EXECUTIVE SUMMARY

GPS Based Positioning System for Geophysical Surveys in Heavy Foliage Areas

ESTCP Project MR-201311

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Integrated Solutions for Systems

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ACRONYMS AND ABBREVIATIONS

ASIC	application-specific integrated circuit
CSAC	chip-scale atomic clock
FPGA	field-programmable gate array
GPS	global positioning system
IMU	inertial measurement unit
INS	inertial navigation system
PVT	position, velocity, and time
RF	radio frequency
SDR	software defined receiver
SoC	system-on-chip
UXO	unexploded ordnance

ACKNOWLEDGMENTS

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1.0 INTRODUCTION

Geophysical mapping is a key step in the process of remediating sites contaminated with unexploded ordnance (UXO). In order to accurately locate UXO, accurate measurements of the positions of the geophysical sensors are needed. The need for accurate, real-time pose (position and attitude) estimates has increased in recent years as more advanced sensors are developed that are capable of not only detecting anomalies, but also discriminating items of interest from cultural debris. A combination of a global positioning system (GPS) receiver and an inertial navigation system (INS) is a common method of determining the pose of these sensors.

Currently, in areas where there are strong or frequent attenuations or blockages of the GPS signal, alternative methods of positioning are used, such as laser or radio frequency (RF) based ranging systems or odometry. Ranging based systems such as robotic total stations that are traditionally used in surveying applications or more developmental RF based ranging systems are capable of providing very accurate position measurements in GPS-denied areas. They often, however, require line of sight to the receiver and are cumbersome and time consuming to set up. Systems such as total stations are also generally considerably more expensive than a GPS receiver. Odometry solutions, based on wheel encoders or inertial measurement units (IMU), have error characteristics that grow over time and require prohibitively expensive sensors to provide accurate positions for periods longer than a few minutes.

In this effort, a system has been developed that improves the accuracy and availability of position measurements for geophysical surveys by providing a GPS/INS system capable of providing positions in environments where standard GPS receivers provide a poor solution or fail to provide a solution at all. A GPS software defined receiver (SDR) has been developed that is capable of providing a position solution in degraded GPS environments, such as under heavy foliage, by making use of vector tracking techniques. The GPS position can be optionally blended with the output of a commercial IMU to provide attitude measurements and allow brief periods of dead-reckoning during complete GPS outages. A chip-scale atomic clock (CSAC) is also optionally used as a stable frequency reference to further improve the receiver's ability to operate with a limited number of satellites. The SDR based design allows the receiver algorithms to be defined completely in software, allowing an easy upgrade path as more advanced algorithms are developed. This design also drastically reduces development cost when compared to a traditional application-specific integrated circuit (ASIC).

2.0 OBJECTIVES

The objective of the demonstrations performed was to validate the performance of the developed GPS receiver under controlled conditions and compare its performance to GPS/INS systems currently used for geophysical surveys. Additionally, surveyed ground truth points and a ranging based positioning system (*e.g.,* robotic total station) were used to provide truth measurements allowing the absolute performance of the system to be determined in addition to comparing it to a traditional GPS receiver.

The primary performance objective for the system demonstration was to improve the availability of position measurements for geophysical surveys when compared to currently used survey methods such as GPS receivers. The setup time required and ease of use of the system was also evaluated qualitatively. The accuracy of the system was also evaluated.

3.0 TECHNOLOGY DESCRIPTION

The developed system is a GPS SDR that makes use of vector tracking techniques to improve the receiver's ability to track and reacquire weak signals. The GPS position is blended with the output of a commercial IMU to provide attitude measurements and allow brief periods of dead-reckoning during complete GPS outages. A CSAC is used as the receiver clock to further improve reacquisition time and the receiver's ability to operate with a limited number of satellites. The SDR based design allows the receiver algorithms to be defined completely in software, allowing an easy upgrade path as more advanced algorithms are developed. This design also drastically reduces development cost when compared to a traditional ASIC.

3.1 VECTOR TRACKING ARCHITECTURE

In this work, the tracking loops used in traditional receivers are replaced with a vector tracking architecture. Vector tracking loops are an advanced receiver architecture that combine signal tracking and position, velocity, and time (PVT) estimation into a single process. The vector tracking algorithm used is based on a vector delay / frequency locked loop. This architecture differs from a standard commercial receiver in two main areas: (1) a vector tracking architecture is used in place of the scalar tracking architecture; and (2) the phase locked loop is replaced with a frequency locked loop. An overview of the receiver algorithm as implemented in this work is given in the following sections.

3.2 SCALAR VS VECTOR TRACKING LOOPS

Standard GPS receivers use scalar tracking loops to process the received satellite signals. As shown on the left in Figure ES-1, the tracking loops in different channels of the receiver operate independently of each other. Measurements are generated in each channel and then fed into a navigation processor for determining a position solution. No information is shared between channels and there is no feedback from the navigation processor to the tracking loops. Vector tracking exploits the correlations between the received satellite signals and receiver position to improve tracking performance. The right side of Figure ES-1 shows a generic block diagram of the vector tracking architecture. In a vector tracking architecture, the navigation filter directly drives the correlators, combining the navigation solution estimation and tracking loops into a single operation. This allows the different channels of the receiver to share information, so that strong signals can assist in the tracking of weaker signals.

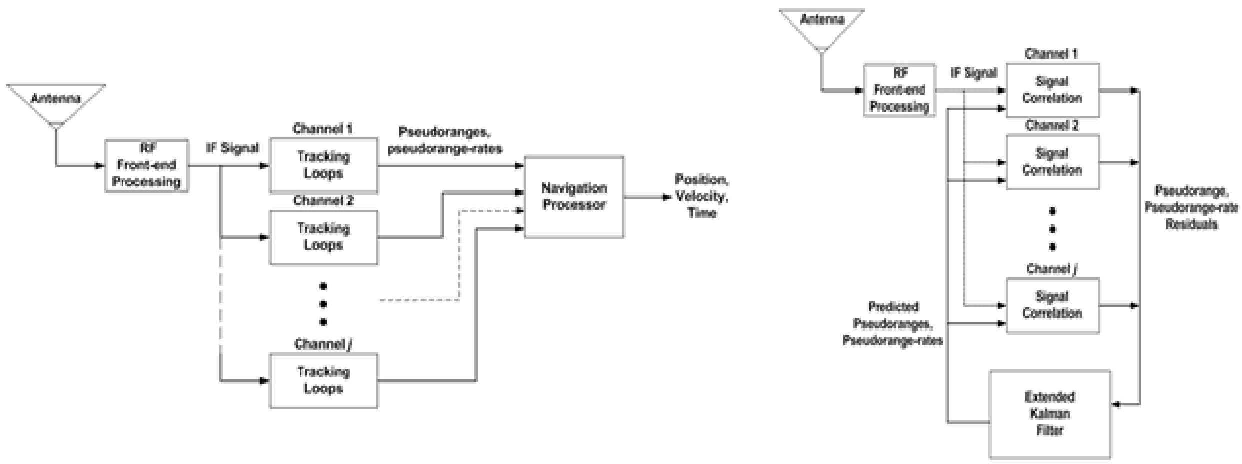

Figure ES-1. [Left] Standard, Scalar GPS Tracking Loop Architecture [Right] Vector Tracking GPS Receiver Architecture

The phase and frequency of the received signals are predicted from the receiver's estimated position and velocity. Residuals are formed in each channel by taking the difference between the predicted and received signals. The residuals are then used to update the estimates of the receiver's position and velocity. The vector tracking approach exploits the coupling between the receiver's dynamics and the dynamics seen by the tracking loops. Instead of every channel of the receiver tracking the dynamics of the individual signals, the user dynamics that are causing the change in the signals are tracked. Since the code phase and frequency of each channel are calculated based on the current navigation solution, rather than tracking an individual satellite signal, these values can continue to be estimated even when the satellite is not in view allowing for near instant reacquisition when the satellite comes back into view.

3.3 HARDWARE IMPLEMENTATION

A typical, commercial GPS receiver is based around a custom designed ASIC with most of the receiver functionality implemented in custom designed hardware. While this approach allows for substantial cost savings in mass production, the significant development and manufacturing setup costs make it an unsuitable approach for an experimental or prototype receiver. Field - programmable gate arrays (FPGA) provide an effective method for prototyping devices before converting to an ASIC design, or for low-volume applications can be a cost-effective production platform. FPGAs can be programmed after production using hardware description languages similar to those used to develop ASICs and can be programmed to perform most any function that can be developed in an ASIC.

A real-time implementation of the vector-tracking receiver described above has been developed based on a Xilinx Zynq All-Programmable System-on-Chip (SoC). The Zynq SoC features an FPGA, a dual-core ARM Cortex-A9 processor, and several peripheral devices on a single chip. An overview of the Zynq SoC is shown in Figure ES-2. It provides an ideal development platform for a real-time, GPS SDR.

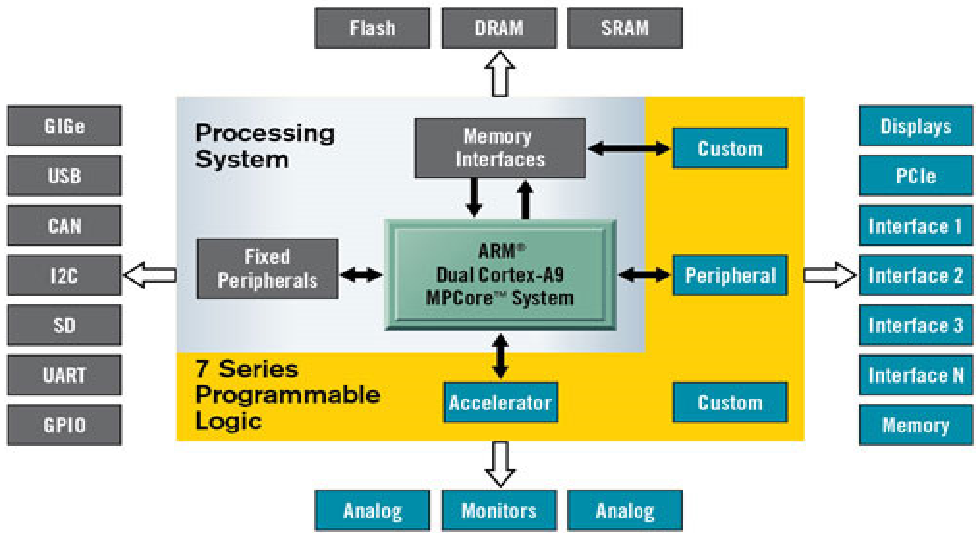

Figure ES-2. Xilinx Zynq Architecture

The SoC based design allows the FPGA and processor to maintain the same tight coupling seen with soft-core processors while gaining the performance from including a hard-core processor with two cores. The block diagram in Figure ES-3 shows the components of the VTRx receiver including peripheral sensors (*i.e.,* CSAC, HG1930, Microstrain IMU). The Zynq SOC is represented by the dark blue SDR Processor block.

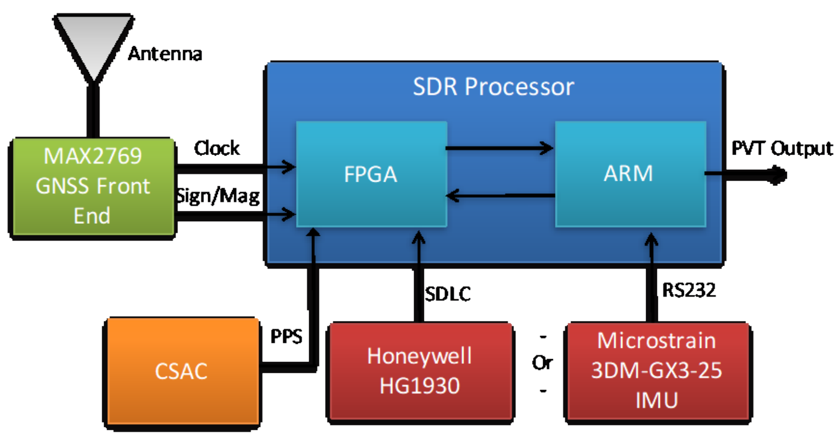

Figure ES-3. Block Diagram of Hardware Components for the VTRx Receiver.

RF data is received by the antenna and then down-converted to an intermediate frequency and sampled by a Maxim Integrated Circuits MAX2769 front-end integrated circuit. The samples are then processed in the Zynq and the PVT estimate output over either a serial or Ethernet port. Acquisition and correlator functions are implemented as Xilinx custom peripherals in the programmable logic of the Zynq. These peripherals are interfaced to the ARM based processing system (PS) through an Advanced Microcontroller Bus Architecture Advanced eXtensible Interface (AXI) bus. The tracking loop filters and navigation filter are implemented in C++ on the processor system and are run without an operating system.

Pictures of the final printed circuit board hardware and enclosure are shown in Figure ES-4. A MicroZed development board contains the Zynq 7020 and various input/output including ethernet, USB, and serial connections. The Microzed is attached to a custom board that provides power and CSAC/IMU interfaces. The unit requires 3W of power excluding the IMU power requirement. The enclosure has dimensions of 6.5x5x2.2 inches or roughly the size of a Novatel Propak V3.

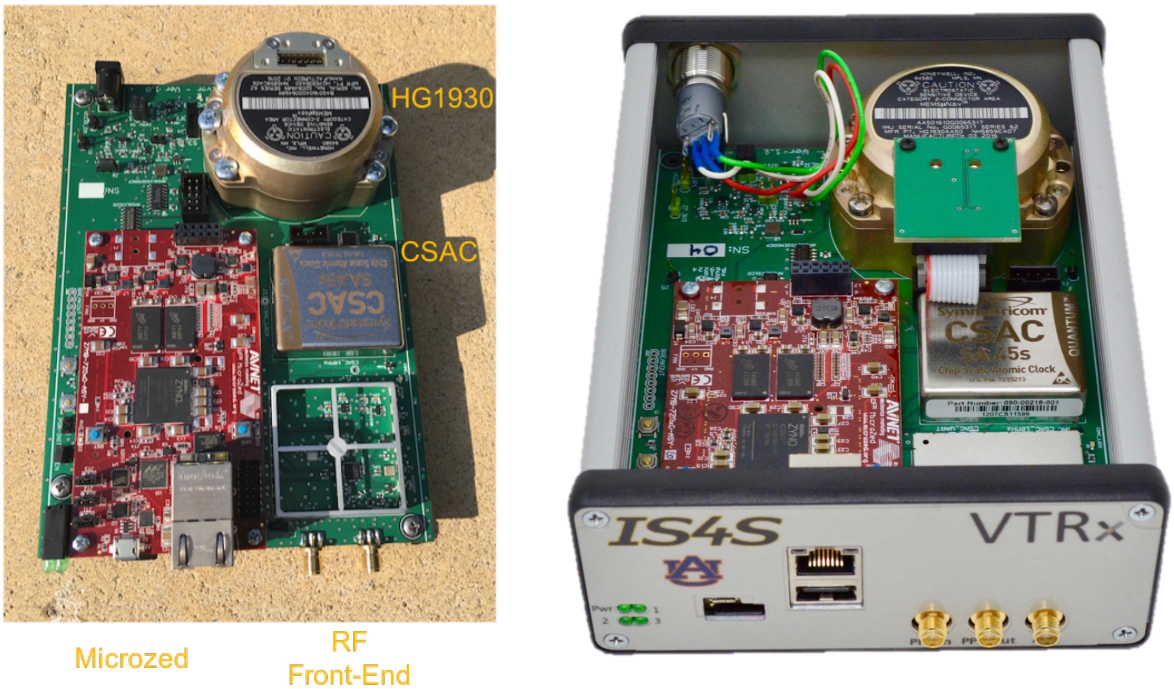

Figure ES-4. Final Prototype Hardware

4.0 PERFORMANCE ASSESSMENT

Fields tests were conducted to determine the positioning performance of the proposed system in a realistic environment and allow the performance to be compared to existing systems. The prototype VTRx system as well as a Novatel RTK capable GPS receiver were installed in a survey backpack. A Trimble Integrated Surveying system consisting of a Trimble R8 GPS receiver and a Trimble VX Total Station provided truth data. Tests were repeated numerous times in two different sites on Redstone Arsenal in Huntsville, AL.

An example result from Site 9 is provided below. Site 9 featured both open sky areas and dense foliage allowing the system to be tested in a wide range of environments. Representative pictures of the site are shown in Figure ES-5.

Figure ES-5. Site 9 Open Sky Areas [Left] and Dense Foliage [Right]

An example run in the dense portion of the site is shown in Figure ES-6.

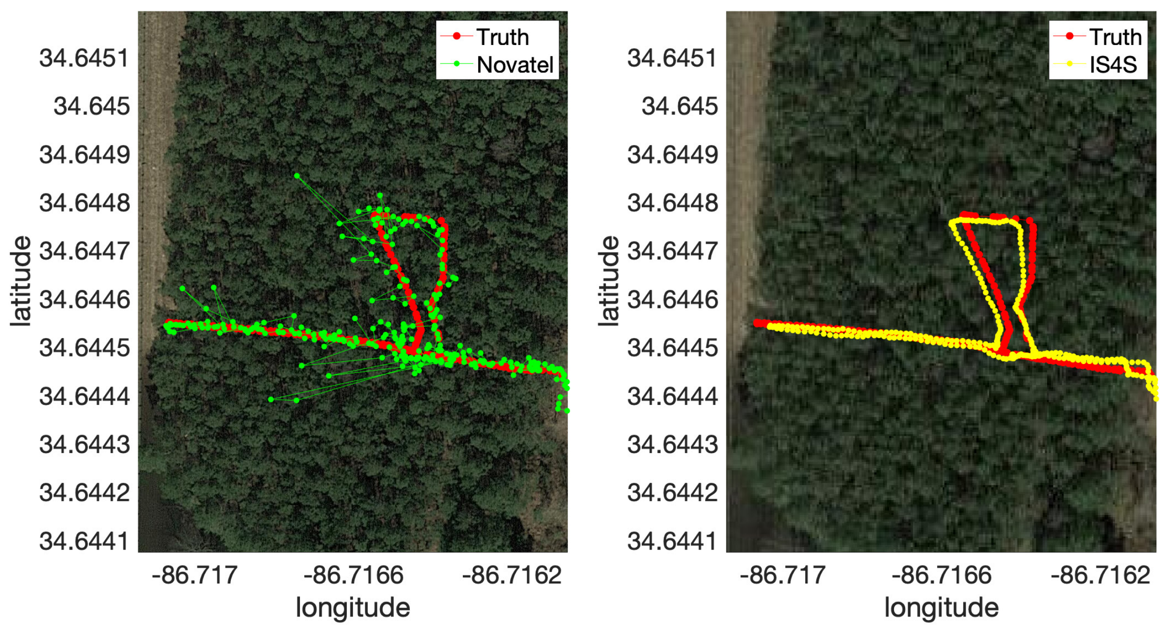

Figure ES-6. Receiver Outputs in Dense Foliage Portion of Site 9

The error from both the Novatel and VTRx receiver are shown in the Figure ES-7 and Table ES-1 below. While both receivers showed a bias with respect to the truth data, the VTRx receiver produced a solution 100% of the time through the heavy foliage section with an error standard deviation more than three times smaller than that of the Novatel.

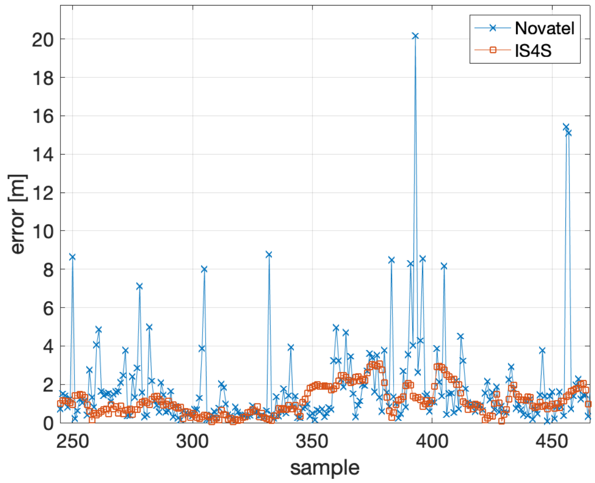

Figure ES-7. VTRx and Novatel Error for Sample Run on Site 9

Table ES-1. Error Mean and Standard Deviation for Site 9 Sample Run

Receiver	Mean [m]	Std. Dev [m]
VTRx	1.13	0.74
Novatel	1.8	2.47

5.0 COST ASSESSMENT

The primary cost associated with the system is the cost of the receiver and other hardware components. In standalone (non-differential) mode the produces real-time outputs and is designed to replace the GPS receiver typically used in surveys. No additional setup or calibration is required beyond what is required for currently used receivers and so survey costs are expected to be unchanged when replacing an existing GPS based setup.

The costs of the system components are given in the Table ES-2. A base system requires a VTRx receiver and a GPS antenna for an approximate total cost of $2500. This cost is based on using the dual-frequency Novatel Pinwheel antenna used in the demonstration. Since the VTRx only receives on the L1 band, a lower-cost antenna could be substituted without changing performance. The CSAC and IMU can be optionally added to the system to improve performance, particularly when less than three satellites are visible.

Table ES-2. System Component Costs

Component	Cost
VTRx Receiver	$1,500
CSAC [Optional]	$4,500
HG1930 IMU [Optional]	$7,000-10,000
Novatel Pinwheel Antenna	$1,000

A primary driver of the cost effectiveness of the system is the amount of GPS challenging terrain (such as heavy foliage areas) that is present on the site. For sites with areas that a traditional GPS receiver cannot reliably track satellites and produce an accurate position, the VTRx provides significant cost savings over other alternatives such as robotic total stations or systems containing high-end IMUs.

The primary cost benefit of the VTRx system is in the ability to use GPS based survey methods in areas where a standard GPS receiver would not provide acceptable availability. The ability to continue to use GPS deeper into foliage areas provides a significant cost benefit over alternatives such as robotic total stations. The system hardware is less expensive than most robotic total stations or other alternative systems containing high-end IMUs. Additionally, in contrast to a robotic total station, no additional setup is required greatly improving productivity and reducing the per-acre survey cost.

6.0 IMPLEMENTATION ISSUES

The demonstrated system consists primarily of a custom-built prototype that makes use of commercial-off-the-shelf components to the extent possible. The prototype system was developed exclusively for this effort and is not currently commercially available. Six prototype systems have been built to date and two are available as deliverables on this effort.

Since the conclusion of this effort, however, IS4S has developed a next generation software receiver (VTRx V2) based on lessons learned in this effort and demand from other Department of Defense customers. While not yet a commercial product, approximately 25 of the receivers have been built and a significant portion of those delivered to customers. The VTRx V2 hardware is shown in Figure ES-8. This system improves on the demonstrated platform in several areas:

- RF front-end replaced by a wide-band front-end capable of receiving signals with bandwidths up to 36 MHz on L1, L2, or L5.
- Two RF receive chains for multi-band operation.
- Improved enclosure and mechanical designs improve robustness and reduces assembly costs.
- Improved channel manager drastically reduces acquisition time and tracking robustness.

Figure ES-8. VTRx V2 SDR Platform