U.S. Army Intelligence Center and School
Software Analysis and Management System

BRAGG-CELL Receiver Study

Technical Memorandum No. 19

Lonnie A. Wilson

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National Aeronautics and
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Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

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A software implementation of a model of the Bragg-cell radar receiver is the product of this memo. Initially, the ideal Bragg-cell is described mathematically. The first-order AG transducer non-linearities are then introduced. This model is then tested with either constant or Gaussian input and constant or Gaussian first-order non-linearity (distortion signal). This model still required validation against actual Bragg-cell data. The model code is included in the appendix.
U.S. ARMY INTELLIGENCE CENTER AND SCHOOL
Software Analysis and Management System

BRAGG-CELL RECEIVER STUDY
EAAF

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PREFACE

The work described in this publication was sponsored by the United States Army Intelligence Center and School. The writing and publication of this paper was supported by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration, NAS 7-918, RE 182, A187.
This Technical Memorandum was prepared originally as part of the Generic ELINT/COMINT Sensor Report (FY-86) which was eliminated under the FY-87 statement of work (SOW #2), undated (delivered to JPL 19 November 1986).

The purpose of the Generic ELINT/COMINT Sensor Report, of which this paper was intended (in its final form) to become part of, was to establish a basic superheterodyne receiver based sensor model and perform simulations with it to determine the shaping or coloring of the statistical distributions of the radar free-space signal parametrics by a typical sensor prior to reaching the self-correlation processes. It was also intended for incorporation into the algorithm test bed so algorithms could be tested with realistic distorted data rather than unrealistic stastically pure data.

This work was originated in support of unanswered questions from previous self-correlation studies. The modeling and simulation approach was used because "live date" could not be obtained.

This paper is being published because it was completed in FY-86 with FY-86 funds and still serves a useful function.

Several significant results were noted while performing simulations on this model. The first order math model is developed for the Bragg-cell receiver. Whether the input distributions were uniform or Gaussian, the output distributions were found to be shaped so as to append a staircased triangular distribution.
BRAGG-CELL RECEIVER STUDY

FINAL REPORT

MARCH 1987

JPL CONTRACT NO. 957474 MOD. NO. 1

This work was performed for the Jet Propulsion Laboratory, California Institute of Technology, sponsored by the National Aeronautics and Space Administration.

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ABSTRACT

Bragg-cell receivers are employed in specialized Electronic Warfare (EW) applications for the measurement of frequency. Bragg-cell receiver characteristics are fully characterized for simple RF emitter conditions, but less understood for complex and wideband RF emitter signals. This receiver is early in its development cycle when compared to the IFM receiver.

Functional mathematical models are derived and presented in this report for the Bragg-cell receiver. Theoretical analysis is presented and digital computer signal processing results are presented for the Bragg-cell receiver. Probability density function analysis are performed for output frequency.

Probability density function distributions are observed to depart from assumed distributions for wideband and complex RF signals. This analysis is significant for high resolution and fine grain EW Bragg-cell receiver systems.
NEW TECHNOLOGY

None
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INTRODUCTION

The development effort is for theoretical analysis, software algorithms implementations, signal processing analysis, and test analysis for probability density function characterization of a Bragg-cell receiver system. SigPro Systems Inc. is performing this work under JPL Contract No. 957474, Mod. No. 1.

This final report describes the completed study on the Bragg-cell receiver. A functional mathematical model is derived for the receiver. This math model is implemented into digital computer software and signal processing analyses are performed.

Theoretical analysis is developed for the Bragg-cell receiver. Ideal and practical subsystem implementations are presented and analyzed. The key ELINT parameter of interest is frequency, hence, the theoretical analysis presents the basic analysis approach for frequency. Probability density function analysis is presented for first-order subsystem model.

The theoretical model for the Bragg-cell is developed into a digital computer program. All computer programs are listed in Appendix A.

Signal processing analysis is performed using the derived first-order model. The pdf characteristics of the Bragg-cell receiver's output frequency are determined for assumed input frequency pdf (constant and Gaussian) characteristics.
BRAGG CELL RECEIVER

INTRODUCTION

A Bragg-cell receiver is used to measure frequencies of input RF radar pulses, with wide frequency coverage, large dynamic ranges and simultaneous or time coincident signals. The ideal Bragg-cell receiver will measure the frequency parameter on a single pulse basis with no distortion. Practical Bragg-cell receivers will distort the frequency characteristic of a radar emitter because the ideal Bragg-cell receiver characteristics are difficult to approximate in real life.

The radar's frequency parameter can be characterized using a random variable. The random variable may be quantified by the probability density function (pdf), mean value, variance and other moments. As a radar signal passes through the Bragg-cell receiver the random signal description is modified or distorted by the receiver's nonlinear transfer function characteristic. Bragg-cell receiver characterization of RF frequency will differ from actual radar emitter characterization by multifaceted distortion effects.

This section presents a functional description of the Bragg-cell receiver with potential distortion sources and mechanisms and a first-order Bragg-cell receiver model is developed. This Bragg-cell receiver model is used to analyze the distortion of the frequency's pdf. The first-order Bragg-cell receiver model is limited to key distortion effects.

IDEAL BRAGG-CELL RECEIVER CHARACTERIZATION

A functional block diagram of a Bragg-cell receiver is shown in Figure 1. The basic receiver includes an RF-to-IF downconverter, Bragg-cell with AO transducer, laser source, beam expander optics, beam focusing optics, detector array and processing electronics.
FIGURE 1. Functional Block Diagram of a Bragg-Cell Receiver.
The RF input signal is characterized by

\[ x(t) = X(t) \cos[\omega_c t + \phi(t)] \]  

Eq. 1

where

\[ x(t) = \text{Pulsed or CW signal,} \]
\[ X(t) = \text{amplitude modulation function,} \]
\[ \omega_c = \text{fixed angular carrier frequency,} \]
\[ \phi(t) = \text{phase deviation function.} \]

The RF-to-IF downconverter is described in Reference 1. The ideal downconverter is composed of an ideal local oscillator which is a perfect CW signal, a perfect product mixer, and an ideal bandpass filter. The ideal IF signal output from the downconverter is described quantitatively by:

\[ y(t) = X(t) \cos[\omega_{IF} t + \phi(t)] \]  

Eq. 2

Equation 2 is identical to Equation 1 with the fixed angular frequency being changed from \( \omega_c \) to \( \omega_{IF} \). The IF center frequency is chosen to match the center frequency of the Bragg-cell and AO transducer. Ideally the IF signal replicates the input RF signal. The RF-to-IF downconverter is described and characterized in Reference 1. RF-to-IF downconverter analysis will not be presented in this report.

The IF signal drives the AO transducer which launches an acoustic signal through the Bragg-cell. Specifically, the IF electronic signal is converted into an acoustic wave (slow wave replication of the IF signal) which propagates
through the optically transparent Bragg–cell. Through the elasto-optic effect, the acoustic wave produces a spatial modulation of the refractive index in the Bragg–cell (Reference 2.)

The laser source is expanded by the beam expander optics and illuminates the Bragg–cell. As the laser light passes through the Bragg–cell, the refractive index variations produced by the acoustics wave (which is a slow form replica of the IF signal) are impressed onto the optical signal as a spatial phase modulation.

Focusing optics are used to equivalently Fourier transform the modulated optical beam. Resultant optical Fourier transform signal is focused onto the detector array or frequency focal plane (see Figure 1.) The photodiode detector array is used to capture and convert the optical signal to an electronic signal representation. The detector array is a linear photodiode array which is functionally used to detect and measure light intensity versus frequency of the transformed optical signal. The detector array is electronically read by the processing electronics, which also provides follow-on signal processing functions.

The Bragg–cell modulator is depicted in Figure 2. The incident laser light interacts with the acoustic signal in the cell to produce a diffracted light information signal along with undeflected laser light signal. The diffracted laser signal is also frequency shifted by the acoustic signal frequency. The incident laser light hits the Bragg–cell at an angle $\theta_{i}$ with respect to the z axis. The IF electronic signal is sent to the AO transducer to convert the IF signal to a replica acoustic signal. The acoustic wave of frequency $f_{1}$ propagates with velocity $v_{s}$ along the x–axis in the Bragg–cell.

The diffracted laser light signal results from the AO interaction effects between the incident laser beam and the acoustic information bearing signal
in the Bragg-cell. Maximum diffracted laser light energy occurs in the first
order beam when (Reference 2):

\[ \theta_i = \sin^{-1} \left[ \frac{\lambda f_i}{2 V_s} \right] \quad \text{Eq. 3.} \]

and

\[ \theta_d = \theta_i \quad \text{Eq. 4} \]

where

\( \lambda \) = Wavelength of laser light
\( f_i \) = Frequency of acoustic wave
\( V_s \) = Velocity of acoustic wave in Bragg-cell along the x-axis.
\( \theta_i \) = Effective angle of incident laser light.
\( \theta_d \) = Effective angle of first order diffracted laser light information signal.

Detailed Bragg-cell analysis would require AO cell refractive index variations analysis for precise quantification. This first order Bragg-cell model does not require this detailed analysis. Functionally the Bragg-cell model is accurate and conceptually clear for the external angles \( \theta_i \) and \( \theta_d \).

Bragg-cell processors are, in general, configured so that \( \theta_i << 0.1 \) radian, hence, Equation 3 can be readily and accurately simplified to:
Using Equation 4 and 5, the following equation for the effective angle of the first order diffracted laser light information signal is:

\[
\Theta_d = \frac{\lambda f_1}{2 V_s} \quad \text{Eq. 6}
\]

Equation 6 reveals that \( \Theta_d \) varies directly with the acoustic wave frequency. As stated earlier, the IF signal frequency is related to the acoustic wave frequency by: (Reference 2)

\[
f_{IF} = K f_1 \quad \text{Eq. 7}
\]

where \( K \) is a constant.

Equation 8 results by combining Equations 6 and 7,

\[
\Theta_d = \frac{\lambda f_{IF}}{2 K V_s} \quad \text{Eq. 8}
\]

Equation 8 shows that \( \Theta_d \) varies directly with the IF signal carrier frequency.

The actual displacement of the diffracted laser information signal from the undeflected laser light (see Figure 2) is given by (Reference 2.)

\[
d = \frac{F \lambda f_{IF}}{K V_s} \quad \text{Eq. 9}
\]
where $F$ is the focal length of the focusing optics.

A fixed Bragg-cell receiver will result in Equation 9 reducing to:

$$d = K_1 \cdot \frac{f_{IF}}{F} \quad \text{Eq. 10}$$

The actual displacement, $d$, of the diffracted laser beam relative to the undeflected laser light passing through the Bragg-cell is directly proportional to the IF frequency of the input IF electronic signal. The diffracted laser beam will hit the linear detector array at a specific location which corresponds to one IF frequency. The Bragg-cell receiver is calibrated by varying the IF frequency of the input IF signal over the entire operating bandwidth and capturing and analyzing the electrical output signal from the linear detector array. Detector array element signal versus IF frequency characteristic is used to quantify the Bragg-cell receiver's frequency measurement performance.

The undeflected laser light is (the zero-order output from the Bragg-cell) described by:

$$L_0(t) = L_0(t) \cos\left[2\pi f_a t + \gamma(t)\right] \quad \text{Eq. 11.}$$

where

- $L_0(t)$ = undeflected laser light signal.
- $L_0(t)$ = amplitude or intensity of undeflected laser light signal.
- $f_a$ = laser light frequency
- $\gamma(t)$ = phase variations on laser light signal.

The diffracted laser information signal is quantified mathematically as:
where

\[ L_1(t) = \cos \left[ 2\pi (f_2 + f_1) t + \delta(t) \right] \]

Eq. 12.

Equation 12 reveals that the diffracted laser output signal is frequency shifted. The frequency shift is produced by the laser light signal and acoustic signal interaction in the Bragg-cell.

The Bragg-cell receiver is conceptually a parallel, multi-channel spectrum analyzer, which determines the Fourier magnitude spectrum of the input IF signal. The electronic circuit model for the Bragg-cell receiver is depicted in Figure 3. The IF signal input is applied to a parallel narrowband filter bank with an associated diode detector and filter bank. Each output signal is a power or energy indicator of the IF signal spectral content in each selected narrowband filter.

**PRACTICAL BRAGG-CELL RECEIVERS**

The ideal Bragg-cell receiver is characterized in the previous section, with the measured frequency being derived from Equations 9, 10, and 12. This section will identify and briefly present some key differences between practical Bragg-cell receivers and the ideal bragg-cell receiver. The Bragg-cell receiver, shown in Figure 1, is a reference for this discussion.
FIGURE 3. ELECTRONIC CIRCUIT MODEL FOR BRAGG-CELL RECEIVER
BRAGG CELL

The ideal Bragg-cell is assumed to have an undistorted acoustic signal replica (at acoustic frequency) of the IF input signal propagating through the cell. The AO transducer provides this electronic IF signal to acoustic signal conversion. The AO transducer has transfer function nonlinearities, which produces unwanted and added acoustic signal components. Simple sinusoidal electronic signals are subject to minor variations, while complex and wideband signals may be significantly distorted by the nonlinear transducer action.

The ideal Bragg-cell is assumed to provide a perfect acoustic signal termination, at the far end of the cell. In general, the acoustic signal termination is not perfect, which cause low level acoustic signal reflections and distortion generated signal components to propagate back through the cell. These reflected acoustic signals are considered as additional distortion sources, hence, variations in the diffracted laser information signal can be expected.

Actual distortion effects are determined by AO transducer nonlinearities, reflected acoustic signal levels, total acoustic signal parameter descriptors and Bragg-cell properties. The complete acoustic signal's instantaneous frequency is determined by amplitudes, frequencies, and phases of desired acoustic signal, undesired reflected acoustic signals and nonlinearly generated and unwanted acoustic signals. Frequency variations produced by instantaneous frequency changes will produce angle variations in the diffracted laser information signal; thus, frequency measurement errors in the Bragg-cell receiver.
LASER SOURCE

The laser light source is ideally assumed to be constant amplitude and fixed frequency signal. Actual laser sources can have some minor frequency shifts. Minor frequency shifts will result in small angle variations in the diffracted laser information signal. (See Equation 3.)

Frequency variations will widen the effective spot size and change the angle of the diffracted laser beam, which means the light energy may be spread over more detector elements in the linear detector array.

The laser light signal does not have a constant intensity or amplitude. The amplitude is quantified by deterministic and random signal components. These amplitude variations will result in diffracted laser information signal intensity level variations at the detector plane.

OPTICS

Beam expander optics and diffraction signal focusing optics are fundamental modules in the Bragg-cell receiver. Beam expander optics shape the coherent laser beam to illuminate one entire side of the Bragg-cell. This beam expansion provides a long path interaction between the acoustic signal and laser light within the Bragg-cell. Beam expander optics and laser source are positioned so that the laser light strikes the cell at the Bragg angle. Nonlinearities, positional variations, and rotational variations in the beam expander optics can produce amplitude and angle variations in the diffracted laser information signal. These errors are usually very small for well-designed optics.

Focusing optics are used as the so-called Fourier transform lens. The Bragg-cell is positioned in the front focal plane of the lens. The photodetector
array is positioned at the back focal plane of the lens. (Reference 3.) Again, nonlinearities and location variations in the focusing optics variations can produce intensity and angle variations in the diffracted laser information signal. These errors are also very small in well-designed optics.

**DETECTOR ARRAY**

The ideal detector array is assumed to be a long linear array with high frequency resolution and sensitivity. Practical Bragg-cell receivers use long linear photodiode arrays, where typically 512 or 1024 photodiodes are closely spaced along the array length.

Figure 4 presents an illustration of two diffracted laser information signals striking the photodetector array at two different diodes (two different frequencies.) In actual practice, the light spot size for each beam is larger than the area of one photodiode; hence, the light spills onto the area between detectors and also onto adjacent detectors.

Diffracted laser information signal angle variations (frequency variations) produce energy spread over several or many photodiode cells. Each photodiode cell is used to determine the signal energy in resolved and calibrated frequency space. The photodetector array is electronically readout to determine frequency and amplitude information for each diffracted laser light information signal. The photodetector array is functionally and practically described as a frequency sampling unit, with 512 to 1024 frequency bins. Each photodiode determines the elemental frequency resolution.

Bragg-cell receivers can accurately measure frequencies of time coincident or time overlapped signals, which is a big advantage over other receivers, such as the IFM receiver. These receivers are available with bandwidths to approximately 1 GHz, and frequency resolutions of 100 KHz to 10 MHz.
Figure 4. Simplified Diagram of Bragg-cell Receiver with Two Input Signals.
Bragg-cell receiver's dynamic range is approximately 30 to 40 dB, with the photodetector array's dynamic range being the critical limiting factor.

PROBABILITY DENSITY FUNCTION ANALYSIS

BRAGG-CELL RECEIVER

The probability density function (pdf) of the Bragg-cell receiver's measured frequency parameter is considered in this section. The pdf characteristic is developed for a first order Bragg-cell receiver model under high signal-to-noise ratio conditions. The IF signal's frequency characteristic is assumed to have a constant pdf or a Gaussian pdf.

Ideal and practical Bragg-cell receivers are discussed earlier in this report, and characteristics equations are provided for the ideal receiver. The Bragg-cell and AO transducer are key producers of first-order distortion effects. Distortion effects include AO transducer nonlinearities and reflected acoustic signals returning from the far end of the Bragg-cell. This analysis assumed that acoustic signals generated by AO transducer nonlinearities are significantly larger than reflected acoustic signals.

The ideal Bragg-cell receiver contains a single acoustic signal

\[ g(t) = Z(t) \cos \left( 2\pi f_1 t + \phi(t) \right) \]  

Eq. 13.

which results in the diffracted laser information signal given in Equation 12. \( f_1 \) is the frequency of the acoustic signal, which is directly related to the frequency of the input IF signal. (See Equation 7.)

AO transducer nonlinearities are producing undesired acoustic signals
in the Bragg-cell. Undesired or unwanted acoustic signals are described as a cosinusoidal series of \( N \) components (harmonics and intermodulation components at a significant energy level) which are characterized as:

\[
\eta(t) = \sum_{n=2}^{N} U_n(t) \cos \left[ 2\pi f_n t + \phi_n(t) \right] \quad \text{Eq. 14.}
\]

where

\( \eta(t) = \) Total unwanted acoustic signals in Bragg-cell. The AO transducer will generate harmonics of \( f_1 \) and other intermodulation frequency components.

\( U_n(t) = \) Amplitude of \( n \) \text{th.} unwanted acoustic signal component.

\( f_n = \) Frequency of \( n \) \text{th.} unwanted acoustic signal component. Harmonics of \( f_1 \) and intermodulation frequency components are present.

\( \phi_n(t) = \) Phase variations of \( n \) \text{th.} unwanted acoustic signal component.

The total acoustic signal in the Bragg-cell is found by summing Equations 13 and 14:

\[
\omega(t) = \beta(t) + \eta(t) \quad \text{Eq. 15.}
\]

Equation 15 can be rewritten, with a lot of work, as:

\[
\omega(t) = \Xi(t) A(t) \cos \left[ 2\pi f_1 t + \phi_1(t) + \beta(t) \right] \quad \text{Eq. 16.}
\]
where
\[ A(t) = \sqrt{\left[ \sum_{m=2}^{N} S_m(t) \right]^2 + \left[ 1 + \sum_{m=2}^{N} C_m(t) \right]^2} \]

\[ \beta(t) = \tan^{-1} \left[ \frac{\sum_{m=2}^{N} S_m(t)}{1 + \sum_{m=2}^{N} C_m(t)} \right] \]

\[ S_m(t) = K_m \sin(2\pi \Delta f_m t + \Delta \theta_m) \]

\[ C_m(t) = K_m \cos(2\pi \Delta f_m t + \Delta \theta_m) \]

\[ K_m = \frac{U_m(t)}{\mathbb{E}(t)} \]

\[ \Delta f_m = f_m - f_1 \]

\[ \Delta \theta_m = \alpha_m(t) - \alpha_1(t) \]

The instantaneous frequency variation, resulting from \( \beta(t) \) phase variations in Equation 18, is
The instantaneous frequency variation is a very complex function of amplitudes, frequencies, and phases of all unwanted acoustic signal components in the Bragg-cell. Equation 17 can be rewritten using the Fourier series expansion as a fixed frequency plus a series of harmonically related frequency components. A first-order approximation is the reduction of Equation 17 to a fixed frequency,

\[ \Delta f_i(t) \approx f_2 \]  

Eq. 18.

\( f_2 \) is used to approximate the resultant frequency component, which is produced by unwanted acoustic signal components propagating in the Bragg-cell.

Resultant phase variations are approximated as:

\[ \phi(t) \approx 2\pi f_2 t \]  

Eq. 19.
The total acoustic signal (Eq. 16) can be approximated as:

\[ \omega(t) = \Xi(t) A(t) \cos \left[ 2\pi f_1 t + 2\pi f_2 t + \alpha_1(t) \right] \quad \text{Eq. 20.} \]

The total instantaneous frequency of \( \omega(t) \) (Equation 20) is:

\[ f_i(t) = f_1 + f_2 \quad \text{Eq. 21.} \]

Equation 12 can be easily changed to approximate unwanted acoustic signals. The modified Equation 12 results in the following equation:

\[ \omega_1(t) = L_1'(t) \cos \left[ 2\pi \left( f_2 + f_1 + f_2 \right) t + \delta'(t) \right] \quad \text{Eq. 22.} \]

The actual displacement of the diffracted laser information signal (Equation 22) relative to the undeflected laser light is

\[ d = \frac{F \lambda (f_1 + f_2)}{V_s} \quad \text{Eq. 23.} \]

Equation 23 reveals that \( d \) is a random variable since it is a summation of two random variables \( f_1 \) and \( f_2 \). Conceptually, the spot size of the diffracted laser information signal is increased by the unwanted acoustic signal components. The actual displacement \( d \) is directly calibrated to a photodiode.
cell in the linear detector array, which corresponds to a specified frequency bin.

$f_1$ and $f_2$ are assumed to be independent random variables for this analysis. Pdf characteristics of $f_1$ and $f_2$ are assumed to be either constant or Gaussian. The pdf characteristic of $d'$ is the convolution of pdf ($f_1$) and pdf ($f_2$), if the random variables are independent (Reference 4.)

\[
pdf(d') = \int_{-\infty}^{\infty} pdf(d' - f_1) pdf(f_1) df_1
\]

where

\[d' = d \frac{V_s}{F \lambda}.
\]

Each frequency bin in the linear photodiode array exactly corresponds to $\Delta d$ bin coverage in displacement space.

The output frequency of the detector array is

\[
\hat{f}_0 = K_2 d
\]

Substituting Equation 25 into Equation 23, the result is:

\[
\hat{f}_0 = \frac{K_2 F \lambda (f_1 + f_2)}{V_s}
\]

The Bragg-cell receiver's measured output frequency can be stated in terms of the input IF signal's frequency by using Equations 26 and a modified version of Equation 7. The output frequency is:
\[ f_D = K_3 (f_{IF} + f_2^4) \]  
\text{Eq. 27.}

where
\[ K_3 = \frac{K_2 F A}{K V_s}. \]

\[ f_2^4 = \text{The equivalent IF frequency of unwanted acoustic signal components approximated as acoustic frequency } f_2^4. \]

\( f_D \) is a linear combination of two random variables \( f_{IF} \) and \( f_2^4 \), which are assumed to be independent. The pdf \( f_D \) is the convolution of pdf \( f_{IF} \) and pdf \( f_2^4 \), which is expressed mathematically as:

\[ \text{pdf} (f_D) = \int_{-\infty}^{\infty} \text{pdf} (f_D - f_{IF}) \text{pdf} (f_{IF}) \, df_{IF}. \]  
\text{Eq. 28.}

The pdf \( f_D \) characteristic is functionally divided into sampled \( \Delta f_D \) bins by the photodiode cells in the linear detector array. This frequency domain binning process is equivalent to discrete sampling of the pdf \( f_D \) characteristics in \( \Delta f_D \) bin widths. \( \Delta f_D \) is the basic frequency resolution of the Bragg-cell receiver at the linear detector array. The actual pdf characteristic of the Bragg-cell receiver's frequency parameter is a discrete characteristic, which is a function of the pdf of the IF signal frequency and pdf characteristic of the equivalent unwanted signal components.
SIGNAL PROCESSING ANALYSIS

INTRODUCTION

Signal processing analysis results are presented in this section. The Bragg-cell receiver model is implemented on a Hewlett Packard Integral computer. Computer software program listings are contained in Appendix A of this report.

Pdf analysis of the Bragg-cell receiver's frequency parameter is performed, assuming constant and Gaussian pdf characteristics for the input signal's IF frequency. Pdf analysis is performed for selected frequency resolutions of the Bragg-cell receiver. Also, statistical analysis are performed on output pdf signals and summary results are presented.

BRAGG-CELL RECEIVER MODEL RESULTS

The Bragg-cell receiver is math modeled in the previous section. First-order model implementation is shown to be a convolution of pdf \( f_{IF} \) and pdf \( f_{1/2} \) for the Bragg-cell receiver's output frequency pdf characteristic. Equation 28 is the final descriptive equation for the output frequency pdf characteristic.

Bragg-cell receiver signal processing results are summarized in Table 1. Signal processing analysis programs are presented in Appendix A. Figures 5 through 70 contain detailed pdf plots for the Bragg-cell receiver's output frequency parameters. These plots are made for selected pdf characteristic of \( f_{IF} \) and \( f_{1/2} \) and selected Bragg-cell receiver frequency resolutions.

Table 1 defines the input signal or \( f_{IF} \) in terms of DF1 or DF1 and \( \sigma_1 \). The pdf \( f_{IF} \) is assumed to be a constant if only a value for DF1 is given. DF1 (MHz) indicates the frequency excursion of the input frequency \( f_{IF} \).

For a Gaussian pdf \( f_{IF} \), DF1(MHz) and \( \sigma_1(MHz) \) is selected as 1.166 MHz or 4.166 MHz for Gaussian pdf's.
# TABLE 1

## BRAGG-CELL RECEIVER

### SIGNAL PROCESSING RESULTS

<table>
<thead>
<tr>
<th>FIGURE</th>
<th>INPUT SIGNAL</th>
<th>DISTORTION SIGNAL</th>
<th>FREQUENCY RESOLUTION (MHz)</th>
<th>OUTPUT FREQUENCY: STATISTICAL RESULTS</th>
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TABLE 1 CONT'D
BRAGG-CELL RECEIVER
SIGNAL PROCESSING RESULTS

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<th>FIGURE</th>
<th>INPUT SIGNAL</th>
<th>DISTORTION SIGNAL</th>
<th>FREQUENCY RESOLUTION (MHz)</th>
<th>OUTPUT FREQUENCY: STATISTICAL RESULTS</th>
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The distortion signal or $f_2^1$ is quantified in terms of DF2 or DF2 and $\sigma_2$. The pdf($f_2^1$) is assumed to be a constant if only a value for DF2 is given. DF2(MHz) indicates the frequency excursion of the distortion signal $f_2^1$.

For a Gaussian pdf($f_2^1$), DF2(MHz) and $\sigma_2$(MHz) indicates six times sigma and standard deviation, respectively. DF2 is selected as 2, 5, 9, 15, and 24 MHz. $\sigma_2$(MHz) is selected as 0.333, 0.833, 1.5, 2.5 and 4.0 MHz for Gaussian pdfs.

Bragg-cell receiver frequency resolution (MHz) is chosen to be 0.5, 1.0, 2.0 or 5.0 MHz. These frequency resolution selections are readily expected with current Bragg-cell receiver technology.

The last three columns of Table 1 contain statistical results of the Bragg-cell receiver's output frequency. Sigma (MHz), skew and kurtosis are computed for each output frequency pdf characteristic shown in Figure 5 through 70.

The pdf($f_d$) characteristic is a staircased trapezoidal function for pdf($f_{IP}$) = constant and pdf($f_2^1$) = constant. Figures 5 through 22 show numerous examples of pdf($f_d$) characteristics for selected input signal and distortion signal constant pdf characteristics. Pdf($f_d$) is observed to significantly depart from a constant characteristic and approach a staircased triangular characteristic as DF2 approaches DF1.

Figures 23 through 34 reveal output frequency pdf($f_d$) characteristics with input frequency characteristics assumed to be Gaussian pdf and distortion signal frequency characteristics assumed to be constant pdf. These pdf characteristics are staircased Gaussian characteristics. The pdf characteristic departs from the Gaussian characteristics as the Bragg-cell receiver's frequency resolution is decreased.
Figures 23 through 34 reveal output frequency pdf(f_d) characteristics with input frequency characteristics assumed to be Gaussian pdf and distortion signal frequency characteristics assumed to be constant pdf. These pdf characteristics are staircased Gaussian characteristics. The pdf characteristic departs from the Gaussian characteristics as the Bragg-cell receiver's frequency resolution is decreased.

Figures 35 through 52 reveal output frequency pdf(f_d) characteristics with input frequency characteristics assumed to be constant pdf and distortion signal frequency characteristics assumed to be Gaussian pdf. For most example plots the long constant pdf characteristic of the input frequency tends to dominate the overall pdf characteristic. The pdf characteristics are approximately a staircased trapezoidal characteristic.

The pdf(f_d) characteristic is a staircased Gaussian function for pdf(f_{IF}) = Gaussian and pdf(f_{IF}^1) = Gaussian. Figures 53 through 70 show numerous examples of pdf(f_d) for selected input signal and distortion signal frequency characteristics. Pdf(f_d) is observed to be close to a Gaussian characteristic for all DF2 and DF1 selections. For low frequency resolution in the Bragg-cell receiver, the pdf characteristic departs from a Gaussian characteristic.
Figure 6

BRAGG-CELL RECEIVER PDF ANALYSIS
CONSTANT PDF FOR F1, DF1= 10.0 CONSTANT PDF FOR F2, DF2= 2.00

INTEGRAL=1.033
XMEAN= 498.249
SIGMA= 3.404
SKEW= +1.257
KURTOSIS= 2.253
RESOLUTION=1 MHZ

Pdf (F_d) x 1E8

Fd IN MHZ
Figure 7

Bragg-Cell Receiver PDF Analysis

Constant PDF for F1, DF1 = 10.0
Constant PDF for F2, DF2 = 2.00

Integral = 1.033
Xmean = 498.960
Sigma = 3.103
Skew = +1.010
Kurtosis = 2.185
Resolution = 2 MHz

Fd IN MHZ
Figure 8

Bragg-Cell Receiver PDF Analysis

Constant PDF for F1, DF1 = 10.0  Constant PDF for F2, DF2 = 5.00

Integral = 1.013
XMean = 500.132
Sigma = 3.250
Skew = -0.119
Kurtosis = 2.182
Resolution = 0.5 MHz
Figure 9

Bragg-Cell Receiver PDF Analysis

Constant PDF for F1, DF1 = 10.0

Constant PDF for F2, DF2 = 5.00

INTEGRAL = 1.013
XMEAN = 501.045
SIGMA = 3.422
SKEW = -.884
KURTOSIS = 2.319
RESOLUTION = 1 MHZ

Fd IN MHZ
Figure 10

BRAGG-CELL RECEIVER PDF ANALYSIS

CONSTANT PDF FOR F1, DFL = 10.0
CONSTANT PDF FOR F2, DFF2 = 5.00

INTEGRAL = 1.013
XMEAN = 497.276
SIGMA = 4.189
SKEW = +1.395
KURTOSIS = 2.369
RESOLUTION = 2 MHz
Figure 11

BRAGG-CELL RECEIVER PDF ANALYSIS

CONSTANT PDF FOR F1, DF1 = 10.0
CONSTANT PDF FOR F2, DF2 = 9.00

INTEGRAL = 1.007
XMEAN = 489.852
SIGMA = 3.010
SKEW = +.038
KURTOSIS = 2.394
RESOLUTION = .5 MHz

Fd IN MHZ
Figure 12

BRAZG-CELL RECEIVER PDF ANALYSIS
CONSTANT PDF FOR F1, DFI= 10.0 CONSTANT PDF FOR F2, DFF2= 9.00

INTEGRAL=1.007
XMEAN= 500.288
SIGMA= 3.922
SKEW= -0.228
KURTOSIS= 2.402
RESOLUTION=1 MHZ

Fd IN MHZ
Figure 13

BRAGG-CELL RECEIVER PDF ANALYSIS

CONSTANT PDF FOR F1, DF1= 10.0 CONSTANT PDF FOR F2, DF2= 9.00

INTEGRAL=1.007
XMEAN= 498.952
SIGMA= 4.017
SKew= +.730
KURTOSIS= 2.442
RESOLUTION=2 MHZ

Fd IN MHZ
Figure 14

BRAHGG-CELL RECEIVER PDF ANALYSIS

CONSTANT PDF FOR F1, DF1 = 25.0
CONSTANT PDF FOR F2, DF2 = 5.00

Integral = 1.033
Xmean = 409.011
Sigma = 7.395
Skew = -0.000
Kurtosis = 1.805
Resolution = 1 MHz
Figure 16

Bragg-Cell Receiver PDF Analysis

Constant PDF for F1, DF1 = 25.0 Constant PDF for F2, DF2 = 5.00

INTEGRAL = 1.033
XMEAN = 499.013
SIGMA = 7.356
SKEW = +.495
KURTOSIS = 1.946
RESOLUTION = 5 MHz

Pd(Fd) x 1E8

Fd IN MHZ
Figure 17

BRAGG-CELL RECEIVER PDF ANALYSIS

CONSTANT PDF FOR F1, DFI = 25.0  CONSTANT PDF FOR F2, DFF2 = 15.00

INTEGRAL = 1.011
XMEAN = 499.915
SIGMA = 8.471
SKEW = -0.000
KURTOSIS = 2.272
RESOLUTION = 1 MHz

Pdf(Fd) X 1E8

Fd IN MHZ
Figure 19

BRAGG-CELL RECEIVER PDF ANALYSIS

CONSTANT PDF FOR F1, DF1= 25.0  CONSTANT PDF FOR F2, DF2= 15.00

INTEGRAL=1.011
XMEAN= 500.340
SIGMA= 6.420
SKEW= -.077
KURTOSIS= 2.268
RESOLUTION=5 MHZ

Fd IN MHZ
Figure 20
BRAGG-CELL RECEIVER PDF ANALYSIS
CONSTANT PDF FOR F1, DF = 25.0 CONSTANT PDF FOR F2, DF=24,00

Fd IN MHZ

FDF (PDF) X 1E8

4.42
3.97
3.53
3.09
2.65
2.21
1.77
1.32
0.88
0.44
0.00

INTEGRAL = 1.007
XMEAN = 499.916
SIGMA = 10.071
SKEW = +.000
KURTOSIS = 2.399
RESOLUTION = 1 MHZ
Figure 21

BRAGG-CELL RECEIVER PDF ANALYSIS

CONSTANT PDF FOR F1, OF1 = 25.0
CONSTANT PDF FOR F2, OF2 = 24.0

INTEGRAL = 1.007
MEAN = 489.595
SIGMA = 10.062
SKEW = +0.996
KURTOSIS = -2.398
RESOLUTION = 2 MHz

Pdfs X 10^8

Fds IN MHZ
Figure 22

BRAGG-CELL RECEIVER PDF ANALYSIS

CONSTANT PDF FOR F1, DF1= 25.0  CONSTANT PDF FOR F2, DF2= 24.00

- INTEGRAL = 1.007
- XMEAN = 499.978
- SIGMA = 0.990
- SKEW = +.026
- KURTOSIS = 2.389
- RESOLUTION = 5 MHz

Pdf (Fd) x 1E8

Fd IN MHZ

475 480 485 490 495 500 505 510 515 520 525

4.42

3.97

3.53

3.09

2.65

2.21

1.77

1.32

.88

.44

0.00
Figure 24

BRAGG-CELL RECEIVER PDF ANALYSIS

GAUSSIAN PDF FOR F1, DF1 = 10.0
CONSTANT PDF FOR F2, DFF2 = 2.00

INTEGRAL = 1.031
XMEAN = 490.947
SIGMA = 1.755
SKEW = +.086
KURTOSIS = 2.844
RESOLUTION = 1 MHz

Pdf(Fd) x 1E8

Fd IN MHZ
Figure 25

**BRAGG-CELL RECEIVER PDF ANALYSIS**

GAUSSIAN PDF FOR F1, Df1 = 10.0  CONSTANT PDF FOR F2, DfF2 = 2.00

INTEGRAL = 1.031
XMEAN = 499.940
SIGMA = 1.753
SKEW = 1.111
KURTOSIS = 2.824
RESOLUTION = 2 MHz

Fd IN MHZ
**Figure 26**

**BRAGG-CELL RECEIVER PDF ANALYSIS**

GAUSSIAN PDF FOR F1, DF1 = 10.0  CONSTANT PDF FOR F2, DF2 = 5.00

- INTEGRAL = 1.011
- XMEAN = 500.036
- SIGMA = 2.208
- SKEW = -0.006
- KURTOSIS = 2.713
- RESOLUTION = 0.5 MHz

Fd IN MHZ
Figure 21

BRAGG-CELL RECEIVER PDF ANALYSIS

GAUSSIAN PDF FOR F1, OF1 = 10.0
CONSTANT PDF FOR F2, DF2 = 5.00

INTEGRAL = 1.011
XMEAN = 500.062
SIGMA = 2.209
SKEW = -0.042
KURTOSIS = 2.714
RESOLUTION = 1 MHZ

Fd IN MHZ
Figure 28

Bragg-Cell Receiver PDF Analysis

Gaussian PDF for F1, DF1 = 10.0
Constant PDF for F2, DF2 = 5.00

Integral = 1.011
Xmean = 500.009
Sigma = 2.207
Skew = +0.023
Kurtosis = 2.704
Resolution = 2 MHz

Pdf(Fd) x 1E8

Fd in MHZ
Figure 29

BRAGG-CELL RECEIVER PDF ANALYSIS

GAUSSIAN PDF FOR F1, DF1= 25.0  CONSTANT PDF FOR F2, DF2= 15.00

INTEGRAL=1.000
XMEAN= 499.999
SIGMA= 0.028
SKEW= -0.001
KURTOSIS= 2.624
RESOLUTION=1 MHZ

F_d IN MHZ

Pdf(F_d) X 1E8
BRAGG-CELL RECEIVER PDF ANALYSIS

GAUSSIAN PDF FOR F1, Df1 = 25.0
CONSTANT PDF FOR F2, Df2 = 15.00

INTEGRAL = 1.000
XMEAN = 500.011
SIGMA = 6.028
SKEW = -0.009
KURTOSIS = 2.625
RESOLUTION = 2 MHz
Figure 31

BRAgg-CELL RECEIVER PDF ANALYSIS
GAUSSIAN PDF FOR F1, DF1= 25.0  CONSTANT PDF FOR F2, OFF2= 15.00

INTEGRAL=1.008
XMEAN= 499.988
SIGMA= 6.022
SKEW= +.009
KURTOSIS= 2.617
RESOLUTION=5 MHZ
Figure 32

BRAGG-CELL RECEIVER PDF ANALYSIS

GAUSSIAN PDF FOR $F_1$, $D_F^1 = 25.0$
CONSTANT PDF FOR $F_2$, $D_F^2 = 24.00$

INTEGRAL=1.004
XMEAN= 499.998
SIGMA = 8.124
SKEW = -.000
KURTOSIS= 2.327
RESOLUTION=1 MHz

$F_d$ IN MHZ
Figure 33

BRAGG-CELL RECEIVER PDF ANALYSIS

GAUSSIAN PDF FOR F1, DF1= 25.0  CONSTANT PDF FOR F2, DFF2= 24.00

![Graph showing PDF analysis with calculated integral, mean, standard deviation, skewness, kurtosis, and resolution.]

- Integral = 1.004
- Xmean = 499.999
- Sigma = 8.124
- Skew = 0.003
- Kurtosis = 2.327
- Resolution = 2 MHz

Fd IN MHZ
Figure 34

BRAGG-CELL RECEIVER PDF ANALYSIS
GAUSSIAN PDF FOR F1, DF1 = 25.0 CONSTANT PDF FOR F2, DF2 = 24.00

INTEGRAL = 1.004
XMEAN = 499.999
SIGMA = 8.122
SKEW = +.000
KURTOSIS = 2.324
RESOLUTION = 5 MHZ

Pdf (Fd) x 1E8

Fd IN MHZ
Figure 35

BRAGG-CELL RECEIVER PDF ANALYSIS
CONSTANT PDF FOR F1, DF1 = 10.0 GAUSSIAN PDF FOR F2, DF2 = 2.00

INTEGRAL = .998
XMEAN = 499.983
SIGMA = 2.915
SKEW = + .003
KURTOSIS = 1.831
RESOLUTION = 5 MHz

Pdf (Fd) x 1E8

Fd IN MHZ
Figure 38

BRAGG-CELL RECEIVER PDF ANALYSIS

CONSTANT PDF FOR F1, DF1 = 10.0
GAUSSIAN PDF FOR F2, DF2 = 5.00

INTEGRAL = 0.988
XMEAN = 500.004
SIGMA = 3.012
SKEW = -0.004
KURTOSIS = 1.873
RESOLUTION = 5 MHz

Fd IN MHZ
Figure 39

Bragg-Cell Receiver PDF Analysis

Constant PDF for F1, DF1 = 10.0 Gaussian PDF for F2, DF2 = 5.00

Integral = 0.998
X Mean = 500.019
Sigma = 3.012
Skew = -0.019
Kurtosis = 1.973
Resolution = 1 MHz

Pdf (Fd) x 1E8 vs Fd IN MHZ
Figure 40
BRAGG-CELL RECEIVER PDF ANALYSIS

CONSTANT PDF FOR F1, DFI = 10.0 GAUSSIAN PDF FOR F2, DFF2 = 5.00

INTEGRAL = 0.998
ChiSQAURE = 499.415
SIGMA = 3.055
SKEW = +0.564
KURTOSIS = 2.059
RESOLUTION = 2 MHZ

Fd IN MHZ

Pdf(Fd) x 1E8
Figure 41
Bragg-Cell Receiver PDF Analysis

Constant PDF for F1, DFI = 10.0 Gaussian PDF for F2, DF2 = 9.00

Integral = 0.997
XMean = 499.999
Sigma = 3.255
Skew = +0.001
Kurtosis = 2.241
Resolution = 0.5 MHz

Fd IN MHZ
Figure 42

BRAGG-CELL RECEIVER PDF ANALYSIS

CONSTANT PDF FOR F1, Df1 = 10.0 GAUSSIAN PDF FOR F2, Df2 = 9.0

INTEGRAL = .997
XMEAN = 500.009
SIGMA = 3.255
SKEW = -.008
KURTOSIS = 2.241
RESOLUTION = 1 MHZ

Fd IN MHZ

Pdf(Fd) X 1E8

0.00 1.10 2.19 3.29 4.39 5.48 6.58 7.67 8.77 9.87 10.96

490 492 494 496 498 500 502 504 506 508 510
Figure 43

BRAGG-CELL RECEIVER PDF ANALYSIS

CONSTANT PDF FOR F1, DF1= 10.0 GAUSSIAN PDF FOR F2, DFF2= 9.00

INTEGRAL = .997
XMEAN = 499.969
SIGMA = 3.255
SKEW = +.027
KURTOSIS = 2.239
RESOLUTION = 2 MHZ

Fd IN MHZ
Figure 44

BRAGG-CELL RECEIVER PDF ANALYSIS

CONSTANT PDF FOR F1, DF1= 25.0 GAUSSIAN PDF FOR F2, DF2= 5.00

INTEGRAL = .998
XMEAN = 499.916
SICMA = 7.288
SKEW = -.000
KURTOSIS = 1.831
RESOLUTION = 1 MHZ

Fd IN MHZ
Figure 45
Bragg-Cell Receiver PDF Analysis

Constant PDF for F1, DF1 = 25.0 GAUSIAN PDF FOR F2, DF2 = 5.00

INTEGRAL = .998
XMEAN = 500.318
SIGMA = 7.308
SKEW = -.165
KURTOSIS = 1.834
RESOLUTION = 2 MHz

Fd IN MHZ

Pdf (Fd) x 1E8

4.39
3.95
3.51
3.07
2.63
2.19
1.75
1.32
.88
.44
0.00
475 480 485 490 495 500 505 510 515 520 525
Figure 46

Bragg-Cell Receiver PDF Analysis

Constant PDF for F1, DF1 = 25.0 Gaussian PDF for F2, DF2 = 5.00

Integral = 0.998
Xmean = 
Sigma = 
Skew = 
Kurtosis = 
Resolution = 5 MHz

Fd in MHz
Figure 47

Bragg-Cell Receiver PDF Analysis

Constant PDF for $F_1$, $DF_1 = 25.0$ Gaussian PDF for $F_2$, $DF_2 = 15.00$

INTEGRAL = 0.998
XMEAN = 499.918
SIGMA = 7.653
SKEW = -0.000
KURTOSIS = 2.037
RESOLUTION = 1 MHz
Figure 48

Bragg-Cell Receiver PDF Analysis

Constant PDF for F1, Df1 = 25.0 Gaussian PDF for F2, Df2 = 15.00

Integral = .998
Xmean = 489.92
Sigma = 7.653
Skew = -.002
Kurtosis = 2.037
Resolution = 2 MHz

Fd in MHz
Figure 50

BRAGG-CELL RECEIVER PDF ANALYSIS

CONSTANT PDF FOR F1, Df1 = 25.0
GAUSSIAN PDF FOR F2, Df2 = 24.00

INTEGRAL = 0.997
XMEAN = 499.918
SIGMA = 0.254
SKEW = -0.000
KURTOSIS = 2.281
RESOLUTION = 1 MHZ
Figure 51

BRAGG-CELL RECEIVER PDF ANALYSIS

CONSTANT PDF FOR F1, DFF1 = 25.0 GAUSSIAN PDF FOR F2, DFF2 = 24.00

INTEGRAL = .997
XMEAN = 499.911
SIGMA = .254
SKEW = +.002
KURTOSIS = 2.280
RESOLUTION = 2 MHz

Fd IN MHZ
Figure 52
Bragg-Cell Receiver PDF Analysis
Constant PDF for F1, Dff1 = 25.0 Gaussian PDF for F2, Dff2 = 24.00

INTEGRAL = 0.997
XMEAN = 499.902
SIGMA = 8.252
SKEW = +0.008
KURTOSIS = 2.278
RESOLUTION = 5 MHz
Figure 54

Bragg-Cell Receiver PDF Analysis

Gaussian PDF for F1, DF1 = 10.0  Gaussian PDF for F2, DF2 = 2.00

Integral = 0.995
Xmean = 499.956
Sigma = 1.683
Skew = +.076
Kurtosis = 2.842
Resolution = 1 MHz

Pdf (Fd) x 1E8

Fd IN MHZ
Figure 55

BRAGG-CELL RECEIVER PDF ANALYSIS
GAUSSIAN PDF FOR F1, DFF1= 10.0
GAUSSIAN PDF FOR F2, DFF2= 2.00

INTEGRAL = .995
XMEAN = 499.058
SIGMA = 1.680
SKEW = +.039
KURTOSIS = 2.804
RESOLUTION = 2 MHz

Pdf (Fd) X 1E8

Fd IN MHZ
Figure 56

BRAGG-CELL RECEIVER PDF ANALYSIS

GAUSSIAN PDF FOR F1, DFF1 = 10.0
GAUSSIAN PDF FOR F2, DFF2 = 5.0

INTEGRAL = 0.995
MEAN = 500.033
SIGMA = 1.845
SKEW = -0.003
KURTOSIS = 2.084
RESOLUTION = 0.5 MHZ

Fd IN MHZ
Figure 57

BRAGG-CELL RECEIVER PDF ANALYSIS

GAUSSIAN PDF FOR F1, DF1 = 10.0  GAUSSIAN PDF FOR F2, DF2 = 5.0

PDF (Fd) X 1E8

Fd IN MHZ

INTEGRAL = 0.995
XMEAN = 500.033
SIGMA = 1.845
SKEW = -0.003
KURTOSIS = 2.884
RESOLUTION = 1 MHZ
Figure 58

Bragg-Cell Receiver PDF Analysis

Gaussian PDF for F1, Dl = 10.0
Gaussian PDF for F2, DlF2 = 5.0

INTEGRAL = .995
XMEAN = 500.030
SIGMA = 1.845
SKEW = +.002
KURTOSIS = 2.002
RESOLUTION = 2 MHz

Fd in MHz
Figure 59

BRAGG-CELL RECEIVER PDF ANALYSIS
GAUSSIAN PDF FOR F1, DFF1 = 10.0  GAUSSIAN PDF FOR F2, DFF2 = 9.00

INTEGRAL = .995
XMEAN = 500.033
SIGMA = 2.220
SKW = -.001
KURTOSIS = 2.915
RESOLUTION = .5 MHZ

Pdf(Fd) x 1E8

Fd IN MHZ
Figure 60

Bragg-Cell Receiver PDF Analysis

Gaussian PDF for F1, DF1 = 10.0  Gaussian PDF for F2, DF2 = 9.00

INTEGRAL = 0.995
XMEAN = 500.033
SIGMA = 2.220
SKEW = -0.002
KURTOSIS = 2.915
RESOLUTION = 1 MHz

Pdf (Fd) x 1E8

Fd in MHz
Figure 61

BRAGG-CELL RECEIVER PDF ANALYSIS

GAUSSIAN PDF FOR F₁, DFF₁ = 10.0
GAUSSIAN PDF FOR F₂, DFF₂ = 9.00

INTEGRAL = 0.995
XMEAN = 500.032
SIGMA = 2.220
SKEW = -0.001
KURTOSIS = 2.915
RESOLUTION = 2 MHZ
Figure 63

Bragg-Cell Receiver PDF Analysis

Gaussian PDF for F1, Df1 = 25.0  
Gaussian PDF for F2, Df2 = 5.00

Integral = 0.995  
Xmean = 500.009  
Sigma = 4.207  
Skew = -0.011  
Kurtosis = 2.842  
Resolution = 2 MHz
Figure 65

BRAGG-CELL RECEIVER PDF ANALYSIS

GAUSSIAN PDF FOR F1, \( D F_1 = 25.0 \)

GAUSSIAN PDF FOR F2, \( D F_2 = 15.00 \)

\[
\begin{align*}
\text{INTEGRAL} &= 0.995 \\
\text{XMEAN} &= 499.998 \\
\text{SIGMA} &= 4.811 \\
\text{SKEW} &= -0.002 \\
\text{KURTOSIS} &= 2.896 \\
\text{RESOLUTION} &= 1 \text{ MHZ}
\end{align*}
\]
Figure 66
BRAGG-CELL RECEIVER PDF ANALYSIS
GAUSSIAN PDF FOR F1, DF1 = 25.0
GAUSSIAN PDF FOR F2, DF2 = 15.00

INTEGRAL = .995
XMEAN = 499.998
SIGMA = 4.811
SKEW = -.002
KURTOSIS = 2.896
RESOLUTION = 2 MHz

Pdf(Fd) X 1E8

Fd IN MHZ
Figure 67

BRAGG-CELL RECEIVER PDF ANALYSIS

GAUSSIAN PDF FOR F1, DF1 = 25.0  GAUSSIAN PDF FOR F2, DF2 = 15.00

INTEGRAL = 0.995
XMEAN = 499.997
SIGMA = 4.811
SKEW = -0.001
KURTOSIS = 2.895
RESOLUTION = 5 MHz

Fd IN MHZ

Pdf (Fd) X 1E8
Figure 69

BRAGG-CELL RECEIVER PDF ANALYSIS
GAUSSIAN PDF FOR F1, \(DF1=25.0\)  GAUSSIAN PDF FOR F2, \(DF2=24.00\)

- INTEGRAL = 0.995
- XMEAN = 499.998
- SIGMA = 5.719
- SKEW = -0.001
- KURTOSIS = 2.918
- RESOLUTION = 2 MHz

Pdf(\(F_d\)) x 1E8

Fd IN MHZ
Figure 70

Bragg-Cell Receiver PDF Analysis

Gaussian PDF for F1, OF1 = 25.0
Gaussian PDF for F2, OF2 = 24.00

Integral = 0.995
XMean = 499.998
Sigma = 5.719
Skew = -0.001
Kurtosis = 2.915
Resolution = 5 MHz

Fd in MHz
CONCLUSIONS

Bragg-cell receivers can accurately measure frequencies of time coincident and time overlapped RF signals, which is a big advantage over other receiver types. Bragg-cell receivers are available with bandwidths to approximately 1 GHz, and frequency resolutions of 100 KHz to 10 MHz.

The Bragg-cell receiver's frequency parameter is analyzed and results are presented in this report. Probability density function analysis and statistical analysis results are presented for this receiver for selected frequency resolution capabilities.

The first order math model is developed for the Bragg-cell receiver. The input signal's frequency is assumed to be a constant pdf or Gaussian pdf characteristic. The primary distortion signal is generated by nonlinear acoustic transducer characteristics. The distortion signal is also assumed to have a constant pdf or Gaussian pdf characteristic.

Staircased pdf characteristics are observed for all pdf frequency characteristics. The staircased function is introduced by the frequency sampling of the photodiode detector array used in the Bragg-cell receiver. The output frequency pdf characteristic is observed to depart from the input signal's frequency pdf characteristic for many of the wideband RF signal cases and wideband distortion signals produced by the AO transducer. Distortion signals with large DF2 values can significantly change the output frequency's pdf characteristic. Also, the frequency sampling (or detector frequency resolution) at the detector can further distort the pdf characteristic. Low frequency resolution at the detector produces the most significant distortions. EW emitter classification and EW direction finding systems can be affected by Bragg-cell receiver distortions. These distortions are especially important for wideband radar emitters.
Math model validation is recommended for the Bragg-cell receiver.
Model validations are readily performed using an actual Bragg-cell receiver and associated test equipment.
REFERENCES


APPENDIX A
BRAGG-CELL RECEIVER
CONVOLUTION PROGRAM

10 ! "BRAGG" PROGRAM
20 ! BRAGG-CELL RECEIVER ANALYSIS
30 ! CONVOLUTION OF F1 ARRAY AND F2 ARRAY
40 ! THIS VERSION PERMITS STORAGE OF CONVOLVED ARRAY WITH ITS FREQUENCY AXIS
50 ! STORAGE TAKES PLACE PRIOR TO PLOTTING--A STRING NAMED INFO* IS ALSO
60 ! STORED--SHOULD CONTAIN MINIMUM INFORMATION ON STORED DATA
70 ! PLOT BOTH INPUT ARRAYS ON K AXIS
80 ! PLOT CONVOLUTION ON FREQUENCY AXIS
90 ! LABEL TOTAL VALUES FOUND IN CONVOLUTION ARRAY
100 ! ARRAYS MAY BE ANY COMBINATION OF FLAT/GAUSSIAN
110 ! DECEMBER 1986
120 ! "DO YOU WANT TO SAVE CONVOLVED ARRAYS?" @ LINPUT "ENTER Y/N",KP$;
130 ! IF KP$="Y" THEN GOSUB KEEP
140 ! "ENTER INTEGER LENGTH OF LONG ARRAY" @ INPUT DF1
150 ! "ENTER LENGTH OF SHORT ARRAY" @ INPUT DF2
160 ! "MAKE THESE ENTRIES IN MHZ"
170 ! "ENTER DELTA FREQUENCY FOR THE LONG ARRAY" @ INPUT OF1
180 ! "ENTER DELTA FREQUENCY FOR THE SHORT ARRAY" @ INPUT OF2
190 ! DF2=DF1/(DF1/DF2) @ N=DF1*2 @ SGF1=OFF1+1000000/6 @ SGFLO=OFF2+1000000/6
200 ! OF1="OF1", DF2="DF2", N="N", OF1="OF1", SGF1="SGF1", SGFLO="SGFLO"
210 ! OPTION BASE 1 @ RAD @ NMRLO=1/(SGFLO*SQR(2*PI)) @ MU=5000000000
220 ! DIM PX(500),PY(500),T(500),X(500),Y(500),INFOS(80)
230 ! LINPUT "ENTER=<80 CHARACTERS DESCRIBING DATA",INFOS$;
240 ! REDIM PY(N-1),FX(N-1),PX(N),PH(N)
250 ! FOR K=1 TO N ! FILL INPUT ARRAYS WITH ZEROES
260 ! PX(K)=0 @ PH(K)=0
270 ! NEXT K
280 ! "******PICK COMBINATION******"
290 ! "1-BOTH ARRAYS FLAT"
300 ! "2-SHORT FLAT, LONG GAUSSIAN"
310 ! "3-LONG FLAT, SHORT GAUSSIAN"
320 ! "4-BOTH GAUSSIAN"
330 ! "ENTER YOUR CHOICE" @ INPUT PIC
340 ! IF PIC=2 THEN SHRT
350 ! IF PIC=4 THEN GOSUB AR2
360 ! LSTEP=1
370 ! FOR K=1 TO N\2 ! MAKES FLAT LONG ARRAY
380 ! PX(K)=1/(OF1-1)
390 ! NEXT K
400 ! SHRT: ! MAKES FLAT SHORT ARRAY
410 ! IF PIC=3 THEN GOSUB AR3
420 ! SSTEP=1
430 ! FOR K=N/4-DF2/2 TO N/4+DF2/2
440 ! PX(K)=1/(DF2-1)
450 ! NEXT K
460 ! IF PIC=2 THEN GOSUB AR2
470 ! CNVLV:
480 ! YTOT=0
490 ! FOR K=1 TO N-1
iGG

500  YSUM=0
510  STL=500-OFF  @ STPL=500+OFF  @ STZL=STPL-STL/(N-1)  @ IVAL=STL+STZL/2
520  FOR J=1 TO K
530  YSUM=YSUM+PX(J)+PH(K-J+1)
540  PY(K)=YSUM/(STZL*1000000)
550  NEXT J
560  IF K MOD 50=0 THEN DISP "K=":K
570  NEXT K
580  FOR K=1 TO N-1  ! MAKE ARRAY FOR XAXIS
590  FX(K)=IVAL
600  IVAL=IVAL+STZL.
610  NEXT K
620  SUMY=0
630  FOR K=1 TO N-2  !INTEGRATE
640  XS=(FX(K+1)-FX(K))*1000000
650  YS=(PY(K)+PY(K+1))/2
660  SUMY=XS*YS+SUMY
670  NEXT K
680  DISP "SUM=":SUMY
690  IF KPS#111="Y" THEN GOSUB KP1
700  CHOICE:  
710  DISP "1-1-PLOT BOTH ORIGINAL ARRAYS SAME AXIS"
720  DISP "2-2-PLOT CONVOLUTION ON FREQUENCY AXIS"
730  DISP "3-3-EXIT PROGRAM"
740  DISP "4-4-STORE DATA"
750  DISP "ENTER YOUR CHOICE"  @ INPUT CH
760  IF CH=4 THEN GOSUB KP1
770  IF CH#1 THEN 790
780  LINPUT "EXTERNAL PLOTTER? Y/N",HP$ 
790  IF CH=3 THEN BEEP & DISP "DONE"  @ STOP
800  IF CH=1 THEN GOSUB PLT1
810  IF CH=2 THEN GOSUB PLT3
820  PLOTTER IS 1  @ PEN -1  @ GCLEAR  @ LOCATE 30,170,25,00
830  Y1=0  @ YZ=AMAX(Y)*1.1  @ X1=STL  @ X2=STPL
840  START:
850  SCALE X1,XZ,Y1,YZ
860  FXD 2  @ LAXES (XZ-X1)/10,(YZ-Y1)/10,X1,Y1
870  XAXIS YZ,(XZ-X1)/10,X1,XZ
880  YAXIS XZ,(YZ-Y1)/10,Y1,YZ
890  MODDAT: 1  
900  IF CH=1 THEN 950
910  IF CH#4 THEN 950
920  DISP "ENTER BRAAG-RECEIVER FREQUENCY RESOLUTION"
930  INPUT RES
940  KRES=INT(RES/(2*OFF1/N))
950  FOR K=1 TO KRES
960  PLOT X(K),Y(K)  @ IF CH=1 THEN 1040
970  IF CH=4 THEN 1040
980  FOR L=1 TO KRES
990  IF K+L#TOP THEN 1050
1000  PLOT X(K+L),Y(K)
1010  NEXT L
1020  K=K+L-2
1030  L=1
1040  NEXT K
1050  IF HP$="Y" THEN EPLOT
1060  IF CH=1 THEN GOSUB PLT2
1070  IF CH=4 THEN PLOT
"CONSTANT PDF FOR F1, DF1="",DD.D," CONSTANT PDF FOR F2 , OFF2="",DD.D ","
"CONSTANT PDF FOR F1, DF1="",DD.D," GAUSSIAN PDF FOR F2 , OFF2="",DD.D ","
"GAUSSIAN PDF FOR F1, DF1="",DD.D," CONSTANT PDF FOR F2 , OFF2="",DD.
","GAUSSIAN PDF FOR F1, DF1="",DD.D," GAUSSIAN PDF FOR F2 , OFF2="",DD.
",""
"BRAGG-CELL RECEIVER PDF ANALYSIS" @ CSIZE 3,3,1
"LONG 5 @ MOVE XZ-(XZ-X1)/2,YZ+(YZ-Y1)/9 @ LABEL USING "K" ; T$
"CSIZE 3
"MOVE XZ-(XZ-X1)/2,YZ+(YZ-Y1)/18 @ IF PIC=1 THEN LABEL USING 1060 ; OFF1,OFF 
@ CSIZE 3
"IF PIC=3 THEN LABEL USING 1080 ; OFF1,OFF2 @ CSIZE 4
"IF PIC=2 THEN LABEL USING 1100 ; OFF1,OFF2 @ CSIZE 4
"IF PIC=4 THEN LABEL USING 1110 ; OFF1,OFF2 @ CSIZE 4
"MOVE XZ-(XZ-X1)/2,Y1-(YZ-Y1)/5 @ LABEL USING "K" ; "FD IN MHZ"
"MOVE X1-(XZ-X1)/7,Y1-(YZ-Y1)/2 @ DEG @ LOIR 30 @ LABEL USING "K" ; "Pdf(FD) 
X IE8"
"IMAGE "TOTAL="",DD.DDD
"MOVE X1,Y1-(YZ-Y1)/5 & LOIR 0 @ LABEL USING 1210 ; SUMY
"PLOT:
"INPUT "DUMP GRAPHICS? Y/N",DG$
"IF DG=""Y" THEN DUMP GRAPHICS
"EPLOT:
"HP=""N"
"INPUT "PLOT ON EXTERNAL DEVICE? Y/N",PLE$
"IF PLE=""Y" THEN PLOTTER IS 705 & PEN 1 & LOCATE 30,110,29,89 & GOTO START 
"IF CH=4 OR CH=2 THEN CHOICE
"BEEP 150,300 & DISP "DONE"
"END
"PLT1: I
"PLOT SHORT ARRAY
"REDIM X(N),Y(N)
"IF CH=1 THEN MULT=1 ELSE MULT=100000000
"FOR K=1 TO N I FILL X AND Y ARRAYS
"X(K)=K & Y(K)=PX(K)*MULT
"NEXT K
"XI=1 @ XZ=N & Y1=0 & YZ=AMAX(Y)+1.1 & TOP=N & LINE TYPE 1
"PLOTTER IS 1 & PEN -1 & GCLEAR & LOCATE 30,170,25,30
"GOTO START
"RETURN
"PLT2: I
"PLOT LONG ARRAY SAME SCALE
"T=""INPUT ARRAYS"
"IMAGE "CONSTANT ARRAY FOR F1, DF1="",DD.D," CONSTANT ARRAY FOR F2 , OFF2="", 
"DD.DD
"IMAGE "CONSTANT ARRAY FOR F1, DF1="",DD.D," GAUSSIAN ARRAY FOR F2 , OFF2="", 
"DD.DD
"IMAGE "GAUSSIAN ARRAY FOR F1, DF1="",DD.D," CONSTANT ARRAY FOR F2 , OFF2="", 
"DD.DD
"IMAGE "GAUSSIAN ARRAY FOR F1, DF1="",DD.D," GAUSSIAN ARRAY FOR F2 , OFF2="", 
"DD.DD
"LONG 5
"MOVE XZ-(XZ-X1)/2,YZ+(YZ-Y1)/20 @ IF PIC=2 THEN LABEL USING 1470 ; OFF1,OFF 
2 @ CSIZE 4
"MOVE XZ-(XZ-X1)/2,YZ+(YZ-Y1)/20 @ IF PIC=1 THEN LABEL USING 1450 ; OFF1,OFF 
2 @ CSIZE 4
"MOVE XZ-(XZ-X1)/2,YZ+(YZ-Y1)/20 @ IF PIC=3 THEN LABEL USING 1460 ; OFF1,OFF 
2 @ CSIZE 4
MOVE X2-(X2-X1)/Z, Y2+(Y2-Y1)/Z @ IF PIC=4 THEN LABEL USING 1480 : OFF1, OFF2 ; CSIZE 4
LORG 5 @ MOVE X2-(X2-X1)/Z, Y2+(Y2-Y1)/9 @ LABEL USING "X" ; T3
IF CH=1 THEN MULT=1 ELSE MULT=1000000000
MOVE X1-(X2-X1)/7, Y2-(Y2-Y1)/Z @ DEG @ LOIR 30 @ LABEL USING "K" ; "VALUE X" ; MULT
FOR K=1 TO N
Y(K)=PH(K)*MULT
NEXT K
CH=4 @ LINE TYPE 4 @ TOP=N
GOTO MODEAT
RETUR
APPENDIX A
BRAGG-CELL RECEIVER
PDF GENERATION & STATISTICAL ANALYSIS PROGRAM

S: BRAGGPDF  THIS PROGRAM COMPUTES BRAGG-CELL RCVR. PDF AND STATISTICS
10: THIS PROGRAM GETS DATA FROM A CONVOLUTION FILE-DOES GEN MOMS
20: DATA IS THEN PLOTTED WITH LABELLED CENTRAL MOMENTS, INT, ETC....
30: OPTION BASE:
40: DIM FX(500), PH(500), INFO$(80), TS$(75)
50: DISP "PLEASE USE FILENAMES WITH 2 DIGITS FOR DF1"
60: INPUT "FILENAME?", FS
70: ASSIGN# 1 TO FS
80: READ# 1 ; N @ N=N-1
90: REDIM FX(N), PH(N)
100: FOR K=1 TO N
110: FX(K)=FX(K)+100
120: NEXT K
130: ASSIGN# 1 TO *
140: DISP @ DISP INFO@ DISP
150: FS=REV$(FS) @ PS=FS(1,1)
160: IF PS="A" THEN PIC=1
170: IF PS="B" THEN PIC=2
180: IF PS="C" THEN PIC=3
190: IF PS="D" THEN PIC=4
200: DF1=VAL(FS(3,1)) @ DFLO=VAL(FS(6,7))
210: DISP "ENTER RESOLUTION IN MHZ" @ INPUT RES
220: XST=INT(RES*(2*OFI/N))
230: OFM=AMAX(FX)-AMIN(FX) @ FSTPM=OFM/(N-1)*XST @ OF=FSTPM*1000000 @ SUMZ=0
240: FOR K=1 TO N
250: FX(K)=FX(K)+1000000 @ SUMZ=SUMZ+FX(K)*OF
260: FX(K)=FX(K)+1000000 @ SUMZ=SUMZ+FX(K)*OF
270: NEXT K
280: FOR K=1 TO N
290: SUMK=SUMK+FX(K)*OF
300: NEXT K
310: FOR K=1 TO N
320: SUMK=SUMK+FX(K)*OF
330: NEXT K
340: NEW=NEW+FX(K)*OF
350: SUMK=SUMK+FX(K)*OF
360: NEXT K
370: FOR K=1 TO N
380: SUMK=SUMK+FX(K)*OF
390: NEXT K
400: UNK=UNK+FX(K)*OF
410: NEXT K
420: UNK=UNK+FX(K)*OF
430: NEXT K
440: CM3=CM3+CM4=CM4
450: SKEW=CM3/UNK*1.5 @ KURT=CM4/UNK*2
460: PLOTTER IS 1 @ PEN -1 @ GCLEAR @ LOCATE 30,170,25,30
470: Y1=0 @ Y2=AMAX(PH)*1000000000+1.1 @ X1=FX(1)/1000000 @ X2=XS+N/1000000/2+500
480: START:
SCALE X1, X2, Y1, Y2
FX: 3,2 @ LAXES (X2-X1)/10, (Y2-Y1)/10, X1, Y1
YAXIS Y2, (X2-{1}/10, X1, X2
YAXIS X2, (Y2-{1}/10, Y1, Y2
MORDAT: !
FOR K=1 TO N STEP XST
IF K+XST=N THEN SGO
PLOT FX(K/1000000, PM(K)@1000000, PH(K)@1000000
NEXT K
IMAGE "CONSTANT PDF FOR F1, DF1=" .0000" CONSTANT PDF FOR F2, DF2=" .0000
IMAGE "GAUSSIAN PDF FOR F1, DF1=" .0000" GAUSSIAN PDF FOR F2, DF2=" .0000
IMAGE "GAUSSIAN PDF FOR F1, DF1=" .0000" GAUSSIAN PDF FOR F2, DF2=" .0000
IMAGE "SQUARE-COLL RECEIVER PDF ANALYSIS" @ CSIZE 3.5,1
LOG S @ MOVE X2-(X2-X1)/2, Y2-(Y2-Y1)/10 @ LABEL USING "K" ; T
CSIZE 3
MOVE X2-(X2-X1)/2, Y2-(Y2-Y1)/10 @ IF PIC=1 THEN LABEL USING S80 @ DF1, DFLO @
CSIZE 4
IF PIC=3 THEN LABEL USING S90 @ DF1, DFLO @ CSIZE 4
IF PIC=1 THEN LABEL USING S50 @ DF1, DFLO @ CSIZE 4
IF PIC=2 THEN LABEL USING S50 @ DF1, DFLO @ CSIZE 4
IF PIC=4 THEN LABEL USING S10 @ DF1, DFLO @ CSIZE 4
MOVE X2-(X2-X1)/2, Y1-(Y2-Y1)/5 @ LOG S @ LABEL USING "K" ; "F0 IN MHZ"; LORG S @ CSIZE 4 @ LORG 1
MOVE X1-(X2-X1)/7, Y2-(Y2-Y1)/2 @ DEG @ LDIR 90 @ LABEL USING "K" ; "Pd(Fd) X 1E8"; LDIR 0 @ RAD
IMAGE "INTEGRAL" "0.0000
IMAGE "XMEAN" "0.0000.0000
IMAGE "SIGMA" "0.0000.0000
IMAGE "SKEW" "0.0000.0000
IMAGE "KURTOSIS" "0.0000.0000
CSIZE 2.5 @ LORG 2
MOVE X1+(X2-X1)/25, YZ-(Y2-Y1)/10 @ LABEL USING S30 @ SUMZ
LABEL USING 740 @ XMEAN/1000000
LABEL USING 750 @ SIGMA/1000000
LABEL USING 760 @ SKEW
LABEL USING 770 @ KURT
LABEL USING "K" ; "RESOLUTION=" RESI." MHZ"
LABEL USING "DUMP_GRAPHICS? Y/N", SDMS
IF GDMS[1,1]="Y" THEN DUMP GRAPHICS
IF EPLS="Y" THEN SGO
LABEL USING "PLOT ON EXTERNAL DEVICE? Y/N", EPLS
IF EPLS="Y" THEN PLOTTER IS 70S @ PEN 1 @ LOCATE 30,110,29,89 @ GOTO START
SEEP 300, 490 @ DISP "DONE"