Opportunistic Navigation

Finding Your Way with AM Signals of Opportunity

Jonathan McEllroy, John F. Raquet, and Michael A. Temple

IN LAST MONTH'S COLUMN, we took a brief look at some of the technologies that might be used for UbiPos — ubiquitous positioning — to supplement conventional GPS in environments where it performs poorly or not at all such as in concrete canyons and inside buildings. One of the technologies mentioned involves using signals of opportunity — radio signals whose primary purpose is for communications or broadcasting but which could be used for positioning and navigation.

Potential signals of opportunity include the amplitude modulated (AM) broadcast stations in the medium wave band. Invented just over 100 years ago by the Canadian radio pioneer Reginald Fessenden, AM broadcasting covers large parts of the globe. Despite the recent tendency of AM stations to move to the FM band, most large metropolitan areas still boast a dozen or more stations on the "AM dial." The signals from AM stations can be used to determine the position of a mobile receiver with respect to a reference receiver using time difference of arrival (TDOA) measurements and a supplementary link between the two receivers. Measurements on one transmitter establish a hyperbolic line of position for the mobile receiver and the intersection of this line with another from measurements on a second transmitter establishes the receiver's position. Measurements on additional transmitters can improve the position accuracy and estimate unsynchronized receiver clock differences through a multi-lateration approach. It matters not whether the stations are "talk radio" or "country and western," as it is the carrier phase of the signals which provides the TDOA measurements. Of course, the proposed use of AM radio broadcasts for positioning and navigation is not a new idea. Measurements of the angle of arrival of AM broadcasts have long been used for position fixing in marine and other environments.

INNOVATION INSIGHTS
with Richard Langley

The signals from AM stations can be used to determine the position of a mobile receiver.

In this month's column, a team of authors from the U.S. Air Force Institute of Technology describe the simulations and real-world experiments they carried out using a software-defined radio receiver to test the feasibility of AM radio TDOA measurements for positioning and navigation.

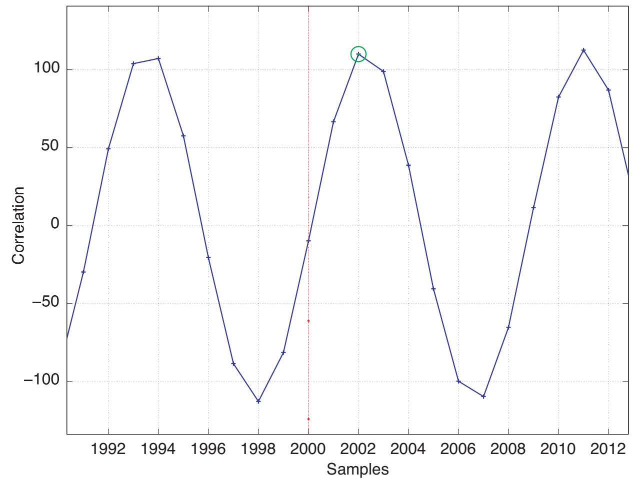
"Innovation" is a regular column that features discussions about recent advances in GPS technology and its applications as well as the fundamentals of GPS positioning. The column is coordinated by Richard Langley of the Department of Geodesy and Geomatics Engineering at the University of New Brunswick, who welcomes your comments and topic ideas. To contact him, see the "Contributing Editors" section on page 10.

GPS is an integral and vital component of both military and commercial ventures. Therefore, when GPS is either unavailable or degraded (intentionally or unintentionally), its operational effectiveness can be greatly impaired. One promising method for navigating when GPS is unavailable involves using a "signal of opportunity" (SoOP) — navigating using signals not intended for navigation purposes. Examples of signals previously investigated include analog and digital television, AM and FM radio, and cellular telephone signals.

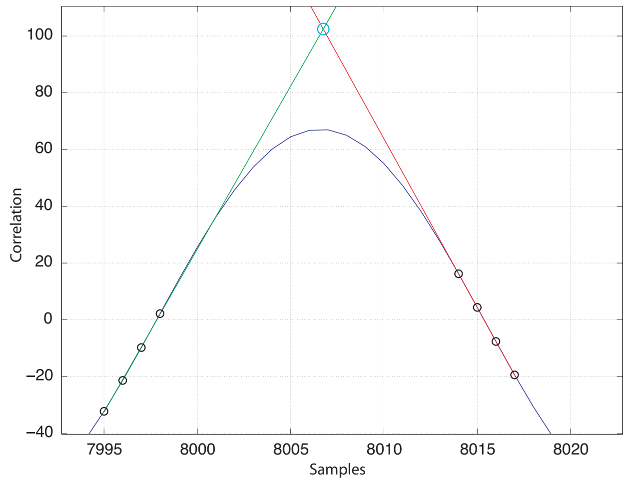
System performance depends on a variety of factors, including signal type and structure, multipath interference, integration time, and algorithm selection. Because most applications for navigating with SoOPs involve being either in or around buildings, the impact of multipath is a particularly significant issue. Multipath is difficult to model accurately, which motivates the need for field-testing to evaluate each potential SoOP for navigation.

This article describes field-test results from a software-defined radio (SDR) receiver used to evaluate SoOPs in the AM broadcast band. The software radio is based on the GNU (a recursive acronym for *GNU's Not Unix*) Radio Universal Software Radio Peripheral (USRP), which has a great deal of flexibility in terms of signal processing and data recording. We evaluated the signals in terms of signal strength, signal-to-noise ratio (SNR), measurement accuracy (related to correlation peak shape and SNR), signal diversity (the number of signals available), and apparent multipath effects in an outdoor environment. Central to the signal evaluation is the concept of time difference of arrival (TDOA).

Positioning based on TDOA involves measuring the difference in arrival times of a particular signal at two receivers or, more



▲ **FIGURE 1** Raw max peak estimate



▲ **FIGURE 2** Quad-sample linear fit estimate

correctly, their antennas. If time differences from three or more transmitters can be measured simultaneously, then the relative coordinates of one receiver with respect to the other plus the receivers' clock difference can be determined.

This work builds upon previous work done at the Advanced Navigation Technology Center at the Air Force Institute of Technology, including field testing of analog television signals for navigation, characterization of how well a small segment of AM and FM broadcast signals can be properly identified within a long segment of data, and development of a theory for quantifying navigation potential for SoOPs in the presence of multipath.

The results using AM radio signals with the USRP SDR hardware presented here are based on the following assumptions:

- A constant frequency carrier signal is present.
- Results are limited to signals in the North American AM broadcast band (525 to 1705 kHz).
- The cycle ambiguity (that is, determining which carrier cycle is being tracked) has already been resolved. (This could be accomplished by starting at a known point. Ambiguity resolution is certainly an important part of obtaining an absolute position solution for constant frequency carrier signals, but was considered outside the scope of the research presented in this article.)
- The data link between receivers is ideal and infinite in bandwidth.

TDOA Calculation Methods

At the heart of the SoOP navigation technique is the TDOA distance calculation. Simply stated, TDOA navigation involves two receivers with a data link between them. This allows for sharing of received signal data from one or more transmission sources (SoOPs). The difference in time of reception between the receivers leads to a multilateration position solution.

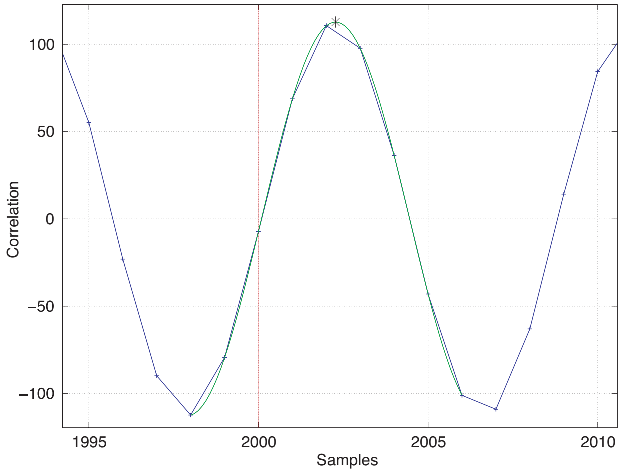
The TDOA distance can be directly related to the maximum peak value of the cross-correlation between the two captured signals. Four methods were developed to allow for precise peak measurement. All that is needed in terms of signal characteristics is the carrier frequency and the hardware sampling rate. (We operated under the implicit assumption that the SNR is sufficiently high to generate identifiable correlation peaks.) By not requiring more specific information on the SoOP characteristics, the system is inherently flexible and dynamic in terms of the signals that can be used for navigation. Given the earlier assumptions, all four methods work on the premise that the correct peak is known and that the primary goal is to determine the correct peak time offset (which directly results in the TDOA measurement).

Raw Max Peak. The simplest method considered is called the raw max(imum) peak method. In this case, the captured signals from both receivers are cross-correlated and for the given peak of interest, the maximum value is found, as illustrated in **FIGURE 1**. Although relatively simple to implement, this method does have one significant drawback in that the algorithm only deals with integer multiples of the sample time interval and can only resolve TDOA to within one sample distance. For example, if the sample time interval is 250 nanoseconds, the resolution of the TDOA is approximately 75 meters.

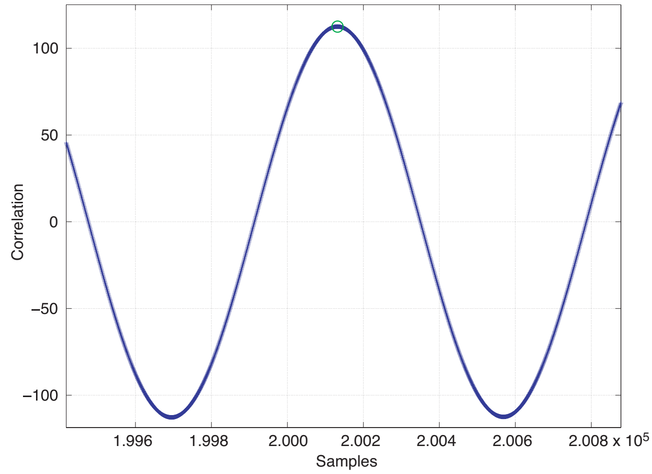
To refine the TDOA calculations further, three additional methods were developed: the quad-sample linear fit peak estimate, the raw sine wave fit estimate, and the high-sample maximum peak estimate. Each of these is described below.

Quad-Sample Linear Fit. The quad-sample linear fit estimate is a variation of the linear fit peak estimator. The cross-correlation data are first resampled at four times the rate to give the linear fit algorithm more precision. The maximum peak is initially found using the raw max peak estimate (described above). Then, the two closest zero crossings to the left and the right of the initial maximum peak are determined. Four points surrounding those zero crossings are used to create linear equations describing lines passing through those points. The intersection of these two lines becomes the updated maximum peak (**FIGURE 2**).

Raw Sine Wave Fit. The raw sine wave fit estimate takes the raw cross-correlation data and attempts to fit a sine wave to it (**FIGURE 3**). Using a cost minimization function, a sine wave mathematical model is created. The sine wave maximum value is then



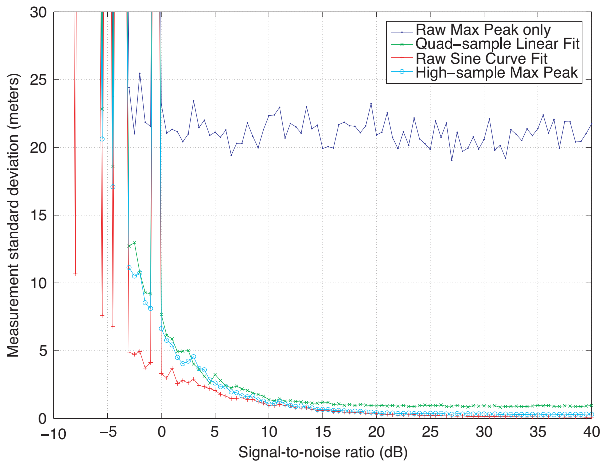
▲ **FIGURE 3** Raw sine wave fit estimate



▲ **FIGURE 4** High-sample max peak estimate

analytically determined from the sine wave mathematical model.

High-Sample Max Peak. Finally, the last method is the high-sample max peak estimate. This method for determining the distance is still based on finding the maximum peak (**FIGURE 4**). However, the raw data is first highly oversampled at 100 times the normal sample rate. This was implemented using Matlab's "resample" function, which implements interpolation via polyphase filtering. After oversampling, the maximum peak calculation process is exactly the same as used for the raw max peak estimate. The benefit here is that the quantization error is much lower than the raw max peak approach.



▲ **FIGURE 5** Standard deviation of TDOA measurement error for different SNRs — 100 runs

Simulated Results

We constructed a simulation that models real-world AM broadcast signals in order to evaluate and characterize expected behavior of both the signal interactions and the TDOA estimation methods. The model incorporates AM signals modulated with audio data from a Waveform audio format (WAV) file, white Gaussian noise, and simple Markov multipath model components. Our overall goal was to create two signals from each transmission source, both sampled at the desired GNU Radio sampling frequency of 4 MHz, which are separated in propagation by some amount of time corresponding to a desired TDOA distance. We then input these two signals to the TDOA calculation processes to produce distance values, pseudoranges, and finally multi-lateration position estimates. It is important to note that the majority of the system was designed to work with either simulated or real data. This allows for the refinement of the TDOA-to-position-estimate process before real-world data is applied.

The simulation results, within the limitations of the wave propagation and multipath models, are promising. **FIGURE 5** shows the TDOA measurement accuracy standard deviation as a function of SNR for the four different TDOA methods described above. Each point on the chart represents the standard deviation from a 100-run Monte Carlo simulation using the 4 MHz simulated sample rate. The raw max peak method showed the expected quantization characteristic. All the other methods showed a general improvement as the SNR was increased. The raw sine wave fit method generally outperformed the others.

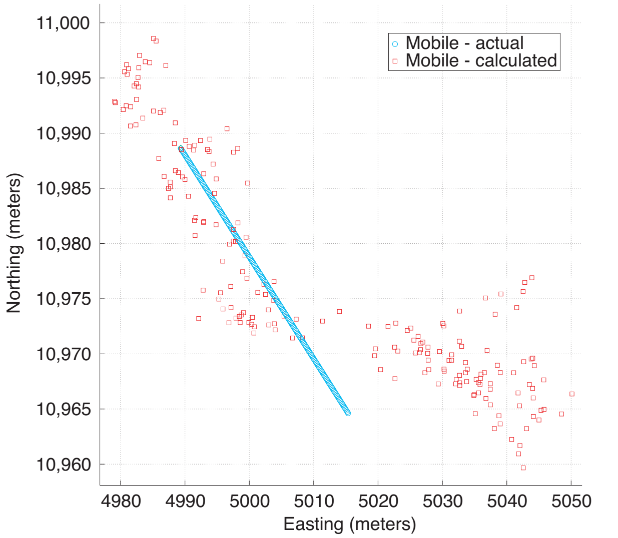
In another simulation-based test, the mobile receiver was moved in a straight line for 2 seconds, and simulated signals were generated for SNR = 60 dB. For this test, a first-order Gauss-Markov multipath model was applied to approximate anticipated multipath effects and included several multipath reflection points.

The expectation was that the position solution would wander over time about the truth path. **FIGURE 6** shows the true path and the horizontal navigation solution results from the test. The time correlation of the errors can be seen. **FIGURE 7** shows the errors in each axis as a function of time. These results clearly show the expected effect of real-world multipath. Note that multipath is highly dependent upon the specific environment (including receiver antenna gain pattern), and a much more rigorous multipath model would be required to precisely predict actual performance for a given environment.

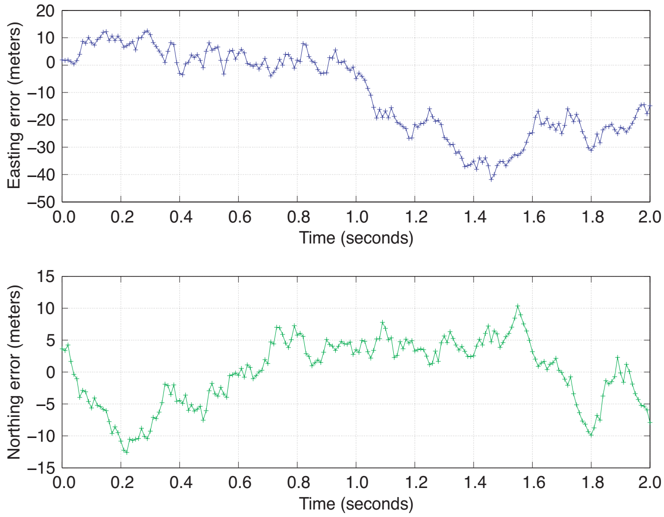
Data Acquisition System

We performed a field test using experimentally captured signals to obtain real-world results. This required developing a data acquisition system.

Software. The center of the data acquisition system is the GNU Radio software suite and the USRP hardware. SDR represents the art and science of constructing radios using software instead of hardware. Given modern technology constraints, there



▲ **FIGURE 6** Simulated trajectory for SNR = 60 dB, Markov multipath case; straight line movement



▲ **FIGURE 7** Simulated trajectory errors for SNR = 60 dB, Markov multipath case; straight line movement

is still minimal hardware involved, but the motivation is to move the software as close to the antenna as is feasible. Typically, an antenna and RF front-end are used to capture the signals of interest that are then shifted to an intermediate frequency (IF) and digitized for processing by the SDR. Ultimately, hardware issues are translated into software issues.

SDR architectures provide significant advantages over classic hardware radios. Software functionality allows for dynamic reconfiguration and is easily upgraded to provide enhanced features at lower costs. Also, software provides the ability to experiment with new radio designs with little increase in resource expenditure. To be fair, SDR architectures do present some disadvantages when compared to hardware-only designs. For example, dependence on underlying software libraries and operating systems can bring about its own complexities.

The GNU Radio project provides free software that enables one to build and deploy an SDR. The project provides complete source code and documentation and supports many popular hardware RF front-ends. Once the signal has been digitized and transported to the computer, the GNU software does all of the complex manipulations to allow meaningful data interpretation or alteration. All GNU Radio system programs are written in Python, typically running on a Linux operating system. The main advantage and power of SDR can been seen most clearly here. Code is easily written to dynamically reconfigure a radio to fit any desired need within the constraints of the RF front-end hardware.

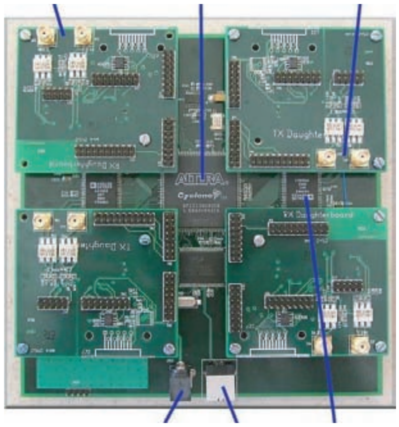
Hardware. The USRP hardware is a low-cost, high-speed implementation of GNU Radio hardware. The hardware consists of a main motherboard that can support up to four daughter boards (**FIGURE 8**). The motherboard provides DC power for itself and all the daughter boards. Analog signals are input through SMA (SubMiniature version A) connectors on the BasicRX daughter board (frequency coverage: 0.1 to 300 MHz). The motherboard converts the signals to digital data using four analog-to-digital (A/D) converters at rates up to 64 megasamples per second (MS/s). A rate of 4 MS/s was used in this research. The binary data is then packaged for transport to the computer via USB.

One of the advantages to software radio is the flexibility of acquisition of many types of radiated signals. However, certain limitations do apply. The USRP hardware only provides rudimentary analog to digital conversion with post-capture digital gain control and filtering. This proved to be most inadequate for capturing AM broadcast signals for the express purpose of TDOA calculation. An analog front-end was required to maximize the USRP capabilities.

To that end, we purchased, built, and modified AM/FM radio hobby kits to suit the needs of our research. These units, containing loopstick antennas, allowed the AM broadcast signals to be amplified and filtered before digitization. An appropriate signal was obtained by tapping off the second-stage amplifier prior to the demodulation circuit. This modification required a 1 kiloOhm resistor to be placed in series with the signal flow to better match the impedance of the USRP inputs. As an added benefit, the hobby kit radio downconverted the signals from native broadcast frequency to an IF of 455 kHz. This allowed the USRP capture parameters to be optimized around a narrow bandwidth.

The SoOP acquisition and evaluation process involved the USRP hardware, the GNU Radio software, two personal computers, and interconnecting cables. All receiver channel connections were made using cables of identical length and type to eliminate any differential delay introduced by cable propagation characteristics. RG-59/U coax was used for the connections between the receivers and the USRP. Short BNC to SMA conversion cables were used to properly mate the coax to the USRP boards. Data was transferred over USB from the USRP to a Linux laptop and stored. For subsequent post-processing, the data was transferred once more via USB to a Windows workstation for input into Matlab for TDOA processing and final position estimation. The overall process is shown in **FIGURE 9**. Note that, as stated earlier, the core processing algorithms can accept data obtained from the USRP hardware or simulated data.

It is important to note that, for this test setup, two front-ends with their corresponding antennas were connected to two sep-



▲ **FIGURE 8** Universal Software Radio Peripheral

arate USRP inputs. However, they were effectively sampled simultaneously to avoid differential clock error that would be present if two different receivers were used. This made measurement-based analysis of results much easier to accomplish because clock error was not a factor. In a practical system, there would be a clock error between the two receivers.

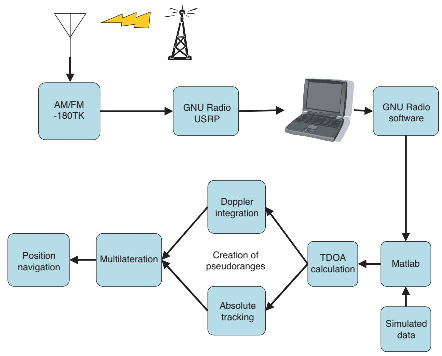
Field Test Results

For actual data acquisition, we took the hardware to an open field on Wright-Patterson Air Force Base in Ohio. For initial testing, our goal was to use an area somewhat free of multipath and electromagnetic disturbance effects. We then surveyed a truth path using kinematic differential GPS as illustrated in **FIGURE 10**, where the square diagonal distance is approximately 60 meters. Additionally, we obtained all transmission source coordinate values from the Federal Communications Commission (FCC) online database. We held the data capture hardware decimation factor constant at 16. Therefore, all data was collected at a constant sampling frequency of 64/16 = 4 MHz. Additionally, we used the high-sample method for all TDOA calculations.

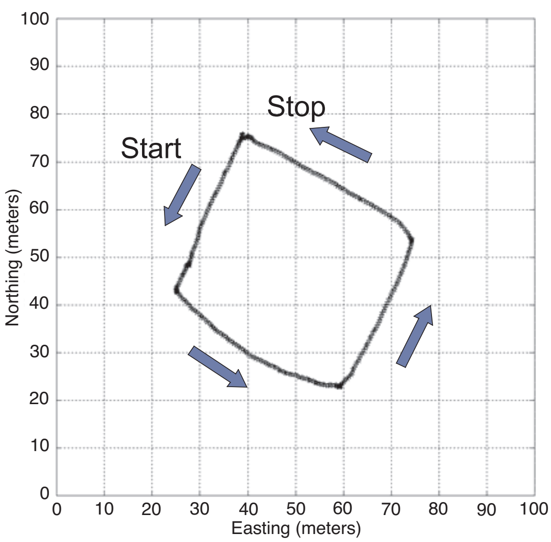
We stationed the reference receiver at the northernmost corner of the square. During the data capture period, the mobile receiver moved completely around the square in a counter-clockwise direction while data was acquired in 0.11-second segments with a 2-second interval between sample segments.

Preliminary results from the test are very promising. The TDOA distances for each radio transmission source generally followed the trend of the expected TDOA distances based on the DGPS truth positions. **FIGURE 11** shows the comparison of DGPS-based expected TDOA distances and the GNU Radio calculated TDOA distances for four different AM stations as the mobile receiver moved completely around the square. Although the TDOA measurements are somewhat noisy, the data has good convergence towards zero at the endpoints. This behavior is expected.

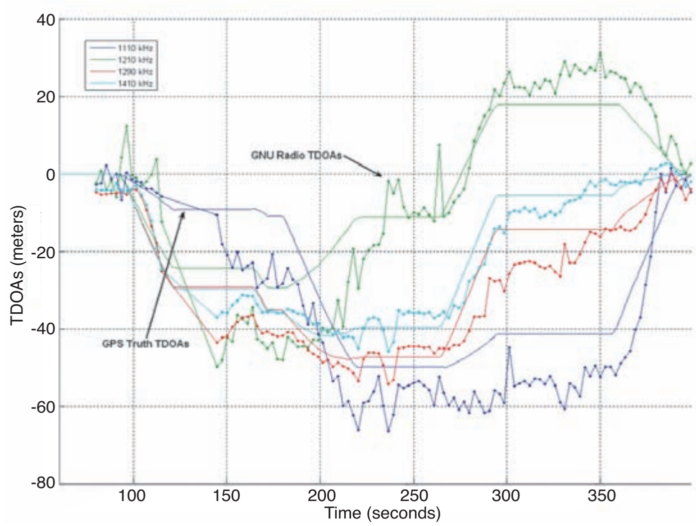
Each individual transmission source data line also follows its corresponding DGPS truth TDOA line. The error in the TDOA measurements is most likely attributable to multipath. In addition, the TDOA measurements were scaled by a factor of 2 to fit the expected DGPS TDOA values. The cause for this scaling factor remains under investigation and may be due USRP-GNU Radio interactions that have not yet been properly accounted for — thus, the preliminary caveat we emphasized for these results. **FIGURE 12** shows the position estimates obtained from these TDOA measurements as the mobile receiver was moved around the square, with the color beginning as red, moving through shades of purple, and finally through shades of blue. The data shows a promising position estimate accuracy approaching 20 meters. Note that while there was essentially no differential clock error between the signals from the two antennas, the algorithm that calculated position from the TDOA measurements used no such assumption. Therefore, the position results are representative of what would be obtained had there been a differential clock error.



▲ **FIGURE 9** Top-level system implementation



▲ **FIGURE 10** DGPS-based truth trajectory



▲ **FIGURE 11** Comparison between expected truth TDOA measurements and actual TDOA measurements for square trajectory test

Cross-Correlation Alternatives

There is an alternative to the cross-correlation method of TDOA calculation. This measurement-based approach involves taking each capture waveform from the receivers and fitting a sine wave model to them using a cost function minimization routine (other phase-tracking methods would be appropriate as well). Then the two mathematical models can be used to produce a phase offset that directly translates into a TDOA distance between the two signals (that is, the two receivers). This method has one major advantage in that the bandwidth required for the inter-receiver data link is very small. The phase parameters are the only data that need to be passed for each transmission source. However, the drawback is that more *a priori* SoOP characteristics must be known before data acquisition and capture. In situations where the signal characteristics are known or determinable *a priori*, this method provides performance very similar to the cross-correlation methods.

Conclusions

We developed four methods for TDOA distance calculation and created a simulation environment to test and evaluate results and behaviors of the TDOA navigation system. We integrated the GNU Radio-USRP system with the TDOA methods to provide a valid navigation system. Finally, we tested the hardware and software implementation in an outdoor environment, which resulted in promising results.

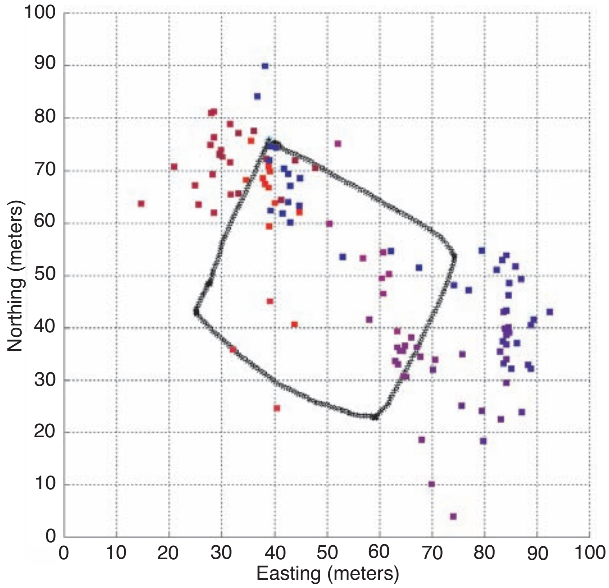
Future Work

Further enhancement of the simulation and models is required. More advanced AM wave propagation and multipath models would allow for more realistic simulation of the entire system and the TDOA methods before field testing. The TDOA distance calculation methods could be refined and expanded to make them more robust and capable in a variety of situations, including use in areas where the integer ambiguity is unknown beforehand. Much research is required on the data-link implementation in both hardware and software. The goal is to find the minimum amount of information to pass between receivers while allowing useful cross-correlation and phase-offset information to be calculated. We suggest further software integration. By porting the TDOA methods from Matlab to Python, the implementation could produce a single platform solution that provides real-time navigation services.

Acknowledgments

The authors would like to thank Don Smith, John Amt, and Lee Patton. Their efforts and expertise were instrumental in the success and completion of this research, which was sponsored by the Sensors Directorate of the Air Force Research Laboratory.

This article is a based on the paper "Use of a Software Radio to Evaluate Signals of Opportunity for Navigation" presented at ION GNSS 2006, the 19th International Technical Meeting of the Satellite Division of The Institute of Navigation, held in Fort Worth, Texas, September 26–29, 2006.



▲ **FIGURE 12** Trajectory plot around the square

Disclaimer

The views expressed in this article are those of the authors and do not reflect the official policy or position of the United States Navy, the United States Air Force, the Department of Defense, or the U.S. government.

Manufacturers

The *Universal Software Radio Peripheral* is manufactured by **Ettus Research LLC** *(www.ettus.com)*. The *AM/FM-108TK radio hobby kits* used were from **Elenco Electronics, Inc.** *(www.elenco.com)*.

JONATHAN MCELLROY is a U.S. naval aviator who has accumulated more than 1100 hours in flight time and more than 300 arrested carrier landings flying combat support missions during both Operations Enduring Freedom and Iraqi Freedom in the S-3B Viking. Lt. McEllroy recently graduated from the Air Force Institute of Technology (AFIT), Wright-Patterson Air Force Base, Ohio, with a master's degree in aeronautical engineering. He is stationed at Naval Air Station Pensacola, Florida, as a flight instructor and fixed-wing aerodynamics expert for the Naval School of Aviation Safety.

JOHN F. RAQUET serves as an associate professor of electrical engineering at AFIT, where he is also the director of the Advanced Navigation Technology Center. He has been working in navigation-related research for more than 16 years.

MICHAEL A. TEMPLE serves as an associate professor of electrical engineering at AFIT, where he conducts sponsored research in command, control, communications and intelligence, radar signal processing, and electronic warfare in support of the Department of Defense and other national agencies.

MORE ONLINE

Further Reading

Visit *www.gpsworld.com* and click on **Innovation** under **Resources** in the left-hand navigation bar for references related to this article.

FURTHER READING

- **Navigation Using AM and FM Broadcast Signals**

Navigation Using Signals of Opportunity in the AM Transmission Band by J. McEllroy, master's thesis, AFIT/GAE/ENG/06-04, Air Force Institute of Technology, Wright-Patterson AFB, Ohio, September 2006.

Evaluating the Correlation Characteristics of Arbitrary AM and FM Radio Signals for the Purpose of Navigation by B. Kim, master's thesis, AFIT/GE/ENG/06-28, Air Force Institute of Technology, Wright-Patterson AFB, Ohio, March 2006.

The Navigation Potential of Signals of Opportunity-Based Time Difference of Arrival Measurements by K. Fisher, Ph.D. dissertation, AFIT/DS/ENG/05-02, Air Force Institute of Technology, Wright-Patterson AFB, Ohio, March 2005.

Radiolocation Using AM Broadcast Signals by T.D. Hall, Ph.D. dissertation, Massachusetts Institute of Technology, Cambridge, Massachusetts, September 2002.

- **Navigation Using Television Broadcast Signals**

"Prime Time Positioning: Using Broadcast TV Signals to Fill GPS Acquisition Gaps" by M. Martone and J. Metzler, *GPS World,* Vol. 16, No. 9, September 2005, pp. 52–60.

"Evaluating the Navigation Potential of the NTSC Analog Television Broadcast Signal" by R.J. Eggert and J.F. Raquet in *Proceedings of ION GNSS 2004,* the 17th International Meeting of the Satellite Division of The Institute of Navigation, Long Beach, California, September 21–24, 2004, pp. 2436–2446.

- **Software-Defined Radios**

GNU Radio: The GNU Software Radio. Available online: http://gnuradio.org/trac/wiki

"Universal Software Radio Peripheral" by E.A. Blossom, online reference material: http://comsec.com/wiki?UniversalSoftwareRadioPeripheral

"GNU Radio Opens an Unseen World" by Quinn Norton, *Wired Magazine Online:* http://www.wired.com/science/discoveries/news/2006/06/70933

"Satellite Navigation Evolution: The Software GNSS Receiver" by G. MacGougan, P.L. Normark, and C. Ståhlberg in *GPS World,* Vol. 16, No. 1, January 2005, pp. 48–55.

Software Radio: A Modern Approach to Radio Engineering by J.H. Reed, Prentice Hall PTR, Upper Saddle River, New Jersey, 2002.