Direct P(Y) Code Acquisition Using An Electro-Optic Correlator

Alison Brown and Neil Gerein, *NAVSYS Corporation*

BIOGRAPHY

Alison Brown is the President and CEO of NAVSYS Corp. She has a PhD in Mechanics, Aerospace, and Nuclear Engineering from UCLA, an MS in Aeronautics and Astronautics from MIT, and an MA in Engineering from Cambridge University. In 1986 she founded NAVSYS Corporation. Currently she is a member of the GPS-III Independent Review Team and Scientific Advisory Board for the USAF and serves on the GPS World editorial advisory board.

Neil Gerein is a Project Manager for NAVSYS Corporation. He is responsible for developing the GPS digital storage receiver used for testing GPS signal processing and rapid acquisition advanced receiver designs. He is currently completing his M.Sc. in Electrical Engineering and holds a BSEE in Electrical Engineering from the University of Saskatchewan.

ABSTRACT

Modern military GPS receivers adopt a digital architecture to facilitate direct P(Y) code signal processing using high speed VHDL electronics. NAVSYS has developed a buffered digital receiver architecture that optimizes the GPS direct acquisition process by operating in the frequency domain. The effectiveness of acquisition in the frequency domain is dictated by the speed of the Fourier Transform implementation. High speed DSPs can perform a 1024 point Fourier Transform in less than 128 microseconds. The Fourier Transform approach can be dramatically improved by using an electro-optic correlator. Digital Spatial Light Modulators (SLM) are under development that can perform 1000 x 1000 2-dimensional correlations at kHz rates, which is equivalent to over 10^6 parallel digital correlations.

This paper describes an electo-optic correlator integrated with a GPS receiver, which was developed and tested to demonstrate the massive parallelism possible using modern electro-optic correlation techniques. This design performs the Fourier Transforms optically. A combination of simulation and live satellite test data was used to demonstrate the search and acquisition of the GPS P(Y) code signals. This paper includes test results showing the predicted performance of the direct P(Y) code acquisition using an optical correlator.

INTRODUCTION

To maintain a strategic advantage in a tactical situation, the DoD is developing the capability to directly acquire the P(Y) code GPS satellite signals without first acquiring the C/A code. The time-to-first-fix for Direct-Y acquisition is a function of the number of correlations that can be performed in parallel. Using conventional digital receiver technology, previous approaches to solving this problem have used large numbers of parallel digital correlation channels (e.g. 1000). The approach presented in this paper uses a frequency domain acquisition technique that lends itself to leveraging electro-optic (EO) correlator technology as a Direct-P(Y) GPS Acquisition Engine (GPS-ACE). Electro-optic correlation has the advantage of being able to perform large-scale correlations at extremely high rates, which has the potential to significantly reduce the acquisition time for direct P(Y) code acquisition.

GPS RECEIVER ARCHITECTURE

The architecture adopted by a conventional GPS receiver is illustrated in Figure 1. The first step in the processing chain is to use an RF Digital Front-End (DFE) to digitally sample the GPS signal spectrum. The digital sampled signals are then processed using digital logic to correlate with the C/A and or P(Y) codes and digitally mix the result to baseband, using a complex multiply operation to remove the effect of the satellite Doppler and receiver frequency offset (from the IF or RF sampling). The baseband digital signals are accumulated and the resulting

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in-phase and quadrature (I&Q) signals output for use in the receiver's software signal processing algorithms.

In the digital storage GPS receiver architecture developed by NAVSYS, the signal processing functions that are performed using digital logic in the conventional receiver architecture shown in Figure 1 are implemented in software or firmware[1]. This allows total flexibility in the signal processing algorithms used. In Figure 2, the digital storage GPS receiver architecture is shown. In this architecture, the GPS signals are first buffered in memory to allow them to be accessed by the software or firmware for processing. Since the GPS signals do not have to be processed in real-time, enhanced signal processing algorithms can be applied that allow the digital signals to be optimally reprocessed, maximizing the probability of acquiring the GPS signals in a challenging environment.

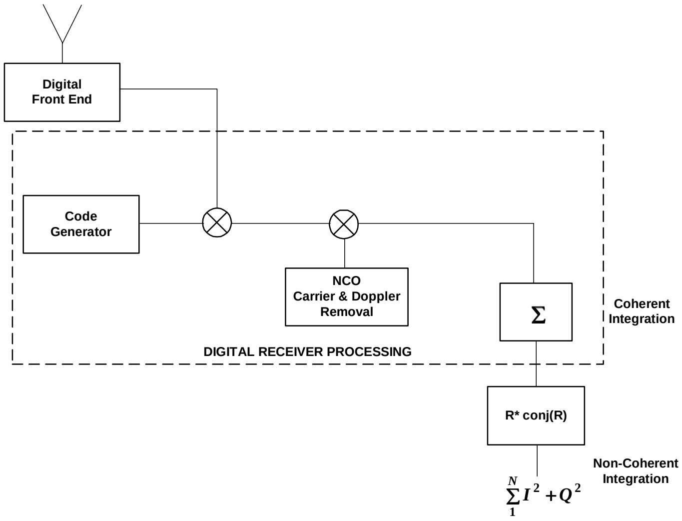

Figure 1 Digital GPS Receiver Architecture

In Figure 2, the equivalent GPS signal processing functions are shown implemented in the digital storage receiver using frequency domain correlation. This approach takes advantage of the Fourier Transform correlation theorem which states that the frequency transform of the correlation function in the time domain is the product of the signals' transforms in the frequency domain[2].

(1)

$$\int_{-\infty}^{\infty} h(\tau)x(t+\tau)d\tau \quad \Leftrightarrow \quad H(f)X^*(f)$$

The Fast Fourier Transform (FFT) algorithm in Equation (1) provides a convenient and computationally efficient method of performing correlations in the digital storage receiver architecture.

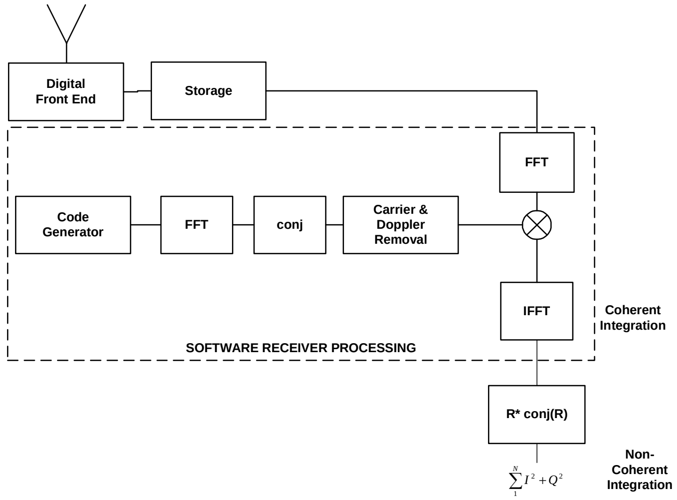

Figure 2 Software GPS Receiver Architecture

GPS SIGNAL ACQUISITION TIME

The process of aligning an internally generated code to the received GPS code, which is biphase modulated on the GPS signals, is referred to as signal acquisition. This internal generated signal is cross correlated with the received signal plus noise, coherently integrated over a predetection integration time denoted as T_c, thereby generating the in-phase and quadrature sample sums (I^2+Q^2). These are summed over N_{NC} non-coherent integration periods to the accumulated signal magnitude above a detection threshold ($\gamma\sigma_n^2$), the magnitude of which is dependent on the allowable probabilities of false alarm and successful detection, which can be computed as shown below from the GPS coherent signal/noise ratio (CN in dB).

(2)

$$\begin{aligned} P_{FA} &= \Pr ob(z \geq \gamma\sigma_n^2 \mid CN_0 = 0) \\ &= Q(\gamma \mid 2N_{NC}) = 1 - P(\gamma \mid 2N_{NC}) \end{aligned}$$

(3)

$$\begin{aligned} P_{MD} &= \Pr ob(z < \gamma\sigma_n^2 \mid CN_0 = CN_T) \\ &= P(\gamma \mid 2N_{NC}, N_{NC} \times CN_T) \end{aligned}$$

Each search must be performed for every possible half code-phase interval and Doppler frequency bin. The uncertainty in code phase is due to user clock uncertainties plus user to satellite range uncertainty. For example, a user clock uncertainty of one millisecond (random zero mean Gaussian bias - one standard deviation) and an additive user to satellite range uncertainty of 30,000 meters (random independent Gaussian bias - one standard deviation) would result in a 3-sigma (99%) search region of (10279 x 2 x 3) x 2 ≅123,345 bins for P(Y) code acquisition. Since the C/A code is repetitive over 1 msec, the search region is much smaller for C/A code acquisition, resulting in 1023 x 2 ≅ 2,046 bins under the same assumptions.

The Doppler bin size is dictated by the coherent integration period. To maintain the correlation loss due to Doppler uncertainty within 3 dB, the size of each frequency window should be kept within $0.442/T_c$. If the Doppler one sigma uncertainty and the receiver oscillator uncertainty is within 1 kilohertz, and the coherent integration period (T_c) was set at 20 milliseconds (the GPS data bit period), then the number of discrete frequencies to search over would be approximately 384. In this scenario, the total number of bins that would need to be searched to assure P(Y) code acquisition would be over 47 million (123,345x384). It is this large number of bins to search which creates, in many operational scenarios, the impracticality of Direct Y acquisition in an acceptable time.

With a conventional GPS receiver, the present approaches to reducing the acquisition time are:

- Time aiding the receiver with external clocks typically better than 1 millisecond. This reduces the number of searches by reducing the code phase uncertainty.
- Massively parallel correlators. This enables the simultaneous or parallel processing of many bins at once.
- Improving the signal-to-noise ratio at the input to the receiver. As will be shown subsequently, the acquisition time varies directly with the product of the coherent integration interval, T_C and the number of summations, N_{NC}. This product is sometimes referred to as the dwell time per bin for a single search frequency.

A simple expression for the average sequential or serial search time in a conventional receiver is:

$$T_{\text{search}} \cong 1/2 N_{BINS} N_{NC} T_C \ / \, \mathrm{M}$$

The average, or expected value of the random variable, search time, is therefore ½ of the product of the number of bins to search and the dwell time per bin, scaled by the number of correlators (M) operating in parallel.

The enhanced signal processing capability of the software GPS receiver is also of benefit for acquisition and tracking of the GPS signals in the presence of a jammer threat. The jammer has the effect of adding additive noise to the GPS signal proportional to the jammer/signal (J/S) power ratio (Campanile, J., Nasuti, T., Nigro J., Engelhart, M. 1992). To operate in the presence of a jammer, the receiver must be able to acquire under very low equivalent signal-to-noise ratios. The equivalent signal/noise ratio can be computed from the effective noise that is added by the jammer signal as shown in the following equation, where N_0 is the thermal density, J is the jammer noise power, R_C is the P(Y) code chipping rate or equivalently the single sided front end bandwidth, and Q is a factor =1 for a narrow band jammer, 1.5 for a broad band spread spectrum jammer, and 2 for a wide band jammer[1].

$$J_{eq} = N_0 R_C + \frac{J}{Q_C}$$

$$N = J_{eq} \ / \ R_C$$

For most cases investigating jamming, the jamming power dominates the noise background. In Figure 3 the acquisition time is calculated as a function of jammer signal power based on the assumptions shown below. Unless otherwise stated, the values shown are 3-sigma.

- Probability of detection of 0.95 and a probability of false alarm of 0.0001.
- Time/frequency uncertainty of 1 second/10 kHz
- Sampling and processing implementation loss of 4.1 dB
- Number of correlators available for a conventional GPS receiver was 50 (Miniature Airborne GPS Receiver) or 1000 (E-MAGR).

The acquisition time shown for the storage receiver assumes an ideal correlation process, i.e. the data can be processed in real-time as it is collected. This represents the minimum time required for collection of sufficient data to detect the GPS signals in the presence of jammer noise. Current digital signal processors cannot approach these speeds in performing the large numbers of correlations needed to search over the P(Y) code uncertainty space. The optical correlator process however shows promise for being able to achieve these types of speeds.

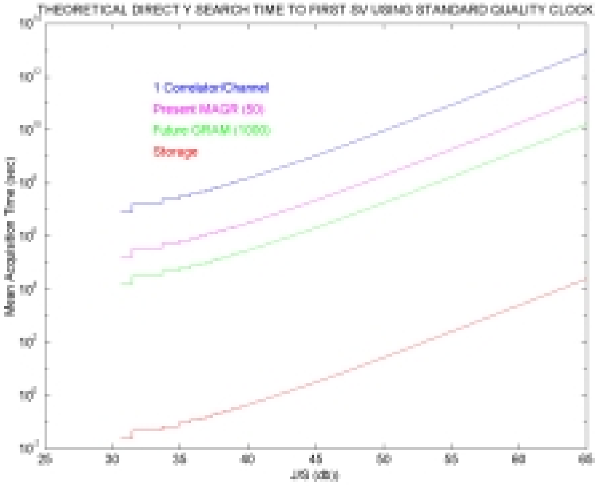

Figure 3 Theoretical Direct Y Search Time to First SV using 1 second Time Uncertainty

ELECTRO-OPTIC CORRELATION

Electro-optic systems have been widely used in radar and image processing for this process, since a Fourier transform can be performed using a Fourier transform (FT) lens[3]. The main advantage of such optical systems is their speed. An optical two-dimensional Fourier transform of a 1000x1000 point image takes a few nanoseconds (the time needed for the light to transverse the system). The same computation on a digital signal processor requires some 10^8 operations (using the FFT algorithm), so the optical system is working at a rate equivalent to more than 10^{16} operations/second. This advantage is due to the inherent parallelism of the system: since the whole image goes through the FT lens at the same time, all of the output points are created simultaneously.

In the GPS Electro-optic Correlator implemented by NAVSYS, the optical processor is used to perform the frequency domain analysis functions used to perform software GPS correlation process shown in Figure 2.

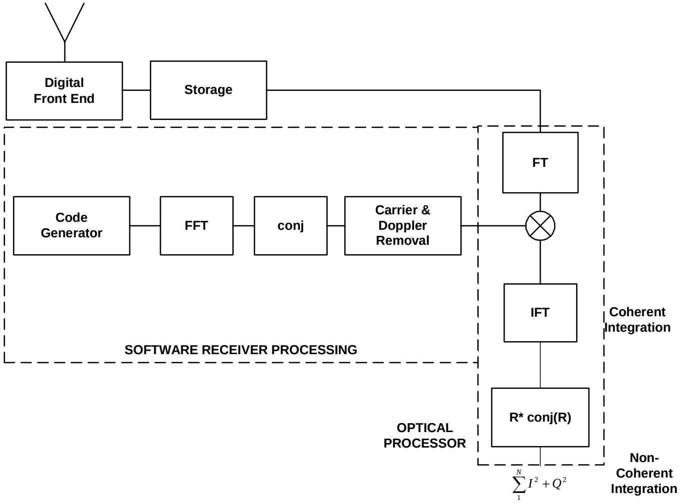

Figure 4 Optical Processing GPS Receiver

As shown in Figure 4, the GPS signal collected by the digital storage receiver is introduced into the optical correlator where the optical processing functions shown in Figure 5 are performed. This includes performing the frequency transform of the input GPS data (A), multiplying this with the input correlation data filter in the frequency domain (B), taking the inverse fourier transform of the results and detecting the output power (coherent accumulation sum) of the result.

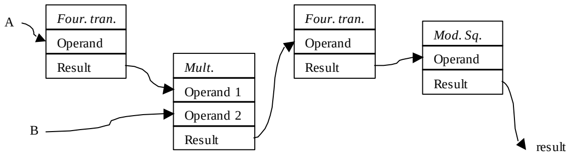

Figure 5 - The data flow graph for an optical processor

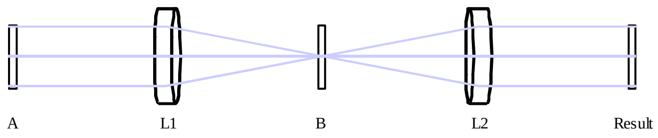

Figure 6 - Conceptual drawing of an optical processor.

The GPS signal is input into Plane A of the optical processor (Figure 6) via a programmable Spatial Light Modulator (SLM). The complex conjugate of the FFT of the P(Y) code is introduced into Plane B via another SLM. Diffraction propagation from the SLM in Plane A results in the first Fourier transform operation shown in Figure 5. The lens L1 scales and locates this Fourier transform plane to a more useful form. The second Fourier transform operation is created in a similar fashion with the SLM at Plane B and the lens L2. The multiplication of the Fourier transform of Plane A with Plane B occurs at Plane B prior to the second Fourier transform. The final modulus squared is a result of the square law intensity detection with a CCD detector. Coherent optical processing is performed by use of a coherent laser as the illumination source for the optical processor[4].

The optical processor performs the operations defined in the activity templates at the speed of light as soon as the operands are present, regardless of the number of pixels in the SLMs or detector. The speed of the optical processing functions are only limited by the speed at which the data can be input to the spatial light modulators and read by the CCD array.

GPS ELECTRO-OPTIC CORRELATOR

The optical correlator used for the GPS acquisition demonstration system is shown in Figure 7 and Figure 8 and was produced by Boulder Nonlinear Systems (BNS). Due to budget limitations, the optical correlator selected utilized two 256x256 binary Spatial Light Modulators (SLMs) to input the GPS signal data. The use of a binary input introduces an additional 1.96 dB of loss in the processing – similar to the loss when using a hardlimiter in the GPS receiver front-end. In follow-on activities, a gray scale correlator with more resolution is proposed to be used. The 256x256 binary SLMs can modulate light in binary amplitude or binary phase[5]. The type of modulation is selected by rotating an output analyzer. Current drive electronics refresh the SLM at a sustained rate of over 18 KHz and support a useful frame rate of over 2000 Hz. The full-frame load time of the 256x256 VLSI chip has been tested to 51.2 µsec. This results in a tested continuous full-frame load rate of 19531 Hz, or equivalently 1.3 gigabits/sec. However, this does not include time for the LC to optically respond to the electric field, or for actual viewing time. The current drive electronics support a load time of 55.4 µsec and response and view times as short as one load time, and a total true/inverse cycle time of 8 load cycles. This time results in a useful frame time of 442.8 µsec, or a rate of 2258 Hz.

Each SLM is driven from a memory bank of 512 images. The output from the correlator is provided using a Dalsa 128x128 high-speed CCD camera with a maximum sustained throughput of 830 Hz. The Dalsa 128x128 camera feeds into a frame grabber for capturing the correlation images. The captured images are then transferred to host memory for post-processing with a peak detection algorithm. Sample input and actual correlation images can be seen in Figure 9.

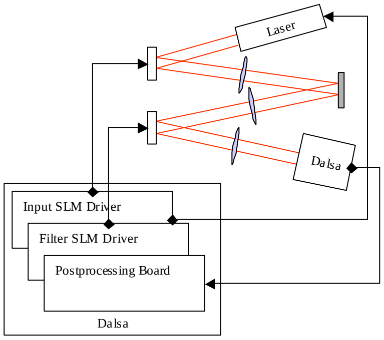

Figure 7 Block diagram of 256x256 binary correlator.

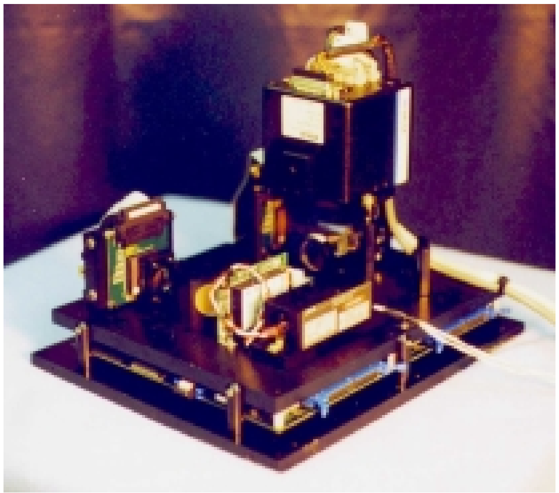

Figure 8 Photograph of 256x256 binary correlator.

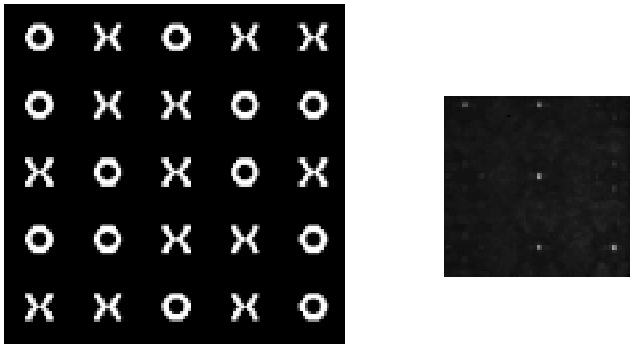

Figure 9 SmallXO input and correlation with a SmallX filter in the 256x256 binary optical correlator with a 128x128 CCD detector.

SYSTEM LOSSES IN AN ELECTRO-OPTIC CORRELATOR

The trade-off between using digital correlation and optical correlation is in the speed and resolution of the signal processing. Digital signal processing is slower than the optical processing but provides higher resolution data. Much of the effort involved with testing the performance of the GPS optical correlator was therefore focused on characterizing the optical signal processing losses and evaluating how they affected the GPS signal acquisition process. The total losses expected in the optical correlation implementation vary depending on the details of the implementation. Each of the losses experienced for the 256x256 binary phase only correlator used are summarized in Table 1.

a) GPS correlation losses

The first set of losses illustrated are inherent in the GPS correlation process. The use of a one-bit digitizer (or binary SLM) causes a loss of 1.96 dB. This loss would be reduced through the use of a grey scale SLMs which would provide the same resolution as an 8 bit A/D converter. Losses are also introduced, as in the GPS correlation process due to offsets in code phase from the sampled signal phase, and offsets in Doppler frequency during the coherent accumulation time interval.

The correlation function only calculates values at discrete time offsets, specifically 1/sample_rate. If the actual correlation is between the correlation samples, there will be a reduction in the signal's correlation. The maximum reduction will occur when the correlation peak is midway between bins. The digital storage receiver generated samples at 40 Msps, which is roughly 4 times the P(Y) chip rate. This means that the maximum correlation peak reduction is 7/8 or 1.15 dB. The search in frequency was performed by shifting the reference P(Y) code filter signal in the frequency domain before downloading to the filter plane (B) SLM. As long as the Doppler offset is within +/- 1/8T, where T is the correlator total sample window in time, the Doppler search loss is less than 0.2 dB.

b) Frequency domain correlation loss

The frequency domain correlation process also introduces a loss which is a function of the initial time offset between the signal and reference code. If the signal in the data is aligned in time with the estimated P(Y) code, then a correlation peak will have a zero offset. If the estimated P(Y) code is offset by T/2 seconds, the signal correlation peak will be down by ½, or 6 dB since only half of the data in the correlation window actually correlates with the reference code. The search process was repeated so that the maximum time offset that could occur would be T/8 seconds, so that the signal correlation peak can only be down by 7/8, or 1.15 dB.

c) 2-dimensional correlation loss
The GPS data was entered into the SLM using a raster process. In this manner 256x256 samples were loaded – or T= 1.638 msecs. The data is written to the array in a left to right manner as shown in (a). To understand the additional 2-D loss, assume that the reference data (the code) has the pattern shown in (b). If the input is identical to the reference and time aligned, then it will have the pattern shown in (c). Since (b) and (c) are identical, the optical 2-dimensional correlator will produce a correlation peak in the center of the correlation plane as shown in (d). If the input is offset by half the array width (128 pixels for a 256x256 array) then it will have the pattern shown in (e). The shaded region is new data, the large cross-hatched pattern has moved to the right, and the small cross-hatched pattern has rolled around to the left and has moved down a row. The correlation that results is shown in (f). Because the correlation pattern is shifted by half the array width, the correlation peaks have moved to the side of the correlation plane. Two correlation peaks have appeared. The large crosshatched pattern is still aligned up and down, so it produces a peak that is centered vertically. The small crosshatched pattern has moved down one row, so it produces a peak that is down one row. The peaks are generated by only half the total signal, so the power in each peak is down by 6 dB. This effect is very similar to the effect described above for the one dimensional FFT, except that it repeats within the FFT window.

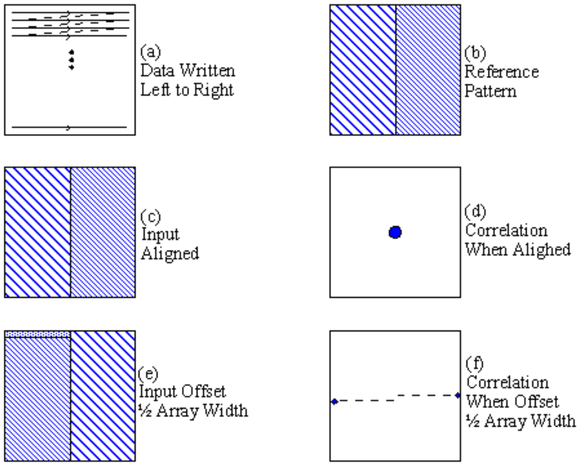

Figure 10 2D Window Loss

To minimize the losses in an operational system, the windows can be offset by fractions of the array width, overlapped, and only the center portion of the correlation array used for detection. Overlapping four windows and looking at the center 1/4 of the correlation array will reduce the maximum loss to 1.15 dB. Overlapping two windows and looking at the center ½ of the correlation array results in a maximum loss of 2.5 dB.

c) Phase Only Correlator
A digital FFT based correlation uses the amplitude and phase resulting from the FFT of the reference signal (the code). The EO correlator is not able to do this since it is not able to independently modulate the amplitude and phase of a signal. The best results occur when the phase is used rather than the amplitude. Losses have been calculated[67] to be on the order of 5 dB for a phase only correlator with gaussian noise. Our simulations measured 4.8 dB with the GPS signals.

d) Binary Phase-only Filter
Further losses occur when the phase of the filter is quantized to a single bit. The EO correlator does not provide a grey scale on the phase and therefore implements a binary phase only correlator. A lower bound of 6 dB additional loss has been established for a binary phase only correlator.[7] Our simulations showed an additional loss of 4.0 dB with GPS signals.

e) Optical Correlator imperfections
Additional losses occur due to slight imperfections in the optical components and the SLMs. Optical imperfections will cause quadratic phase errors and noise phase errors at the filter plane. SLM imperfections occur because the SLM surface is not perfectly flat and cannot be aligned perfectly. For the Phase II system, the expected losses from all of these causes combine to create a loss of about 5 dB.

Table 1 Potential Losses in GPS Optical Correlators

Optical Processing Loss	BPOF Loss	CONDITION
Binary Data	1.96 dB	
Doppler Offset	0.2 dB	Off +/- 1/8T
Correlation Peak Between Bins	1.15 dB	Midway Between Pixels
Correlation Window Loss	1.15 dB	Off +/- T/8 (Overlap 4x)
2 D Window Loss	1.15 dB	Off +/- 1/8 the array width (Overlap 4x)
Phase Only Correlator (POC)	4.8 dB	
Additional for Binary POC	4.0 dB	
Additional Optical & SLM Losses	5.0 dB	
TOTAL	19.4 dB	Observed through testing

Table 1shows that the total loss experienced in the optical correlator is almost 20 dB, compared to an expected loss of 4.5 dB when using the digital or software signal processing shown in Figure 2 (and a 1-bit signal). To make up for the signal processing loss, longer periods of non-coherent summations are required, as shown in Figure 3. A general rule is that the acquisition time is increased by 4x for every additional 3 dB of loss introduced.

ELECTRO-OPTIC CORRELATOR TEST RESULTS

The GPS electro-optic correlator performance was measured using a combination of test and simulation data. Real-world GPS data was collected using the hardware and post-processed to evaluate the GPS signal losses using digital signal processing. Simulated GPS data was generated using NAVSYS' GPS Matlab GPS Signal Simulation tools and also processed using digital optical processing to compare the system performance[8]. Since the hardware architecture uses buffered data, the simulated and real data can be substituted for each other to verify expected performance. The simulated data was converted to image and filter files to be run through the EO correlator. This data was used to verify the optical loss budget shown in Table 1 and measure the acquisition time for optical signal processing, including the additional processing time needed to account for the additional losses introduced by the optical signal processing.

In Figure 11 the optical correlator results are shown for a single correlation step with a simulated input signal of 60.4 dB-Hz. This shows the 2-d correlation peak appearing at the correct offset identified for the GPS signal correlation. To detect lower signal/noise ratio signals, multiple outputs from the optical correlator must be accumulated. The maximum number of input and filter images that can be loaded into the prototype system's SLM drivers at one time is 512. The electro-optic correlation results were generated for a simulated input GPS signal, with 45 dB-Hz signal/noise ratio. This can be detected using 512 accumulations (N_{NC}), which produced the electro-optic correlation test results in Figure 12, which have been mapped to a 1-D correlation process.

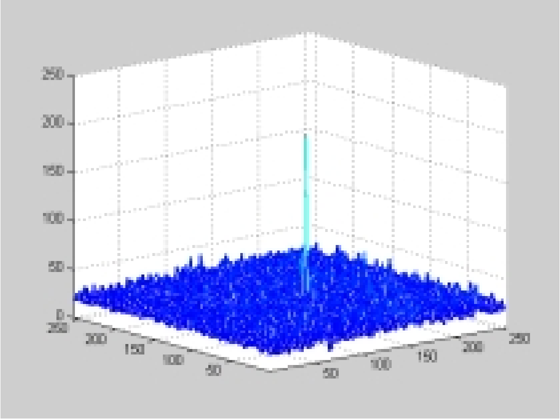

Figure 11 Perspective View of 2D Correlation with C/No = 60.4 dB Hz

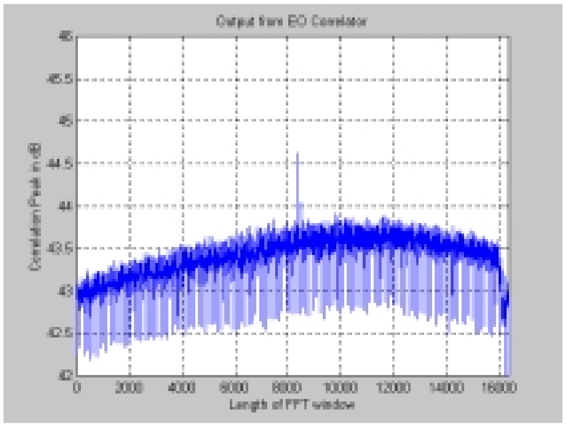

Figure 12 EO Correlator output with 512 accumulations and C/No = 45 dB-Hz

COMPARISON OF ACQUISITION TIMES

The predicted GPS acquisition times for the electro-optic correlator under test and for future GPS optical correlators using larger and faster SLMs with more resolution, are shown in Table 2. These acquisition times assume a +/- 30 ms velocity uncertainty, a +/- 100 km position uncertainty, and a 0.3 ppm oscillator. The limiting speed for performing EO correlation using the prototype system was the frame rate of the camera used to collect the data, which was 830 Hz. In a future design, it would be planned to use a CCD array to generate the detected correlation outputs at the same rate that the SLMs were running. BNS are currently producing a 512x512 grey scale SLM similar in function to the 256x256 binary SLM used for the prototype correlator. In Table 2, the predicted performance of a GPS optical correlator using this current generation 512x512 SLM with a 4 kHz CCD frame rate is shown. Within a year a 1024x1024 gray scale SLM should be available that can run at the same speed. The predicted performance of this correlator is also shown in Table 2.

Table 2 Predicted Performance for Prototype and Follow-on GPS optical Correlator

SLM Type	Binary	Gray	Gray	Digital
SLM Pixel Size	256x256	512x512	1024x1024	1000 correlator
EO Frame Rate	830 Hz	4 kHz	4 kHz	
Predicted Loss	19.5 dB	13.5 dB	13.5 dB	
Coherent Integration Time	1.6 msec	6.5 msec	26.2 msec	
Acquisition Time +/-1 sec J/S =30 dB	3470 min	5.3 min	46 secs	167 min

CONCLUSION

The testing performed under this activity demonstrated that an electro-optical correlator can be used to perform large scale parallel correlations optically for direct P(Y) code acquisition. An analysis was performed of the optical processing loss that is inherent in the optical correlation process and techniques were developed that allowed GPS acquisition to be performed both in the presence of this signal processing loss and in the presence of jammer signal. The analysis showed that significant improvements in direct P(Y) code acquisition time could be achieved using fast optical correlation.

The prototype unit built and tested under the AFRL SBIR contract used off-the-shelf optical processing components. Under a follow-on effort it is proposed to construct an optical correlator with the following capabilities.

- Miniaturized ruggedized design
- Gray scale, 1024x1024 SLM
- High speed CCD array with built-in detection of correlation peaks

The results of the testing and analysis performed to date have shown that this device would enable direct P(Y) code acquisition, even with large initial time uncertainties, within a minute of start-up.

ACKNOWLEDGEMENTS

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