A HILBERT TRANSFORM BASED RECEIVER POST PROCESSOR

1991 Antenna Measurement Techniques Association Conference

D. Slater
Nearfield Systems Inc.
1330 E. 223rd Street Bldg. 524
Carson, CA 90745
310-518-4277

ABSTRACT

This paper describes a software based receiver post processor that corrects circularity and gain errors in coherent receivers. The receiver post processor additionally provides range gating capabilities, signal quality estimation, mixer non-linearity detection and various display functions. This paper will concentrate primarily on the identification of circularity errors by the receiver post processor.

INTRODUCTION

This paper describes a software based receiver post processor now incorporated in near-field measurement systems built by Nearfield Systems Inc. (NSI). The post processor concept is generic in the sense that it may be used with any amplitude/phase measuring receiver providing capabilities not normally available. A significant advantage of the post processor is that a new class of frequency agile yet simple and low cost receivers can be used to provide high quality near-field measurements. A version of this receiver built by NSI currently provides 37,500 CW or multifrequency measurements per second. This type of receiver however has large frequency dependent circularity errors which must be corrected. This is the primary function of the post-processor. The receiver post-processor provides the following functions:

1. Gain and circularity corrector -- Provides quadrature unbalance and gain correction to a measurement set. A Hilbert transform technique is used to identify the frequency dependent gain and circularity errors within the receiver.

2. Range gate - Swept frequency RF measurement may be gated by pulse compression to be within a certain path length differential.

3. Signal quality monitor - Provides a real time estimate of the receiver noise power and signal to noise ratio.

4. Non-linearity detection - Detects the presence of receiver compression and non-linearities by a spatial distortion method.

5. Display module - The receiver post processor includes an extensive signal display capability.

LO GENERATION IN SUPERHETERODYNE RECEIVERS

Virtually all receivers used in antenna and RCS measurements are based on a superheterodyne design. The superheterodyne receiver generally includes a mixer followed by an IF amplifier. The IF amplifier output is then down-converted to DC in a second mixer. The first mixer is driven from a local oscillator (LO) which is offset in frequency from the receive frequency by the IF frequency. The superheterodyne design minimizes leakage, drift and 1/f noise terms as compared to a homodyne receiver.

A significant problem in the design of superheterodyne receiver and vector network analyzers is developing the coherently related LO offset frequency. Four methods of LO frequency generation are summarized below:

Indirect synthesis:

1. Phase locked loop

Direct synthesis:

2. Dual coherent synthesizers

3. Phase modulated (serrodyne) systems
4. Hilbert transform methods

(Method 1) The most common method of generating the LO frequency offset is to use an indirect phase locked loop (PPL). This method is used in phase coherent antenna receivers and vector network analyzers built by Hewlett-Packard, Scientific-Atlanta and others. Disadvantages of this approach include limited frequency switching speed and general complexity.

(Method 2) The frequency agility of a receiver or vector network analyzer can be greatly increased by using a directly synthesized LO. Several vendors offer the option of using a pair of coherently related direct digital frequency synthesizers to provided both the source frequency and offset LO frequency. While this approach can provide very fast frequency switching, it is even more costly and complex than method 1.

(Method 3) Another method of LO generation using direct frequency synthesis is much simpler than either method 1 or 2. The LO frequency offset can be directly synthesized by the phase modulation of the transmitted signal. The phase modulation is accomplished by using a broadband bi-phase or quadra-phase modulator. Either a single or quadrature mixer is then used to down-convert the RF signal (Slater, 1991). The primary disadvantage of this technique is that relatively large frequency dependent circularity errors within the QPSK modulator or quadrature mixer will result in the generation of spurious LO sidebands. These frequency dependent circularity errors however are stable with time and can be readily suppressed if correctly identified. The primary function of the receiver post processor is the precise and quantitative identification of the circularity errors and the associated suppression of these errors.

(Method 4) The receiver post processor creates a truth or reference model of the circularity errors using direct synthesis of the LO frequency offset through the use of a doppler shift technique. A Hilbert transformer is then used to extract an error free quadrature signal (Slater, 1991, Slater, 1985).

The doppler frequency shift is directly equivalent to the IF frequency offset. A doppler frequency shift is produced when the path-length dimensions as measured in wavelengths is dynamically varied. This variation can be accomplished either by a physical change in the interferometer path length difference or by changing the RF test frequency.

Because of the unknown circularity errors, the quadrature signal component is derived through the use of a Hilbert transformer implemented numerically in a digital computer. The Hlbert transformer is conceptually equivalent to a broadband 90° phase shifter (Slater, 1991, Slater, 1985). One requirement for the Hilbert transform to be valid is that the input signal not contain any negative frequencies. The path length changes producing the doppler signal are used to suppress negative frequency components. The I channel signal and Hilbert transform are combined to form an analytic signal which is then used to identify the circularity and gain errors within any receiver configuration.

A phase modulated interferometer suitable for near-field antenna measurement manufactured by NSI uses method 3 to provide a measurement speed of 37,500 CW or multifrequency measurements per second over a continuous frequency span of 2 to 26 GHz. A modification of method 4 is used by the post processor to calibrate the circularity errors in the hardware.

RECEIVER POST PROCESSOR

The receiver post processor includes the following major signal processing software modules:

1. Error corrector – applies a frequency dependent gain and circularity correction to a given RF measurement.
2. Chirp/doppler processor – identifies gain, circularity and linearity errors and provides a range gating function.

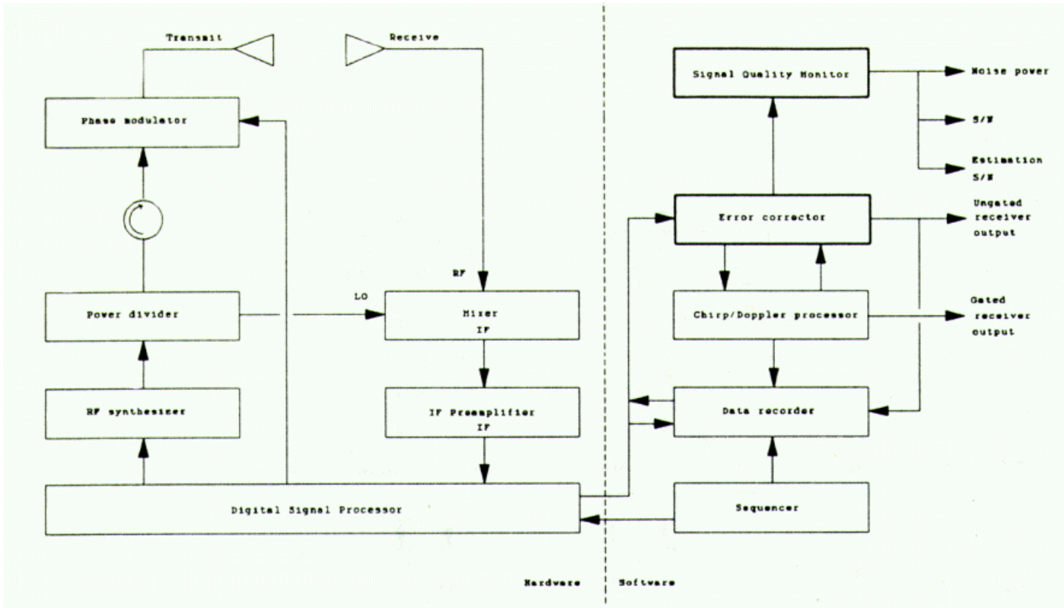


Figure 1 -- Phase Modulated Interferometer and Receiver Post Processor

3. Signal quality monitor – provides an estimate of the receiver noise power and signal to noise ratio.

Figure 1 shows a block diagram of the NSI phase modulated interferometer and major receiver post processor elements.

CIRCULARITY ERROR IDENTIFICATION

Error in the circularity or orthogonality of a quadrature mixer or quadra-phase modulator cause AM to PM and PM to AM conversion error within the receiver. The circularity error consists of differences in the relative gains of the I and Q channels and lack of orthogonality between the I and Q channels. The term circularity error came about from Q vs. I parametric plots where a swept frequency measurement may trace out an ellipse instead of a circle if a quadrature signal was unbalanced. The impact of circularity errors to near-field measurements include spurious sidelobes and gain errors.

The circularity calibration is performed as follows:

1. A swept frequency measurement set is acquired and read into an input vector. If the receiver is limited to operation at a single frequency, the path length is swept instead of frequency. The circularity calibration is not sensitive to multipath, source phase noise or similar terms as long as these terms do not induce negative frequencies. Aliased multipath and excessive source phase noise can be identified in the pulse compressor display.

2. The measurement set is tapered with a Kaiser-Bessel window. This window significantly reduces the level of range sidelobes after the signal is compressed. A pulse compression is performed by a Fourier transform resulting in the complex receiver output sorted in terms of differential path length. In the case of a CW swept path measurement, the output is sorted in terms of spatial frequency. This mode is similar to the time domain mode often seen in network analyzers.

3. The pulse compressed measurement is gated in terms of path length or spatial frequency by applying a range gating window function. This window is designed so as to eliminate all energy at negative ranges. Because the range gate does not cross through zero path

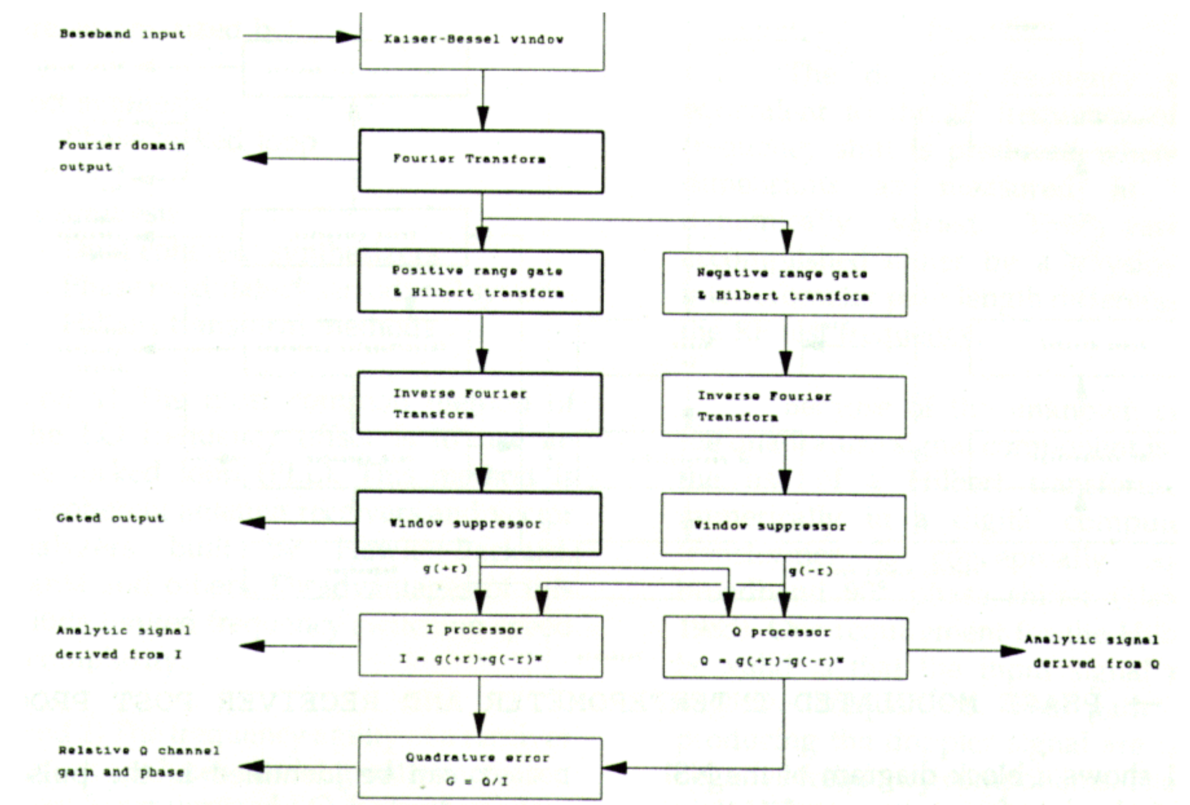


Figure 2-- Cirularity Identification

4. length or spatial frequency offset, a Hilbert transform was performed.

5. Step three is repeated with a mirror image range gate.

6. The results of step 4 and 5 are inverse Fourier transformed and normalized. The normalization removes the frequency or position dependent amplitude distortion introduced in step 2.

6. Because both I and Q channels measurements were passed through both transforms, the derived analytic signals need to be separated. The sum and difference of the gated positive and complex conjugate negative frequency domain vectors is then formed. The sum corresponds to an uncorrupted gated I derived analytic signal. The difference corresponds to the gated Q derived analytic signal.

7. The Q derived analytic signal is divided by the I derived analytic signal. The result is the circularity error. The circularity errors are saved in a table for use by the gain and circularity compensator. The operation of the chirp/doppler processor is better understood by following the signal flow. A simulated receiver input consisting of a swept frequency measurement from 4 to 12 GHz through a 10 foot path length differential including a pair of antennas is used for the following example. The simulation includes a 3.5dB high Q channel gain with a +5° phase unbalanced from 4 to 6GHz, a 3.5dB low Q channel gain with a -5° phase unbalance from 6 to 11 GHz and no error from 11 to 12 GHz.

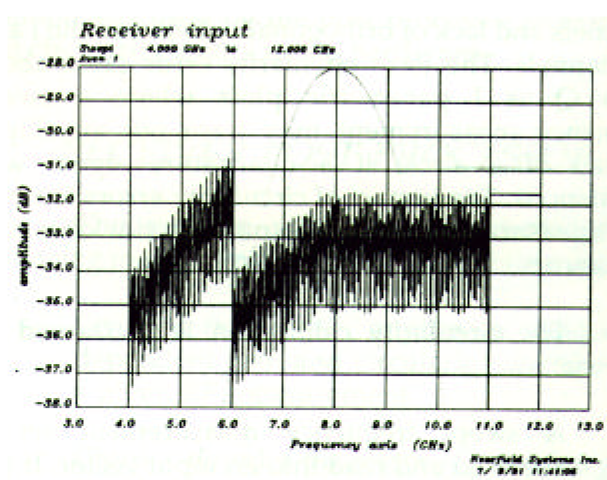


Figure 3 -- Simulated Receiver Input Signal

Figure 3 shows the amplitude of the receiver as a function of frequency. The amplitude ripple in the pattern is equal to the peak to peak quadrature unbalance or 7dB. Note that the Q unbalance is specified relative to the I channel. I channel errors are accounted for by the overall frequency dependent gain correction.

Figure 4 shows the Fourier transform of the input signal. The Fourier domain corresponds to path length differential. A receiver signal with no quadrature error will have a single peak at a 10 foot distance. The peak at the image range (-10 feet) is directly related to the quadrature unbalance. This peak can be alternately considered to the result of a serrodyne LO signal at the image frequency.

Figure 5 shows the analytic signal derived from the I channel. This signal corresponds to measurements made without quadrature or circularity error. Notice that there is no amplitude ripple. The generally ascending power is due to the inverse square law model in the simulator which transitions into a near-field region at the right side.

Figure 6 shows the result of dividing the Q derived analytic signal by the I derived analytic signal. This ratio is frequency dependent and corresponds to the gain and phase unbalance between the Q and I channels.

RESULTS

The receiver post processor has been used with both the HP-8510C network analyzer and with the NSI phase modulated interferometer. The HP-8510C residual circularity errors were extremely low, as expected.

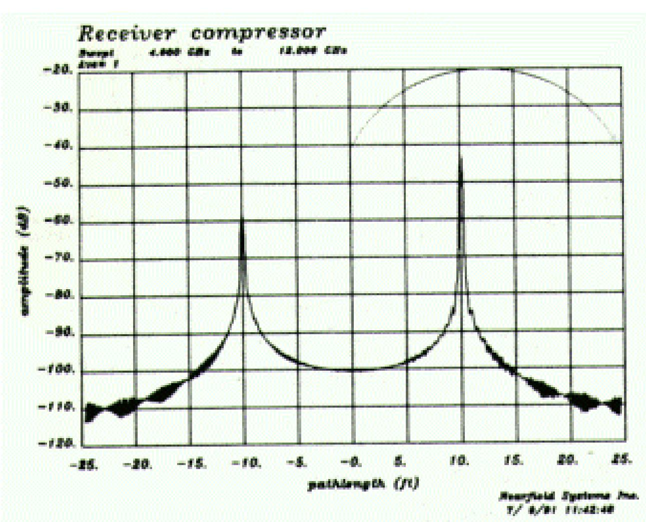


Figure 4 – Pulse Compressor Output

Without compensation, circularity errors in the NSI interferometer are quite large as is shown in Figure 7. Figure 8 shows a near-field derived pattern of a standard gain horn without circularity correction. Figure 9 shows the same pattern with circularity correction enabled. This corrected pattern is virtually identical to a pattern acquired with a HP-8510C receiver in the same test setup.

Correct operation of the circularity calibration can be verified by computing the residual circularity error of the corrected signal and more importantly, by the ratio of the negative to positive path-length amplitude in the pulse-compressor display. This ratio is equivalent to the single-sideband-suppression ratio. In the current version of the NSI interferometer, the sideband-suppression ratio is typically better than 55dB. This corresponds to a residual RMS gain and phase unbalance of 0.02dB and 0.1 degree.

CONCLUSIONS

This paper has described a receiver post-processor which compensated for frequency dependent gain and circularity errors as found in a new class of simple yet high performance receivers. Additional capabilities include signal quality determination, range gating and the detection of compression and non-linearities in a coherent receiver.

REFERENCES

1. Mensa, D., High Resolution Radar Imaging, Artech House, Norwood, MA, 1981

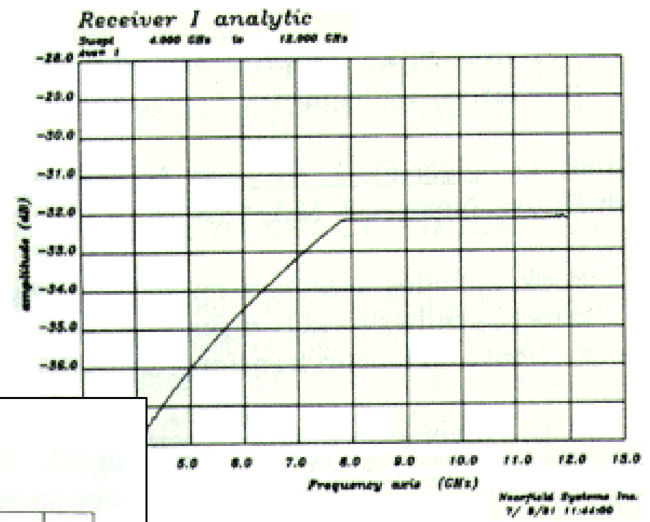
Describes pulse compression and the related processing algorithms.

2. Slater, D., Near-field Antenna Measurements, Artech House, Norwood, MA, 1991

Book includes a section on receivers using direct synthesis LO including serrodyne systems and Hilbert transform based designs.

3. Slater, D., Interverse Synthetic Aperture Imaging Radar, AMTA Conference Proceedings, Melbourne, FL, 1985

Paper describes a swept frequency pulse compression receiver which derives phase information through the use of the Hilbert transform.



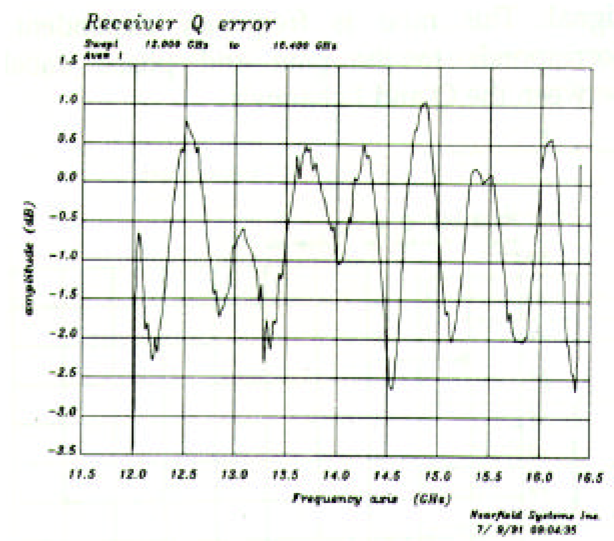


Figure 7 – Pmi Uncorrected Circulirity Error

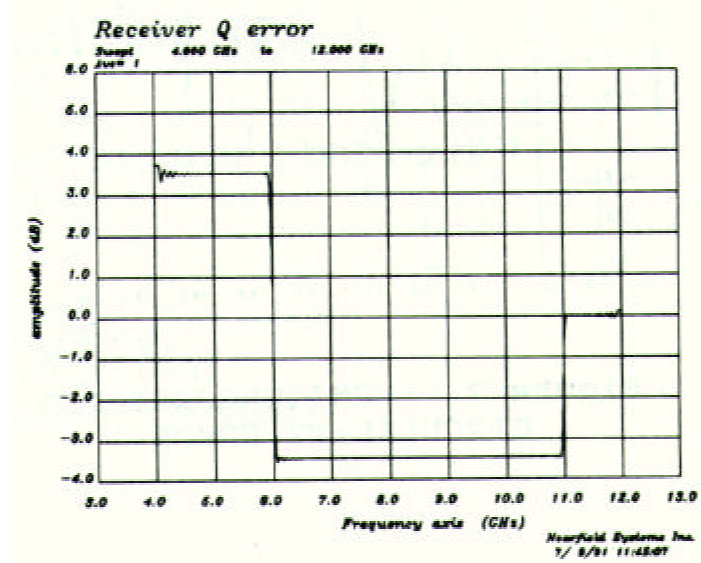


Figure 6 – Derived Circularity Error (Gain)

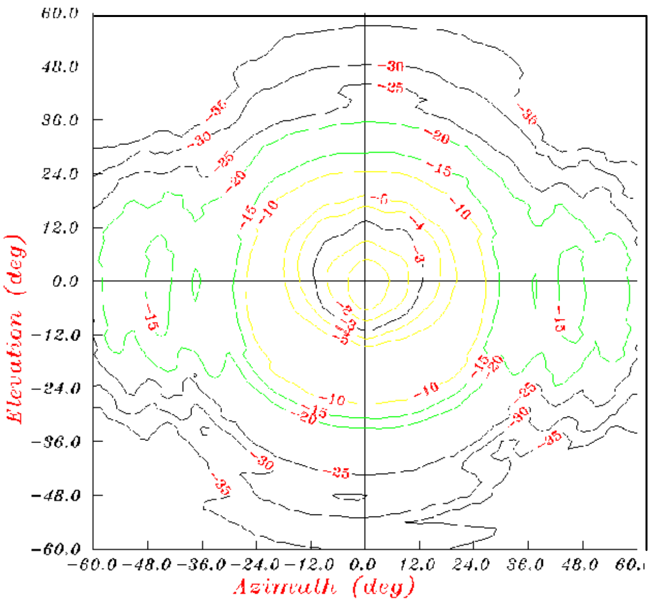


Figure 8 – Horn Pattern With No Circularity Correction

Figure 9 – Horn Pattern With Circularity Correction Enabled