd order IMD (Difference between harmonic with HFE and harmonic with no HFE) 2001 October

dB

Tone 1 Frequency (MHz)
Testing Digital Receiver Performance through an HF Environment Simulator

3rd harmonic (SFDR) 2001 October

3rd harmonic (Difference between harmonic with HFE and harmonic with no HFE) 2001 October
Testing Digital Receiver Performance through an HF Environment Simulator

3rd, 3rd harmonic (SFDR) 2001 October

3rd, 3rd harmonic (Difference between harmonic with HFE and harmonic with no HFE) 2001 October
Testing Digital Receiver Performance through an HF Environment Simulator

**Graph 1:**

2^n+1, 3rd order IMD (SFDR) 2001 October

- 2am
- 5am
- 9am
- 12noon
- 4pm
- 7pm
- 10pm

**Graph 2:**

2^n+1, 3rd order IMD (Difference between harmonic with HFE and harmonic with no HFE) 2001 October

- 2am
- 5am
- 9am
- 12noon
- 4pm
- 7pm
- 10pm
Testing Digital Receiver Performance through an HF Environment Simulator

2^N+1, 3rd order IMD (SFDR) 2001 October

2^{N+1}, 3rd order IMD (Difference between harmonic with HFE and harmonic with no HFE) 2001 October
## Appendix D – Harmonics and IMD Product Plot Frequencies

### 2\*f1, 2nd Harmonic

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Testing Digital Receiver Performance through an HF Environment Simulator

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### Testing Digital Receiver Performance through an HF Environment Simulator

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### 3*f2, 3rd Harmonic

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Testing Digital Receiver Performance through an HF Environment Simulator

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**2*f1+f2, 3rd order IMD**

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Testing Digital Receiver Performance through an HF Environment Simulator

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| 16 | 6597728 | 6597628 | 19793084 |
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2*f2-f1, 3rd order IMD
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Appendix E  – Worst Case SFDR Plots
Testing Digital Receiver Performance through an HF Environment Simulator

Worst case spur (1997 January)

Difference between worst case spur with HF E and worst case spur with no HF E (1997 January)
Testing Digital Receiver Performance through an HF Environment Simulator

Worst case spur (1997 April)

![Graph showing SFDR (dB) vs. Tone 1 Frequency (MHz) for different times of the day with various lines representing different times.]

Difference between worst case spur with HFE and worst case spur with no HFE (1997 April)

![Graph showing SFDR (dB) vs. Tone 1 Frequency (MHz) for the difference between spur with HFE and no HFE with various times of the day.]

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Testing Digital Receiver Performance through an HF Environment Simulator

Worst case spur (1997 July)

Difference between worst case spur with HFE and worst case spur with no HFE (1997 July)
Testing Digital Receiver Performance through an HF Environment Simulator

**Worst case spur (1997 October)**

- 2am
- 5am
- 9am
- 12noon
- 4pm
- 7pm
- 10pm

**Difference between worst case spur with HF and worst case spur with no HF (1997 October)**

- 2am
- 5am
- 9am
- 12noon
- 4pm
- 7pm
- 10pm
Testing Digital Receiver Performance through an HF Environment Simulator

Worst case spur (2001 April)

Difference between worst case spur with HFE and worst case spur with no HFE (2001 April)
Testing Digital Receiver Performance through an HF Environment Simulator

Worst case spur (2001 July)

Difference between worst case spur with HFE and worst case spur with no HFE (2001 July)
Testing Digital Receiver Performance through an HF Environment Simulator

Worst case spur (2001 October)

Difference between worst case spur with HFE and worst case spur with no HFE (2001 October)
Appendix F – MATLAB Code (creating the HF environment from the FMS database)

%%% Reads JFAS surveillance data created by Brett Northey into an array % called spec with a frequency range between (5-30MHz) %
%%% Used in conjunction with gain_removal_1997.m, gain_removal_2001.m, %
%%% HF_environ_nulling.m, HF_environ_creation.m %
%%% Created for Research Masters by Wayne Pennington 24 May 2004 %
%%% Created for Research Masters by Wayne Pennington 24 May 2004 %
%%% Created for Research Masters by Wayne Pennington 24 May 2004 %
%%% Created for Research Masters by Wayne Pennington 24 May 2004 %
%%% Created for Research Masters by Wayne Pennington 24 May 2004 %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%
%% Reads JFAS survelliance data created by Brett Northey into an array %
%% called spec with a frequency range between (5-30MHz) %
%% Used in conjunction with gain_removal_1997.m, gain_removal_2001.m, %
%% HF_environ_nulling.m, HF_environ_creation.m %
%% Created for Research Masters by Wayne Pennington 24 May 2004 %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%
close all
clear all

% --------------- START ---------------
% Read in the surveilance data text file

% Open file
[fid, msg] = fopen('D:\SM Data\SURV_A0_2001_288.txt', 'r');
error(msg);

% % Now search for the first line of useful data (a line % starting with the local time)
% inhdr = 1;
while inhdr
    tline = fgetl(fid);
    if ~ischar(tline) % Must be at EOF
        fprintf(1, 'End of file reached\n');
        break;
    end
    if length(tline >=6)
        if strncmp(tline(length(tline)-1:length(tline)), 'LT', 2)
            fprintf(1, 'Found first line %s\n', tline);
            inhdr = 0;
        end
    end
end

% Create spec matrix
spec = zeros(20000,1);
% Start reading data into spec array
count=1;
j = 0;
i = 1;
tline = fgetl(fid);
if ~inhdr
    while 1
        len = length(tline);
        idx = 1;
        if length(tline)>1
            [data, cnt, msg, p] = sscanf(tline(idx:len), '%f');
            idx = idx+p;
            spec(j+1,i) = data(1);
            spec(j+2,i) = data(2);
            spec(j+3,i) = data(3);
            spec(j+4,i) = data(4);
            spec(j+5,i) = data(5);
            spec(j+6,i) = data(6);
            spec(j+7,i) = data(7);
            spec(j+8,i) = data(8);
            spec(j+9,i) = data(9);
            spec(j+10,i) = data(10);
            count=count+1;
            % if rem(count,100) == 0, fprintf(1, '	%d\r', count); end
            j = j+10;
        end
    end
    tline = fgetl(fid);
if ~ischar(tline)    % Must be at EOF
    fprintf(1, 'End of file reached\n');
    size(spec);
    break;
elseif length(tline >=6) % Look fo next run
    if strncmp(tline(length(tline)-1:length(tline)), 'LT', 2)
        fprintf(1, 'Next Run -> %s\n', tline);
        j = 0;
        i = i+1;
        count=0;
        inhdr = 0;
        tline = fgetl(fid);
        size(spec);
        spec = [spec zeros(20000,1)];
    end
end
end
% Close file
fclose(fid);

% Remove 30-45MHz section
spec=spec(1:12500,:);

% Save the spec array
save('SURV_A0_2001_288.mat', 'spec');

size(spec)
clear all
close all

% Loads 1997 spectrum data
load 'H:\Digital Rx\Matlab\JFAS Spec mat files\SURV_A0_1997_298.mat' spec;

freq = 5:0.002:30-0.002; % in MHz

figure
plot(freq, spec(:,3));
%title('Spectrum before gain removal (1997 15 January 2am)');
xlabel('Frequency (MHz)');
ylabel('Mag (dB)');

% Remove preamp gain of 18.1dB
spec = spec - 18.1;

% Remove splitter loss of 4.8dB
spec = spec + 4.8;

% Remove cable loss (215m)
cable_constant = -0.00365;
cable_len = 215;

for i=1:length(freq)
    cable_loss = cable_len * sqrt(freq(i)) * cable_constant;
    spec(i,:) = spec(i,:) + abs(cable_loss);
end

%figure
%plot(freq, spec);
%title('Spectrums after gain removal');
xlabel('Frequency (MHz)');
ylabel('Mag (dB)');

% Save the spec array
Testing Digital Receiver Performance through an HF Environment Simulator

save('SURV_A0_1997_298_nogain.mat', 'spec');
clear all
close all

% Loads 1997 spectrum data
load 'H:\Digital Rx\Matlab\JFAS Spec mat files\SURV_A0_2001_288.mat' spec;

% Remove preamp gain of 18.1dB
spec = spec - 18.1;

% Remove splitter loss of 3.45dB
spec = spec + 3.45;

% Remove cable loss (448m)
cable_constant = -0.00365;
cable_len = 448;
freq = 5:0.002:30-0.002; % in MHz
for i=1:length(freq)
    cable_loss = cable_len * sqrt(freq(i)) * cable_constant;
    spec(i,:) = spec(i,:) + abs(cable_loss);
end

% Save the spec array
save('SURV_A0_2001_288_nogain.mat', 'spec');
Testing Digital Receiver Performance through an HF Environment Simulator

%% HF ENVIRONMENT CREATION (using AM techniques)
%% Used before HF_environ_nulling.m
%%
%% Used after read_HF_environ.m, gain_removal_****.m
%%
%% Created for Research Masters by Wayne Pennington 21 May 2004

close all
clear all

for iii=1:3

    % Loads 1997 spectrum data
    load 'C:\Wayne\Gain removed JFAS Spec mat files\SURV_A0_1997_014_nogain.mat' spec;

    if iii == 1
        spec_no = 2;
    elseif iii == 2
        spec_no = 5;
    elseif iii == 3
        spec_no = 9;
    end

    %spec_no = input('What number spectrum from the mat file would you like to load?\n');

    data = spec(:,spec_no);
    clear spec

    % Removes every second sample
    spec = data(1:2:length(data));

    once = 1;
    Npts = 600000;  % Reduce the number of samples down to 300000 (after the imaginary component removed
    fc = 5e6;  % Carrier Frequency for AM
    final_array = zeros(Npts,1);  % Create null array

    DEB=0;
    for i=1:length(spec)
        %for i=1:5

        %
    end
if rem(i,10) == 0, fprintf(1, '\t%d\n', i); end

% ------------------------ START -----------------------------------------
% Create random signal with close to signal level of the carrier frequency

FreqRes = 10;
fs = 10e3; %Hz
ln = round(fs/FreqRes); % length of the array
x = wgn(ln,1,spec(i)); % (use spectrum magnitude for this)

if DEB
    figure
    plot(x);
    title('Random Signal x(t)');
end

% FFT of random signal
lgth=length(x);
if DEB
    figure
    omeg = -fs/2:fs/length(x):fs/2-fs/length(x);
    plot(omeg, fftshift(20*log10(abs(fft(x(1:lgth).*hanning(lgth))))));
    title('FFT of x(t)');
    xlabel('Frequency (Hz)');
    ylabel('Mag (dB)');
end
% ------------------------ END -----------------------------------------

% ****************** START ******************
% Filter x(t) to get a 4kHz BW

if once
    fcut = 2e3; % cut off frequency
    Wn = [fcut/(fs/2)];
    Rp = 0.5; % Ripple in the passband in dB, 0.5 = 0.9441
    [b,a] = cheby1(30,Rp,Wn); % 30th order Lowpass filter
    fq = freqz(b,a);
    x_value = 0:fs/2/length(fq):fs/2-fs/2/length(fq);
end
once = 0;

if DEB
    figure
    plot(x_value,abs(fq));
    title('Filter Response');
    xlabel('Frequency (Hz)');
    ylabel('Mag');
end
x = filter(b,a,x);  % Apply filter to x(t)

if DEB
    figure
    lgth=length(x);
    plot(omeg, fftshift(20*log10(abs(fft(x(1:lgth).*hanning(lgth))))));
    title('FFT of filtered x(t)');
    xlabel('Frequency (Hz)');
    ylabel('Mag (dB)');
end

% ------------------ START ------------------

% Perform Massaging to data

BW = 4000;  %Hz
Res = 100;  %Hz

ll = length(x);
x_temp = interp1(1:ll, x, 1:(ll-1)/Npts:ll-(ll-1)/Npts, 'linear')/(Npts/ll);  
    % interpolate
    lgth = length(x_temp);
x_temp = x_temp';

if DEB
    figure
    plot(fftshift(20*log10(abs(fft(x_temp(1:lgth).*hanning(lgth))))));
    title('FFT of filtered and interpolated x(t)');
    ylabel('Mag (dB)');
end

% Suppress values outside of the 4kHz BW in the frequency domain
x_temp = abs(fft(x_temp));
x_temp(BW/Res/2:Npts-(BW/Res/2)) = min(abs(x_temp));

% Convert back to time
x_temp = ifft(x_temp);

if DEB
    figure
    plot(fftshift(20*log10(abs(fft(x_temp(1:lgth).*hanning(lgth))))));
    title('FFT of filtered, interpolated, outside BW suppressed x(t)');
    ylabel('Mag (dB)');
end
x = x_temp;
% ------------------ END ------------------

% ********************* START *********************
% Perform modulation
fs = 60e6;    % Sampling Frequency of the signal generator
y = modulate(x,fc,fs,'am');

% Choose a random AM technique
r_num = rand(1,1);              % Random number
if (r_num >= 0) & (r_num <= 1/3)
    y = modulate(x,fc,fs,'am');         % Double-sideband suppressed carrier
elseif (r_num > 1/3) & (r_num <= 2/3)
    y = modulate(x,fc,fs,'amdsb-tc');   % Double-sideband trasmitted carrier
elseif (r_num > 2/3) & (r_num <= 1)
    y = modulate(x,fc,fs,'amssb');      % Single-sideband
end

fc = fc + 4e3;                  % Increment frequencey by 4kHz

% FFT of modulated signal
lgth=length(y);
k=20*log10(abs(fft(y(1:lgth).*hanning(lgth))));   %scaled fft if data in file
omeg = -fs/2:fs/length(y):fs/2-fs/length(y);
if DEB
    figure
    plot(omeg,fftshift(k));      %plot fft
title('FFT of single fc');
xlabel('Frequency (Hz)')
end
% ********************* END *********************

final_array = final_array + y;

if DEB
    lgth=length(final_array);
k2=20*log10(abs(fft(final_array(1:lgth).*hanning(lgth))));   %scaled fft if data in file
    omeg = -fs/2:fs/length(final_array):fs/2-fs/length(final_array);
    figure
    plot(omeg,fftshift(k2));   %plot fft
title('FFT of multiple fc')
xlabel('Frequency (Hz)')
end
end
k=20*log10(abs(fft(final_array(1:lgth).*hanning(lgth))));  %scaled fft if data in file
omeg = -fs/2:fs/length(final_array):fs/2-fs/length(final_array);
figure
plot(omeg,fftshift(k));  %plot fft
xlabel('Frequency (Hz)')

% IMAGINARY SIDE OFF SPECTRUM REMOVED %
Spectrum = k(1:length(k)/2);

if iii == 1
    save('SURV_A0_1997_15Jan_2am_recreated.mat', 'Spectrum');
elseif iii == 2
    save('SURV_A0_1997_15Jan_5am_recreated.mat', 'Spectrum');
elseif iii == 3
    save('SURV_A0_1997_15Jan_9am_recreated.mat', 'Spectrum');
end

clear all

end
clear all
close all

DEBUG = 0;

clear Spectrum
% Loads spectrum data
%load 'H:\Digital Rx\Matlab\Adelaide Spec\JFAS_adel_HF_environ_creation.mat'
Spectrum;
load 'C:\Wayne\HF Env Recreation\SURV_A0_1997_15Jul_12noon_recreated.mat'
Spectrum;

% Read out data from the file and load spectrum
for xxx=1:30
  xxx
  InterpSpec = Spectrum;

  if xxx==1
    testset = 'testset_1.txt';
  elseif xxx==2
    testset = 'testset_2.txt';
  elseif xxx==3
    testset = 'testset_3.txt';
  elseif xxx==4
    testset = 'testset_4.txt';
  elseif xxx==5
    testset = 'testset_5.txt';
  elseif xxx==6
    testset = 'testset_6.txt';
  elseif xxx==7
    testset = 'testset_7.txt';
  elseif xxx==8
    testset = 'testset_8.txt';
Testing Digital Receiver Performance through an HF Environment Simulator

elseif xxx==9
    testset = 'testset_9.txt';
elseif xxx==10
    testset = 'testset_10.txt';
elseif xxx==11
    testset = 'testset_11.txt';
elseif xxx==12
    testset = 'testset_12.txt';
elseif xxx==13
    testset = 'testset_13.txt';
elseif xxx==14
    testset = 'testset_14.txt';
elseif xxx==15
    testset = 'testset_15.txt';
elseif xxx==16
    testset = 'testset_16.txt';
elseif xxx==17
    testset = 'testset_17.txt';
elseif xxx==18
    testset = 'testset_18.txt';
elseif xxx==19
    testset = 'testset_19.txt';
elseif xxx==20
    testset = 'testset_20.txt';
elseif xxx==21
    testset = 'testset_21.txt';
elseif xxx==22
    testset = 'testset_22.txt';
elseif xxx==23
    testset = 'testset_23.txt';
elseif xxx==24
    testset = 'testset_24.txt';
elseif xxx==25
    testset = 'testset_25.txt';
elseif xxx==26
    testset = 'testset_26.txt';
elseif xxx==27
    testset = 'testset_27.txt';
elseif xxx==28
    testset = 'testset_28.txt';
elseif xxx==29
    testset = 'testset_29.txt';
elseif xxx==30
    testset = 'testset_30.txt';
end

[sig1_mag,sig1_freq,sig2_mag,sig2_freq,spur1,spur2,spur3,spur4,spur5,spur6,spur7,spur8,spur9,spur10] = textread(testset,'%*c %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f %f');
FreqRes = 0.0001;  % 100Hz
xaxis_array = 0:FreqRes:30-FreqRes;
xaxis_array = xaxis_array';

% Find out which array number the frequencies will lie at and suppress the
% signal at that frequency
i=1;
for k=4:length(xaxis_array)-1
    for m=1:length(spur1)
        if (spur1(m) > xaxis_array(k-1)) & (spur1(m) < xaxis_array(k+1))
            null_array(i,1) = k;
            null_array(i,2) = spur1(m);
            null_array(i,3) = xaxis_array(k);
            null_array(i,4) = InterpSpec(k);
            InterpSpec(k-2:k+2) = -300;
            i = i + 1;
        elseif (spur2(m) > xaxis_array(k-1)) & (spur2(m) < xaxis_array(k+1))
            null_array(i,1) = k;
            null_array(i,2) = spur2(m);
            null_array(i,3) = xaxis_array(k);
            null_array(i,4) = InterpSpec(k);
            InterpSpec(k-2:k+2) = -300;
            i = i + 1;
        elseif (spur3(m) > xaxis_array(k-1)) & (spur3(m) < xaxis_array(k+1))
            null_array(i,1) = k;
            null_array(i,2) = spur3(m);
            null_array(i,3) = xaxis_array(k);
            null_array(i,4) = InterpSpec(k);
            InterpSpec(k-2:k+2) = -300;
            i = i + 1;
        elseif (spur4(m) > xaxis_array(k-1)) & (spur4(m) < xaxis_array(k+1))
            null_array(i,1) = k;
            null_array(i,2) = spur4(m);
            null_array(i,3) = xaxis_array(k);
            null_array(i,4) = InterpSpec(k);
            InterpSpec(k-2:k+2) = -300;
            i = i + 1;
        elseif (spur5(m) > xaxis_array(k-1)) & (spur5(m) < xaxis_array(k+1))
            null_array(i,1) = k;
            null_array(i,2) = spur5(m);
            null_array(i,3) = xaxis_array(k);
            null_array(i,4) = InterpSpec(k);
            InterpSpec(k-2:k+2) = -300;
            i = i + 1;
        elseif (spur6(m) > xaxis_array(k-1)) & (spur6(m) < xaxis_array(k+1))
            null_array(i,1) = k;
            null_array(i,2) = spur6(m);
            null_array(i,3) = xaxis_array(k);
            null_array(i,4) = InterpSpec(k);
            InterpSpec(k-2:k+2) = -300;
            i = i + 1;
        end
    end
end
null_array(i,2) = spur6(m);
null_array(i,3) = xaxis_array(k);
null_array(i,4) = InterpSpec(k);
InterpSpec(k-2:k+2) = -300;
i = i + 1;
elseif (spur7(m) > xaxis_array(k-1)) & (spur7(m) < xaxis_array(k+1))
    null_array(i,1) = k;
    null_array(i,2) = spur7(m);
    null_array(i,3) = xaxis_array(k);
    null_array(i,4) = InterpSpec(k);
    InterpSpec(k-2:k+2) = -300;
i = i + 1;
elseif (spur8(m) > xaxis_array(k-1)) & (spur8(m) < xaxis_array(k+1))
    null_array(i,1) = k;
    null_array(i,2) = spur8(m);
    null_array(i,3) = xaxis_array(k);
    null_array(i,4) = InterpSpec(k);
    InterpSpec(k-2:k+2) = -300;
i = i + 1;
elseif (spur9(m) > xaxis_array(k-1)) & (spur9(m) < xaxis_array(k+1))
    null_array(i,1) = k;
    null_array(i,2) = spur9(m);
    null_array(i,3) = xaxis_array(k);
    null_array(i,4) = InterpSpec(k);
    InterpSpec(k-2:k+2) = -300;
i = i + 1;
elseif (spur10(m) > xaxis_array(k-1)) & (spur10(m) < xaxis_array(k+1))
    null_array(i,1) = k;
    null_array(i,2) = spur10(m);
    null_array(i,3) = xaxis_array(k);
    null_array(i,4) = InterpSpec(k);
    InterpSpec(k-2:k+2) = -300;
i = i + 1;
end
end
end

if DEBUG
    figure
    plot(xaxis_array,InterpSpec);
xlabel('Frequency (MHz)');
ylabel('Power (dBW)');
title('Interpolated noise + 2kHz Spectrum (spur locations supressed)');
end

if DEBUG
    figure
    plot(InterpSpec);
ylabel('Power (dBW)');
title('Interpolated noise + 2kHz Spectrum (spur locations supressed)');
end

% Add 20dB to take into account for 20dB PAD on output
InterpSpec = InterpSpec + 20;

% [a, ind] = max(InterpSpec);
% FreqInd = (ind-1)*FreqRes;
% fprintf('Max signal of %0.2fdBm, at %0.3fMHz, ind %d\n', 20*log10(a)-10*log10(50)+30, FreqInd, ind);

if DEBUG
    figure
    plot(xaxis_array,InterpSpec);
    xlabel('Frequency (MHz)');
    ylabel('Power (dBW)');
    title('Interpolated noise + 2kHz Spectrum (after +20dB)');
end;

% Convert the dBW to voltage before adding random phase
InterpSpec = 10.^(InterpSpec+17)/20;

% Add random phase
% fprintf('Adding Random Phase\n');
randphase=(rand(length(InterpSpec),1)*2*pi - pi);
randphase(1) = 1+j*0;
Newspec=((InterpSpec).*exp(j*randphase));
conjNewspec = flipud(conj(Newspec(2:length(Newspec))));
Spectrum2 = [Newspec; Newspec(1); conjNewspec];
b=length(Spectrum2);

% Output some stuff to the workspace
null_array(:,1);     % Array Number
null_array(:,2);     % Text File Frequency
null_array(:,3);    % Matlab frequency
null_array(:,4);     % Mag Before nulling

%**************************************************************************
%break
%**************************************************************************

% Convert the voltage frequency spectrum to a time series
% fprintf('Inverse FFT\n');
timeser1 = ifft(Spectrum2);

% Plot power spectral magnitude
if DEBUG
    figure;
    psd(timeser1, 65536, 65e6);
end;

% Plot time series
if DEBUG
    figure;
    plot(real(timeser1));
    title('time series');
end;

%fprintf('Scaling Data to 16bit\n');
%timeser1 = 32767*timeser1/max(timeser1);

% Plot scaled time series
if DEBUG
    figure;
    plot(real(timeser1));
    title('scaled time series');
end;

% ---------- START -----------
% Convert signal to mat file for sig gen

V = timeser1;

m=max(real(V));
data(1:2:length(V))=((real(V)/m*32767));
data(2:2:length(V))=0;

% plots
if DEBUG
    data = data';
    lgth = length(data);
    y = 20*log10(abs(fft((data(1:2:lgth)*m/32767).*hanning(lgth/2))));
    figure
    plot(y);
    title('Check Spectrum sent to sig gen');
end;

fname1=['C:\Program Files\WS_FTP\'];
fname2=['1997_15Jul_12noon'];

% Send data to file
if xxx==1
    fname3=['_1.dat'];
elseif xxx==2
    fname3=['_2.dat'];
elseif xxx==3
    fname3=['_3.dat'];
elseif xxx==4
fname3=['_4.dat'];
elseif xxx==5
  fname3=['_5.dat'];
elseif xxx==6
  fname3=['_6.dat'];
elseif xxx==7
  fname3=['_7.dat'];
elseif xxx==8
  fname3=['_8.dat'];
elseif xxx==9
  fname3=['_9.dat'];
elseif xxx==10
  fname3=['_10.dat'];
elseif xxx==11
  fname3=['_11.dat'];
elseif xxx==12
  fname3=['_12.dat'];
elseif xxx==13
  fname3=['_13.dat'];
elseif xxx==14
  fname3=['_14.dat'];
elseif xxx==15
  fname3=['_15.dat'];
elseif xxx==16
  fname3=['_16.dat'];
elseif xxx==17
  fname3=['_17.dat'];
elseif xxx==18
  fname3=['_18.dat'];
elseif xxx==19
  fname3=['_19.dat'];
elseif xxx==20
  fname3=['_20.dat'];
elseif xxx==21
  fname3=['_21.dat'];
elseif xxx==22
  fname3=['_22.dat'];
elseif xxx==23
  fname3=['_23.dat'];
elseif xxx==24
  fname3=['_24.dat'];
elseif xxx==25
  fname3=['_25.dat'];
elseif xxx==26
  fname3=['_26.dat'];
elseif xxx==27
  fname3=['_27.dat'];
elseif xxx==28
  fname3=['_28.dat'];
elseif xxx==29
fname3=['_29.dat'];
elseif xxx==30
    fname3=['_30.dat'];
end

fname=[fname1 fname2 fname3];
fd=fopen(fname,'w','b');
fwrite(fd,data,'short');
fclose(fd);

% ----------- FINISH ------------
clear xa*
clear s*
clear t*
clear r*
clear i k m
clear n*
clear f*
clear F*
clear I*
clear N*
clear Spectrum2
clear V ans b
clear conj*
clear d*

end
Appendix G – MATLAB Code (JFAS system gain removal)

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% Removes the gains associated with the JFAS system to put the data
%% at the
%% antenna base not at the receiver input (at the year 1997)
%%
%% Used after read_HF_environ.m
%%
%% Used in conjunction with HF_environ_nulling.m,
%% HF_environ_creation.m
%%
%% Created for Research Masters by Wayne Pennington 24 May 2004
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
clearall
close all

% Loads 1997 spectrum data
load 'H:\Digital Rx\Matlab\JFAS Spec mat files\SURV_A0_1997_298.mat'
spec;

freq = 5:0.002:30-0.002; % in MHz

figure
plot(freq, spec(:,3));
%title('Spectrum before gain removal (1997 15 January 2am)');
xlabel('Frequency (MHz)');
ylabel('Mag (dB)');

% Remove preamp gain of 18.1dB
spec = spec - 18.1;

% Remove splitter loss of 4.8dB
spec = spec + 4.8;

% Remove cable loss (215m)
cable_constant = -0.00365;
cable_len = 215;

for i=1:length(freq)
    cable_loss = cable_len * sqrt(freq(i)) * cable_constant;
    spec(i,:) = spec(i,:) + abs(cable_loss);
end

%figure
%plot(freq, spec);
%title('Spectrums after gain removal');
%xlabel('Frequency (MHz)');
ylabel('Mag (dB)');

% Save the spec array
save('SURV_A0_1997_298_nogain.mat', 'spec');
clear all
close all

% Loads 1997 spectrum data
load 'H:\Digital Rx\Matlab\JFAS Spec mat files\SURV_A0_2001_288.mat'
spec;

% Remove preamp gain of 18.1dB
spec = spec - 18.1;

% Remove splitter loss of 3.45dB
spec = spec + 3.45;

% Remove cable loss (448m)
cable_constant = -0.00365;
cable_len = 448;
freq = 5:0.002:30-0.002; % in MHz
for i=1:length(freq)
    cable_loss = cable_len * sqrt(freq(i)) * cable_constant;
    spec(i,:) = spec(i,:) + abs(cable_loss);
end

% Save the spec array
save('SURV_A0_2001_288_nogain.mat', 'spec');
## Appendix H – Two Tone Test Frequencies

<table>
<thead>
<tr>
<th>Test Signal Freq (MHz)</th>
<th>Signal 1</th>
<th>Signal 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-10MHz</td>
<td>-1MHz</td>
</tr>
<tr>
<td></td>
<td>-100kHz</td>
<td>-10kHz</td>
</tr>
<tr>
<td></td>
<td>-1kHz</td>
<td>-100Hz</td>
</tr>
<tr>
<td></td>
<td>+100Hz</td>
<td>+1kHz</td>
</tr>
<tr>
<td></td>
<td>+10kHz</td>
<td>+100kHz</td>
</tr>
<tr>
<td></td>
<td>+1MHz</td>
<td>+10MHz</td>
</tr>
<tr>
<td>-1.865973</td>
<td>7.134027</td>
<td>8.034027</td>
</tr>
<tr>
<td>0.460327</td>
<td>-10MHz</td>
<td>-100kHz</td>
</tr>
<tr>
<td>1.503276</td>
<td>10.503276</td>
<td>11.403276</td>
</tr>
<tr>
<td>2.762936</td>
<td>11.762936</td>
<td>12.662936</td>
</tr>
<tr>
<td>3.944276</td>
<td>12.944276</td>
<td>13.844276</td>
</tr>
<tr>
<td>4.693846</td>
<td>14.693846</td>
<td>15.593846</td>
</tr>
<tr>
<td>5.946370</td>
<td>14.946370</td>
<td>15.846370</td>
</tr>
<tr>
<td>6.463716</td>
<td>15.463716</td>
<td>16.363716</td>
</tr>
<tr>
<td>7.271172</td>
<td>16.271172</td>
<td>17.171172</td>
</tr>
<tr>
<td>8.069388</td>
<td>17.069388</td>
<td>17.969388</td>
</tr>
<tr>
<td>9.187384</td>
<td>18.187384</td>
<td>19.087384</td>
</tr>
<tr>
<td>10.349388</td>
<td>19.349388</td>
<td>20.249388</td>
</tr>
<tr>
<td>11.914304</td>
<td>20.914304</td>
<td>21.814304</td>
</tr>
<tr>
<td>12.013763</td>
<td>21.013763</td>
<td>21.913763</td>
</tr>
<tr>
<td>13.987530</td>
<td>22.987530</td>
<td>23.887530</td>
</tr>
<tr>
<td>14.174023</td>
<td>23.174023</td>
<td>24.074023</td>
</tr>
<tr>
<td>15.402955</td>
<td>24.402955</td>
<td>25.302955</td>
</tr>
<tr>
<td>16.399260</td>
<td>25.399260</td>
<td>26.299260</td>
</tr>
<tr>
<td>17.785657</td>
<td>26.785657</td>
<td>27.685657</td>
</tr>
<tr>
<td>18.505884</td>
<td>27.505884</td>
<td>28.405884</td>
</tr>
</tbody>
</table>

**Notes:**
- The frequencies are given in MHz.
- The table lists frequencies for the test signals in signal 1 and signal 2, covering a range from -10MHz to +10MHz.
- The test frequencies are used to evaluate the performance of a digital receiver in an HF environment simulator.

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