LA-UR-04-5787

Rapid Prototyping for Radio-Frequency Geolocation Applications

Scott Briles, PhD
Los Alamos National Laboratory
Los Alamos, NM, 87545, USA
(505) 667-4298
briles@lanl.gov

Joseph Arrowood, PhD
Los Alamos National Laboratory
Los Alamos, NM, 87545, USA
(505) 667-4818
arrowood@lanl.gov

Thomas Braun
Los Alamos National Laboratory
Los Alamos, NM, 87545, USA
(505) 665-2830
tbraun@lanl.gov

Dakx Turcotte
Lyrtech Inc.
Quebec City, Canada
(418) 877-4644
dakx.turcotte@lyrtech.com

Etienne Fiset
Lyrtech Inc.
Quebec City, Canada
(418) 877-4644
etienne.fiset@lyrtech.com

Abstract: Previous space-to-ground, single-platform geolocation experiments exploiting time-difference-of arrival (TDOA) via interferometry were successful at separating and quantitatively characterizing interfering radio frequency (RF) signals from expected RF transmissions. Much of the success of these experiments rested on the use of embedded processors to perform the required signal processing. The experiments handled data in a "snapshot" fashion: digitized data was collected, the data was processed via a digital signal processing (DSP) microprocessor to yield differential phase measurements, and these measurements were transmitted to the Earth for geolocation processing.

With the utilization of FPGAs (field programmable gate arrays) for the intensive number-crunching algorithms, the processing of streaming real-time data is feasible for bandwidths on the order of 20 MHz. By partitioning the signal processing algorithm so there is a significant reduction in the data rate as data flows through the FPGA, a DSP microprocessor can now be employed to perform further decision-oriented processing on the FPGA output. This hybrid architecture, employing both FPGAs and DSPs, typically requires an expensive and lengthy development cycle. However, the use of graphical development environments with auto-code generation and hardware-in-the-loop testing can result in rapid prototyping for geolocation experiments, which enables adaptation to emerging signals of interest in a cost and time effective manner.

Introduction: Los Alamos National Laboratory is charged with certain aspects of treaty monitoring with respect to nuclear nonproliferation activities. In particular, Los Alamos is interested in detecting any nuclear testing that may occur and uses several sensing methodologies to perform this detection. One of these methods is to look for the radio frequency (RF) emissions that accompany any nuclear device detonation. Not only is it important to detect these detonations, it is imperative to geolocate where they took place.

When multiple sensors across multiple platforms are available, cross-ambiguity function (CAF) processing may be implemented to use any time-difference of arrival (TDOA) or frequency difference of arrival (FDOA) measurements to effectively triangulate where the signal originated.

When only one platform is available – due to cost or other factors – one would like to have multiple sensors on board to determine the TDOA via the phase information for the varying input signals. In essence, differential phase ($\Delta\phi$) is measured between adjacent sensors and this information, combined with measurements of the incoming frequency and knowledge of the sensor baseline distances allows one to determine a set of potential location points for the signal of interest. This process is called interferometry or short baseline TDOA processing.

The purpose of this paper is to demonstrate rapid prototyping techniques for this application. In particular, the Mathworks' Simulink and Matlab commercial software packages will provide an interface to graphically implement a short baseline interferometer for simulation, fixed point testing, hardware-in-the-loop testing and eventual deployment. For cost saving, both deployment and prototyping are to be performed with the same hardware platform from Lyrtech. Lyrtech has developed a heterogeneous system with FPGAs and DSPs and created the necessary software hooks to integrate their product into the Simulink environment.

Interferometry: The cost of putting multiple satellites in orbit precludes using the CAF processing from a long baseline TDOA/FDOA perspective. Therefore, geolocation from a single platform using multiple sensors is desired. The math behind [illegible]ic interferometry is simple. Figure 1 details the configuration for a two sensor array with a separation of D between the sensors and assuming far field for the emitter. The goal is to solve for the angle of bearing, θ, based on the phase difference of the signals s_1 and s_2.

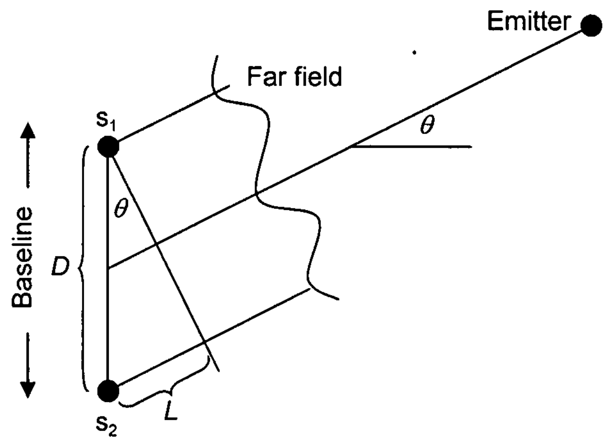

Figure 1: Interferometry Diagram.

This phase difference, $\Delta\phi$, is proportional to the added distance L that the signal must travel to reach s_2. This provides the first equation, once $\Delta\phi$ has been measured to be,

$$\frac{L}{\lambda} = \frac{\Delta\phi}{2\pi},$$

where λ is a measured approximation of the wavelength of the signal of interest. The solution L is then used to determine θ via,

$$\theta = \sin^{-1}\left(\frac{L}{D}\right).$$

Finally, one must examine the geometry and realize that without other constraints, θ defines a cone of bearing. This cone will intersect the surface of the earth and form a parabolic line called an isochrone. Isochrones are considered "lines of position" as they contain the full set of points on which the emitter might lie. If a third sensor is added to the mix and it is not in line with the other two, a new baseline will form and provide a new isochrone. The two isochrones will then intersect at a single point, providing the location of the emitter.

In reality, there are a few caveats that go along with this scenario. If $D > \lambda / 2$, then more than one solution will exist for θ. If such is the case, more than one isochrone will exist for each baseline. This leads to more than one intersection, and ambiguities in the solution. To get around the problem of ambiguities, one can add more baselines (at more expense and processing power) or simply wait for the satellite to move and form a new set of baselines resulting from the change in satellite position.

Even without the ambiguities, there is uncertainty in the answer. In truth, the solution can be identified down to a single point only if the various θ values are precise. Instead, the measurements of both $\Delta\phi$ and λ are approximations limited by the accuracy of the antennas, radios, attitude control, and quantization, to name a few. Thus, instead of thinking of the isochrones as lines, they should be thought of as swathes having width defined by an uncertainty, $\Delta\theta$. It is this $\Delta\theta$ factor that determines the size of the error ellipse and how accurate the resulting geolocation estimate is.

Previous Experiments: Previous Los Alamos efforts at space-based interferometry have had to rely on sub-optimal processing. In particular, obtaining an accurate representation of both θ and $\Delta\theta$ has been an issue. Due to the snapshot nature of data collection on the flight experiment, only three measurements of $\Delta\phi$ value would be employed to yield estimates of θ and $\Delta\theta$. To offset the lack of data, a Kalman filter at the ground station was employed to provide the optimal results given these constraints. Results were adequate for course geolocation, but not to the level that was desired for future experiments.

What was needed was to collect more $\Delta\phi$ measurements over the same time frame to get a histogram of measurements that provides a true statistical look at the values. It was not possible to get around the snapshot processing due to the lack of DSP microprocessors that could process the 20 MHz incoming digitized data in a streaming fashion. A heterogeneous system that makes use of Field Programmable Gate Arrays (FPGAs) allows this to take place.

Heterogeneous Processing: Aside from being extremely flexible, FPGAs offer tremendous computational throughput advantages over traditional DSPs. DSP microprocessors are serial-instruction devices with multiple buses and hardware design to have low overhead on branch and loop operations. A serial-instruction device is at a clear disadvantage to an FPGA that can implement calculations in parallel for certain algorithmic operation. As will be described in the next section, a critical piece of the analysis is to perform a Fourier transform on the incoming data as a first step – an FPGA is ideally suited to this type of operation and can perform this transform in real-time on a large bandwidth. DSPs, on the other hand, are more appropriate for processing the results coming out of the transform section, such as ambiguity resolution, where decision paths are needed instead of parallel data crunch.

Thus, both parallel (FPGAs) and serial (DSPs) devices are advantageous for performing different sections of an overall algorithm. While this may seem obvious, there is the downside of the complexity necessary to seamlessly integrate both chip types on a single platform. To achieve the goal of rapid prototyping, it was mandatory to find a vendor, like Lyrtech, that had already addressed that issue. Before delving into their hardware/software COTS solution, the implementation of the geolocation algorithm will be discussed in some detail.

Algorithm: Only single frequency constant signals, such as a carrier used in communications, are addressed by the algorithm in this paper. Other forms of signals that are not dominated by a carrier are not addressed. Examining only a single frequency, the algorithm produces two phase-difference measurements from three antennas. The single frequency is detected and examined in the frequency domain after employing the Discrete Fourier Transform (DFT).

The DFT, implemented as a Fast Fourier Transform (FFT), is employed to determine both an estimate of frequency and phase difference. After windowing the time-domain discrete data from the three antennas, a 2^{14}-length FFT is performed on the three data streams independently. Phase-difference measurements are produced by performing complex multiplications using these FFT outputs. To be clear, two of the data streams are multiplied with the third data stream that is designated as the "reference" antenna. Multiplying the "reference" transformed data with itself produced its auto power spectral density estimate. Thus after converting to the frequency domain, one auto and two cross power spectral density (PSD) estimates are produced.

These three PSD estimates can be improved via averaging. Non-overlapping segments of data are processed to produces streaming PSD estimates. These estimates can be averaged together to reduce the error in any measurements extracted. Averaging 16 PSD estimates together produces a $\Delta\phi$ measurement with one fourth the error. Given a 50 Mega sample per second sampling rate, there are approximately 3000 PSDs which could potentially be averaged to form an estimate for λ and $\Delta\phi$ each second. The main limiting factor in determining how many measurements to average together is $\Delta\phi$ will change over time as the spacecraft moves and the longer the integration time the more the values will spread, leading to a poorer estimate.

Using the averaged auto PSD for the reference antenna, carriers of interest can be detected. Simple thresholding provides a basis for the decision process, though more sophisticated methods may be used if needed. Once a certain frequency location has been designated as possessing a carrier, that frequency bin can be referenced in the averaged cross PSDs to yield the two $\Delta\phi$ measurements.

Other frequency locations may transcend the threshold, and then all the frequencies might be examined to determine how they are associated. As an example for FSK (frequency shift keying) modulation, the central carrier and associated "rate lines" might be present. Utilizing the phase difference measurements for all frequencies locations with detections, a partitioning algorithm could be employed to divide all detections in to groups were each group is said to be emanating from as single source. Thus only one member of the group needs to have its associated measurements presented for geolcation.

Before geolocation is performed, the streaming nature of the data can be exploited again in improving the $\Delta\phi$ measurements. Assuming stationary conditions, all the $\Delta\phi$ measurements

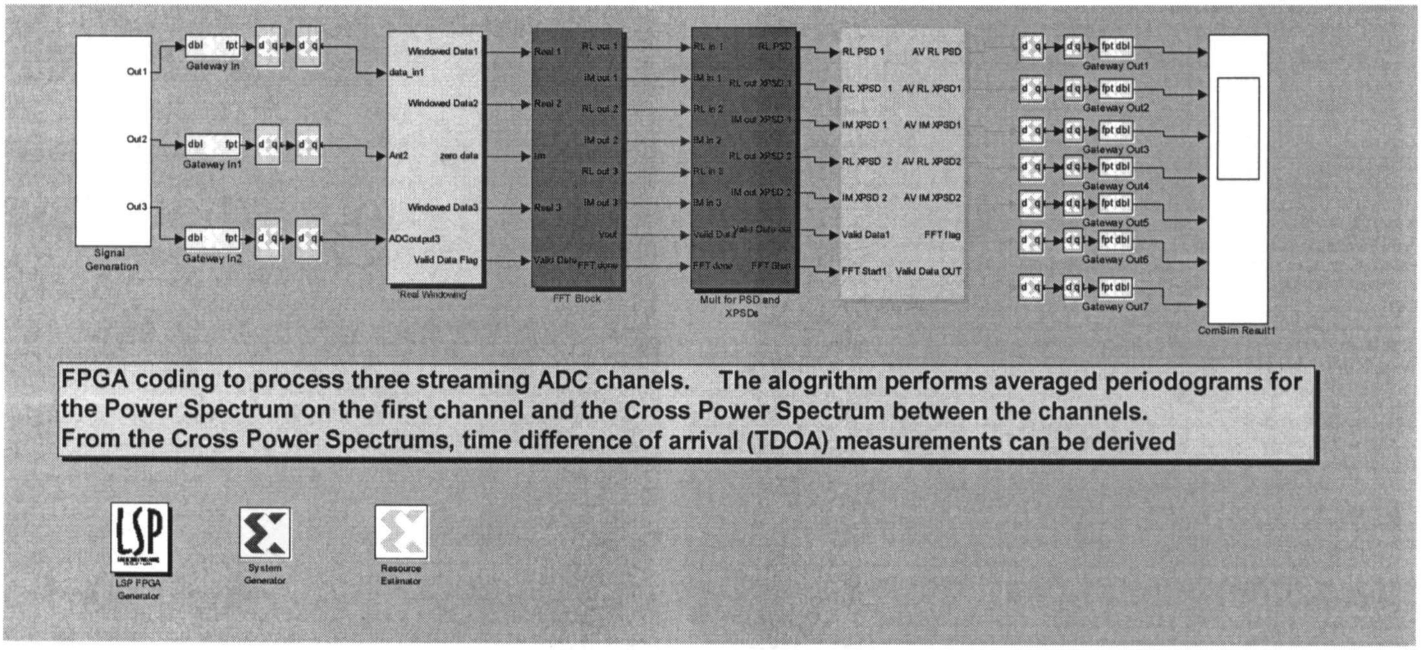

Figure 2: Top-level of program residing in FPGAs.

produced in a given amount of time, (e.g. on second) can be used to produce histograms representing the probability distributions of the measurements. At this point, modes, medians or means can be taken from the histograms to yield a better estimate of the true phase-differences. Better phase-differences measurements; will result in better geolocation accuracy.

Rapid Prototyping Implementation: Auto code generation is taken advantage of in our implementation of rapid prototyping. A single graphical-interface programming tool is used to program both computational elements of the heterogeneous architecture. Two things are sacrificed for the rapid development; the efficiency of the final executable code and the cost of components in that great capacity FPGAs are usually needed. When only a few instruments are being developed and fielded, additional parts costs are easily justified in cost saving in terms of man-hours.

In our heterogeneous-architecture partitioning the algorithm between the two processing entities was straight forward. The calculation of the three averaged periodograms is designated to be performed in FPGAs, and the signal detection tasks are designated to be performed on a DSP µP. The calculation of the angular $\Delta\phi$ measurements from the complex-valued cross PSD estimates does present some consideration as to which device will perform the processing.

Data bandwidth between the FPGA and the DSP µP and accuracy of FPGA-based calculation are the two main factors influencing where the calculation is performed. In the calculation of the averaged periodograms the data rate has been reduced by a factor of 16 due to averaging and a factor of 6/5 due to using only non-negative frequencies and real-values of the auto PSD. Thus if the input streaming data rate is 20 Msps the resulting data rate after FPGA processing is 1.04e6 values per second. If only the angular values from the cross PSD were sent to the DSP µP, then the resulting data rate would be 625e3 values per second. However, precision of the arctangent function performed in the FPGA is not a precise as the arctangent performed in a floating-point DSP µP. Erring on the side of precision, the current design has the angular calculation performed in the DSP µP for only frequency locations where detection occurs.

The programming of the FPGA is accomplished using the graphical programming tool Simulink® by Mathworks, Inc. and the auto code generation tool System Generator for DSP™ from Xilinx, Inc. Figure 2 below shows the top-level of the graphical-represented program that is executed in the FPGAs. Each block is a block in the program represents a subsystem. Each subsystem performs a specific operation to produce the averaged periodogram calculation.

An examination beneath the "windowing" block reveals how the operation is implemented. The values of the window are stored in RAM memory and multiplied simultaneously with the three data streams. Since the window function is symmetric only half the values are stored in memory and addressed in the proper sequence for multiplication. Figure 3 shows the blocks contents. Other blocks in the design are similar in using System Generator™ blocks to build various step of the averaged periodogram operation.

For parts of the algorithm that are implemented on the DSP µP, a similar process using graphical-programming and auto code generation is performed. Combining Simulink with the Mathworks' Real-time Workshop®, an executable program can be compiled and linked from auto generated C-language programming code.

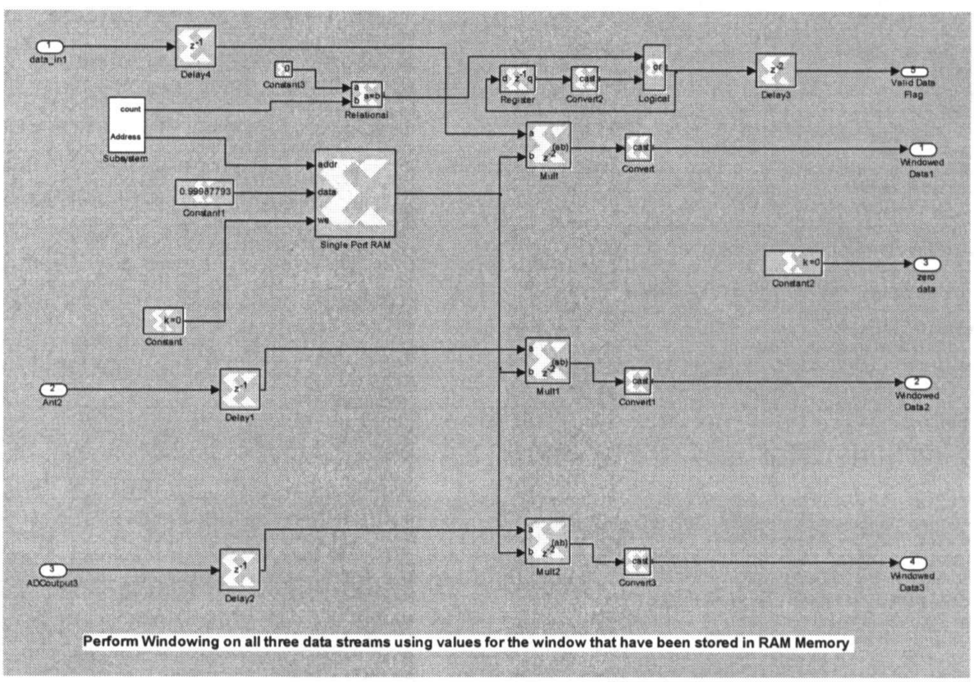

Figure 3: Windowing Block.

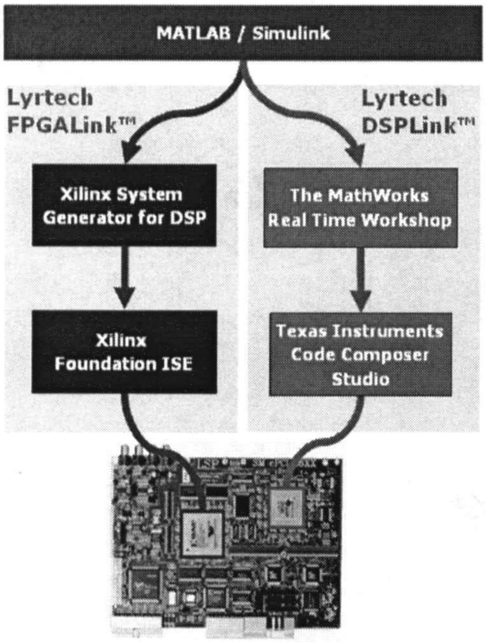

Figure 4: Lyrtech SignalMaster DSP/FPGA Integrated Solution.

Integrated Hardware/Software System: Figure 4 shows how the Lyrtech SignalMaster development platform integrates to the Simulink/System Generator for DSP graphical environment.

Lyrtech's FPGALink features a set of Simulink blocks that provide direct access to diverse FPGA interfaces, such as the high-speed ADC channels and the DSP/FPGA data transfer bus, directly from a Xilinx System Generator block diagram. One can then generate the VHDL code, as the block library maps to Xilinx DSP LogiCores, which are optimized implementations of typical DSP functions. It is then a matter of using the normal Xilinx tool flow of synthesis, place and route, and bit-stream generation to program the FPGA. This process requires virtually no user intervention and bit-stream generation can be accomplished with a single mouse click.

On the DSP side, Lyrtech's DSPLink software provides I/O card drivers, profilers, and memory mapping blocks that one plugs into the Simulink model. C-code is automatically generated using the Real-Time Workshop tool prior to compiling and linking it using Texas Instruments Code Composer Studio.

Using this design flow, unique to Lyrtech DSP/FPGA hardware integration, not a single line of C or VHDL code needs to be manually written by the application developer. Furthermore, the remote operations and real-time data monitoring capabilities of the Lyrtech DSPLink turn the Simulink block diagram into a user interface to control the geolocation system. Switches and sliders on the block diagram can change parameters on-the-fly while the code is executing in the hardware. Scopes and digital readouts can be used to monitor the signal levels in the system under operating conditions. In this manner, the system block diagram becomes a graphical tuning and debugging environment.

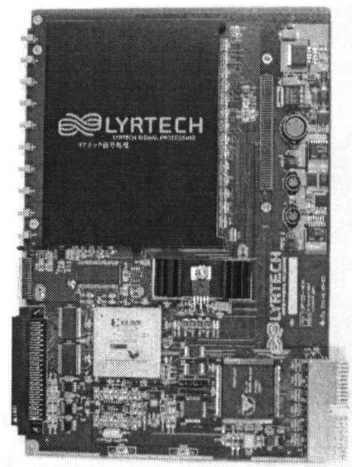

Figure 5: Lyrtech VHS-ADC rapid prototyping platform.

The signal acquisition hardware platform chosen for this project is a Lyrtech VHS-ADC, an ideal card for a sensor array development platform as it features 8 or 16 ADC channels at 105 MHz, a large FPGA for high-speed processing, SDRAM for signal storage and system-level support using Xilinx's System Generator. Its FPDP interface with 400 MB/sec transfer rate allowed the addition of a DSP/FPGA processing board, the Lyrtech C67x SignalMaster cPCI platform, providing a complete and very high performance solution based on two Xilinx XC2V8000 FPGAs and one TI C6701 DSP.

Summary: Though there were problems encountered performing rapid prototyping for this particular algorithm on this particular type of heterogeneous hardware, it is the opinion of the authors that this type of solution is not only viable but advantageous for developing complex applications for real-time hardware deployment. Future applications for Los Alamos will require that the focus is not on the hardware integration issues, but rather on the performance of the algorithm against the collected data. It is for this reason that a COTS heterogeneous hardware/integrated software solution using the COTS Simulink program is recommended. The scientists and engineers can focus on developing the optimum algorithm knowing that they can use both parallel and serial instruction devices and move data between them efficiently and effortlessly. This method of rapid prototyping for complex instruments leans towards an algorithmic-centric design as opposed to hardware-centric so the focus is on the processing itself, not the target hardware.

Acknowledgments: This effort is sponsored by the U. S. Department of Energy, NN-22.

References:

[1] Michael G. Price, "Mathematics of Geolocation," internal paper to Systeka Inc. 9525 Worrell Ave., Seakbrook, MD 20706

[2] Piersol, A. G., "Time Delay Estimation Using Phase Data," IEEE Trans. on Acoustics, Speech, and Signal Processing, Vol. ASSP-29, NO. 3, June 1981.

[3] Oppenheim, A. V. and Schafer, R. W., Discrete-Time Signal Processing, Prentice Hall, Englewood Cliffs, NJ.,1989. Chapter 11.