Testing a Unique Real-Time, High-Precision GPS Concept for Test & Training Range Applications

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The Central Test & Evaluation Investment Program (CTEIP) funds investments in joint Test & Evaluation (T&E) infrastructure and capabilities. CTEIP has initiated a test program to evaluate the performance of a real-time, high precision Global Positioning System (GPS) algorithm that would benefit a number of T&E applications. This algorithm under test was commercially developed by Geodetics, Incorporated, and is referred to as Epoch-by-Epoch Positioning (EBEP). EBEP promises significant advantages over conventional real-time kinematic (RTK) algorithms. This paper addresses the investment of the Office of the Secretary of Defense in several key GPS-based programs, discusses the EBEP algorithm and how it compares operationally with RTK, and describes the proposed EBEP test program. When the test program is complete, a second paper will be forthcoming that focuses on analysis of the data and future CTEIP efforts.

The Central Test & Evaluation Investment Program (CTEIP) resides within the Office of the Director, Operational Test and Evaluation / Resources and Ranges (DOT&E/RR) within the Office of Secretary of Defense (OSD). CTEIP funds investments in joint Test & Evaluation (T&E) infrastructure and capabilities. CTEIP recently identified a number of T&E applications that would benefit from precise, real-time information from the Global Positioning System (GPS). These include:

- *Real-time test of advanced weapons.* The accuracy of instrumentation is required to be ten times higher than that of the system under test. As weapons become more accurate, it is becoming more difficult to provide this level of testing accuracy with today's instrumentation.
- *End game scoring*. GPS on a weapon and target could provide *both* time-space-position information (TSPI) and end game scoring, thus eliminating the need for dedicated instrumentation (for example., Doppler radar, Cine-Ts).
- *Precision-landing*. Auto landing of full-scale drones today requires the integration of a radar altimeter into the target tracking system. Precision GPS would eliminate the need for a radar altimeter and its associated operational constraints. Precision GPS would also support 'zero visibility' landing systems that are under development today, such as the Joint Precision Approach and Landing System (JPALS).

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Background: OSD investment in GPS

In the 1970's, OSD recognized that use of GPS-based TSPI, that is, tracking, offered excellent advantages over conventional TSPI instrumentation. In fact, GPS offered the potential to support an unlimited number of participants in a 'world wide range'. In 1979, OSD conducted a major study to evaluate the potential of GPS as a TSPI source for the test and training range communities. The survey evaluated TSPI requirements at 22 major ranges of three military services. GPS was evaluated considering such factors as real-time and post-mission TSPI and scoring accuracy, supportable versus required data rates, number of participants, and coverage area. The OSD final report was submitted on 31 December 1982 *concluded that GPS could be used as a cost-effective real-time TSPI source for 95 percent of all TSPI requirements.*

Range Applications Program (RAP)

As a result of this report, a tri-Service program was initiated to develop the assets for the real-time GPS-based positioning of low, medium, and high dynamic platforms. These assets were to be put in place at the major Department of Defense (DoD) T&E ranges. Those in the training community initially deferred the introduction of GPS-based TSPI; they are now in the process of converting most of their major range instrumentation to GPS.

The Air Force was designated as the lead activity for this effort. A tri-service office was set up at Eglin Air Force Base, Florida to develop the first GPS-based instrumentation tracking system, referred to as the Range Applications Program (RAP). The office, previously the Range Applications Joint Program Office (RAJPO), is now referred to as the Range Instrumentation Systems Program Office (RISPO).

RAP consists of external pod and internal mount GPS/inertial tracking instrumentation packages. It also includes a data link to pass the TSPI data in real time. The first RAP production equipment became available in 1992. Since then, GPS has found universal acceptance at the national test and training ranges as a major source for TSPI and precise timing.

RAP initial production equipment is now 10 years old. GPS has undergone significant hardware and software enhancements during the last decade. The advances have focused primarily on miniaturization of the GPS package and improvement in the accuracy of the GPS solution. It is now believed that GPS can cost-effectively address the remaining five percent of unmet TSPI requirements that were called out in the 1982 OSD report. For this reason, CTEIP is interested in pursuing advanced, high-precision GPS technologies.

Enhanced Range Applications Program (EnRAP)

The Enhanced RAP (EnRAP) program is a CTEIP initiative to upgrade the basic RAP system in four areas:

- Enhanced data link spectrum efficiency and capacity
- Higher accuracy GPS/inertial TSPI
- Miniaturization of modules
- Development of a plug-and-play architecture

Of particular interest is the EnRAP requirement to enhance the accuracy of today's GPS. The objective is an improvement in accuracy by a factor of 10. In view of this requirement, and given that the EnRAP program is in the formative stage, CTEIP has assigned the EBEP test program to the EnRAP program office. If the test results are favorable, it is envisioned that EnRAP will incorporate the EBEP into the next generation TSPI suite of instrumentation.

Multi-Service Target Control System (MSTCS) Project

The CTEIP is funding the Multi-Service target Control System (MSTCS) project to develop the next generation target control system. MSTCS is a GPS-based system that will replace the following:

- Gulf Range Drone Control System - the Air Force's ground-based multilateration target control system TCS that operates at the Gulf Range, Florida.
- Drone Formation Control System - the Army's ground-based multilateration TCS that operates at White Sands Missile Range, New Mexico.
- Integrated Target Control System - the Navy's radar-based TCS that operates at Pt. Mugu, California.

MSTCS has a requirement for formation control of airborne targets and auto landing of full-scale drones such as the QF-4. Precise real-time GPS would support more realistic presentations of closely spaced airborne targets, and it would provide a cost-effective GPS-only instrumentation package for auto-landing.

Joint Advanced Missile Instrumentation (JAMI) Project

The Joint Advanced Missile Instrumentation (JAMI) project is funded by CTEIP to develop modular instrumentation packages for missile applications. The JAMI package supports four functions:

- Telemetry
- Missile termination
- TSPI
- Vector Scoring.

The TSPI and Vector Scoring will be accomplished with a GPS (and inertial) engine on both the missile and target. Presently, JAMI is proposing the use of RTK to accomplish the vector scoring function. For reasons addressed in the next section, EBEP has operational advantages over RTK. Accordingly, if successful, EBEP will provide JAMI with an alternate solution to the vector scoring requirement.

GPS overview: key terminology

GPS is a space-based multilateration system, akin to triangulation, whereby a user determines position relative to a set of known points. These known points for GPS are the satellites, which are in semi-synchronous orbits (that is, each satellite circles the globe every 12 hours). Approximately eight to 10 satellites can be seen at all times at latitudes below 80 degrees. The satellites transmit their position (ephemeris), a precise time standard and two spread spectrum ranging code sequences (in phase quadrature), referred to as the P(Y)-code and the C/A-code. The P(Y)-code is an encrypted code intended for military use and is broadcast on two L-band frequencies, referred to as L1 and L2. The C/A-code is presently broadcast only on L1. The P(Y)-code provides a more precise position fix than that provided by the C(A)-code.

Basically, a GPS receiver uses the location of each satellite, the GPS system time, its own clock bias relative to GPS system time, and the time-of-arrival of the P(Y)-code (or C/A-code) from at least four satellite signals to derive radial range, referred to as pseudorange, to each satellite. By combining the range information in sophisticated Kalman filters and coupling this with the satellite locations and knowledge of when the signals were transmitted from each satellite, the participant receiver can determine its precise location and time.

Many receivers also track the Doppler of the L-band signal (L1 or L2) to derive an estimate of the users' velocity. To do this, knowledge of the satellite orbit is used to remove the Doppler component that arises from the satellite motion. In addition to providing an excellent estimate of user velocity, the Doppler (or range rate) data can also be used to develop precise position solutions, discussed next.

In GPS positioning processing, in general terms, a GPS receiver performs these three basic functions:

- Tracks either the P(Y)-code or C/A-code to estimate range to a satellite. The range data from as few as four satellites are used to derive user position.
- Tracks the incoming carrier signal (L1 or L2) to estimate range-rate to a satellite. The range-rate data is normally are used to derive user velocity.
- Reads the 50-Hertz data provided on the GPS signal to determine satellite position, GPS system time and other information.

Achievable GPS performance is determined primarily by the system errors,[1] which can be broadly divided into two categories: noise-like and (short-term) biases. Noise-like errors include thermal noise, interference, and multipath. Bias errors include user and satellite clock errors, satellite ephemeris errors, tropospheric and ionospheric errors, and selective availability, which is an intentionally induced error in the C/A-code to deny precise TSPI (presently disabled).

[1] The selection of the satellites to be tracked also introduces errors. The geometry of the constellation determines the 'geometric dilution of precision', a multiplicative error term. However, all-in-view receivers have eliminated this as an issue.

‘Over-specified’ signal processing reduces noise errors. This is normally accomplished by tracking more than four satellites. It is quite common to employ what is referred to as ‘all-in-view’ receivers for this purpose.

Techniques referred to as differential processing are quite successful at reducing the effect of the bias errors. Differential processing involves estimating the bias error by using a reference receiver at a known location. The reference receiver compares its code measurement to a given satellite with its own estimate of what the measurement should be. The difference is a bias that can be used as a correction term by another receiver (tracking the same satellite) operating in the vicinity of the reference receiver.

Differential operation has significantly improved the performance of GPS receivers with an improvement in position accuracy by a factor of four being quite common. However, the greatest improvement in GPS accuracy has occurred by using a class of algorithms that are generally referred to as ‘kinematic’ processing.

The idea behind kinematic processing is quite simple. The GPS P-code has 100-nanosecond (or 100-foot) chips. The GPS L1 carrier has a wavelength of ~0.66 foot. The GPS code loop tracks the code. The GPS carrier loop tracks the carrier. All other things being equal, the GPS carrier loop ‘position’ estimate will be ~150 times more accurate than the position estimate from the code loop (that is, 100 feet / 0.66 foot). The problem with using the carrier loop for position is that the carrier loop does not know what L1 cycle it is tracking. This is referred to as the integer wavelength ambiguity problem. Because the ambiguity stays constant, it drops out when two carrier loop ‘position’ estimates, taken at different times, are differenced. Hence, the carrier loop can provide excellent delta position or velocity estimates.

Kinematic processing attempts to use the carrier loop for positioning through ‘ambiguity resolution’. This is accomplished by using differential processing to limit the size of the ambiguity and employing relationships between the code and carrier signal to estimate the ambiguity. Available data are then used to refine and develop a confidence in the estimate. These data include L1 and L2 measurements, data from all satellites in view, and data taken from a given satellite over time.

Epoch-by Epoch Positioning processing is a class of kinematic processing in the sense that it employs the carrier loop data for precise positioning. Its key difference, however, is that it estimates the integer ambiguities using data from a *single epoch*. This has significant advantages.

EBEP: algorithm under test

OSD will be testing the new class of instantaneous, real-time GPS EBEP algorithms, which are based on dual-frequency phase and pseudorange data. It is claimed that the EBEP’s main advantage over conventional RTK is that, integer phase ambiguities are estimated independently for each and every observation epoch. This would allow precise positions to be estimated based on a single epoch of data from a user receiver and a reference receiver. From empirical data gathered to date, EBEP accuracies of 1 to 10 cm are expected.

The algorithm requires the use of a minimum of two receivers, each of which is tracking a common set of five satellites and providing simultaneous dual-frequency phase data. Normally, one of the receivers is stationary but this is not a requirement. It is believed that EBEP would support end-game scoring between a missile and an airborne platform. In this case, the two receivers would be located on highly dynamic platforms.

EBEP promises numerous benefits including:

- *Computationally efficient algorithms* that can run on a PC and provide a position estimate based on a single epoch in several milliseconds. This would allow the real-time position estimate to be computed on the user platform (assuming reference station data is sent to the user platform).
- *An initialization period is not required*. Because RTK requires some period of time (that can be measured in minutes) to perform ambiguity resolution, this is an important capability for platforms that:
  - Require high accuracy (for example, for end-game scoring);
  - Cannot see the satellites until launch; and
  - Have short flight duration.
- *A reinitialization period following loss-of-lock is not required*, unlike RTK, which needs to restart the ambiguity resolution process. This is another important capability because OSD is considering EBEP for many high dynamic applications where loss-of-lock is likely.

It is also claimed that EBEP provides precise positioning estimates over longer reference receiver-to-user receiver baselines than RTK. This would support testing for long-range operations from a single ship (that is, the reference receiver would be on the ship).

Precise GPS positioning data also could be used to provide platform attitude data. This could be accomplished by multiplexing a single user receiver among three antennas on the platform. Only two antennas would be necessary if only two of the three attitude angles were desired. Geodetics claims that attitude can be determined to an accuracy of about 0.05 degrees. OSD would be interested in exploring this capability at a later time, but for the present, the primary interest is in determining the achievable position accuracy in dynamics.

OSD has seen sufficient static and low dynamic performance data to be convinced that the EBBP concept deserves serious consideration for test applications. A test program is required because the scenarios of interest typically involve high dynamic platforms, and minimal EBEP data exist for these scenarios.

Before describing the test program, one point should be made. There are receivers in production today that will support the EBEP requirement for simultaneous dual-frequency phase estimates[2]. Hence, it is not envisioned that a receiver development effort would be required if the dynamic test results prove favorable. However, it must be mentioned that many of the GPS receivers in use by the test (and training) community today do not support this dual-frequency requirement. As such, those systems could not realize the maximum benefit from EBEP without a receiver upgrade.

Proposed OSD test program

The EBEP algorithm has been used to position platforms in a number of applications ranging from static to medium dynamic. Under normal tracking conditions the real-time horizontal position precision (one-sigma) for a single epoch of GPS data collected from 5 or more satellites can be expressed as a function of baseline range as:

± *[10-20 mm + 0.2 mm/km)]*

The vertical precision is three to five times worse. The higher end of horizontal precision is valid for measurements in geomagnetic mid-latitude zones. The lower end is valid for measurements in geomagnetic equatorial and upper latitude zones. (For relatively short distances of less than 5 km, the horizontal precision is about ± 5 millimeters, with the vertical precision two to three times worse). This precision has been achieved for both static and medium dynamic platforms.

Static applications include the monitoring of dam deformation. *Figure 1* shows the scatter plot for horizontal EBEP positions from a Geodetics software package called CRNet for sites on three earthen dams enclosing a large water reservoir in southern California. The positions are relative to a fixed site on stable rock near the largest of the dams. The data from all sites are streamed in real-time to a central computer where the positions are computed instantaneously. If the motion of one of the sites exceeds a user-defined threshold, an automatic alarm is generated and forwarded electronically to a designated dam operator. Note that almost all single-epoch horizontal positions fall within a circle with a radius of about 2 centimeters.

[2] It is claimed that EBEP will work with single frequency data. However, dual-frequency data allows longer baselines between the user and reference receiver for the same level of precision.

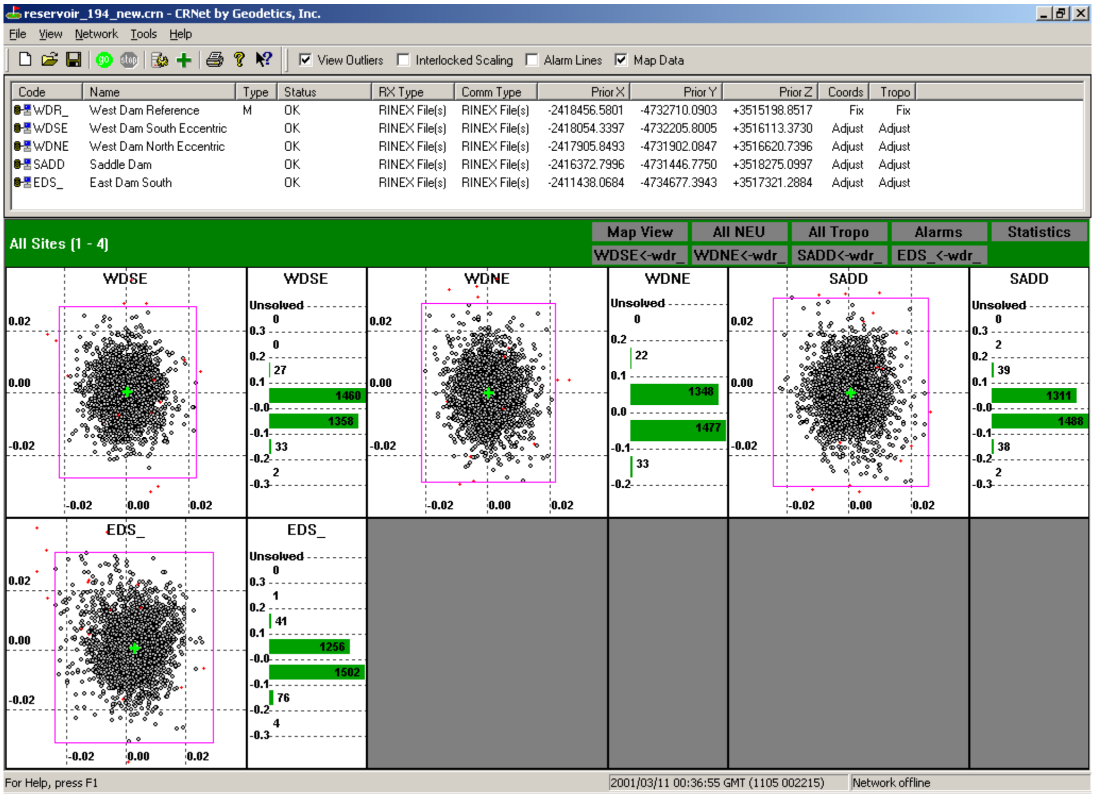

Figure 1. The scatter plot for horizontal Epoch-by-Epoch (EBEP) positioning

EBEP has been tested on a variety of moving platforms including commercial land vehicles at speeds of about 30-40 miles per hour (mph), on race cars at speeds of about 150 mph, and on commercial aircraft in flight. The precision stated above has been achieved in all of these tests. The stated advantages of EBEP are that it does not require initialization or re-initialization times compared to conventional RTK systems, and that it works over extended baseline ranges.

This advantage is demonstrated in *Figure 2* for a test devised by Leica to test EBEP. The test demonstrates Geodetics' horizontal single-epoch positioning between one static and one moving receiver 40 kilometers apart every one second over about a 1.5-hour period. The moving receiver is located atop a model train. An obstacle was located above the train track to obstruct the satellite signals and to cause loss-of-lock (the obstructed area is clearly seen in the lower portion of the train trajectory). Geodetics' epoch-by-epoch approach is unaffected by losses-of-lock so that the train's trajectory is clearly evident. Current GPS RTK systems are unable to compute the trajectory because they require an initialization period of about 30-45 seconds, which is equivalent to almost half of a single revolution of the train around the track.

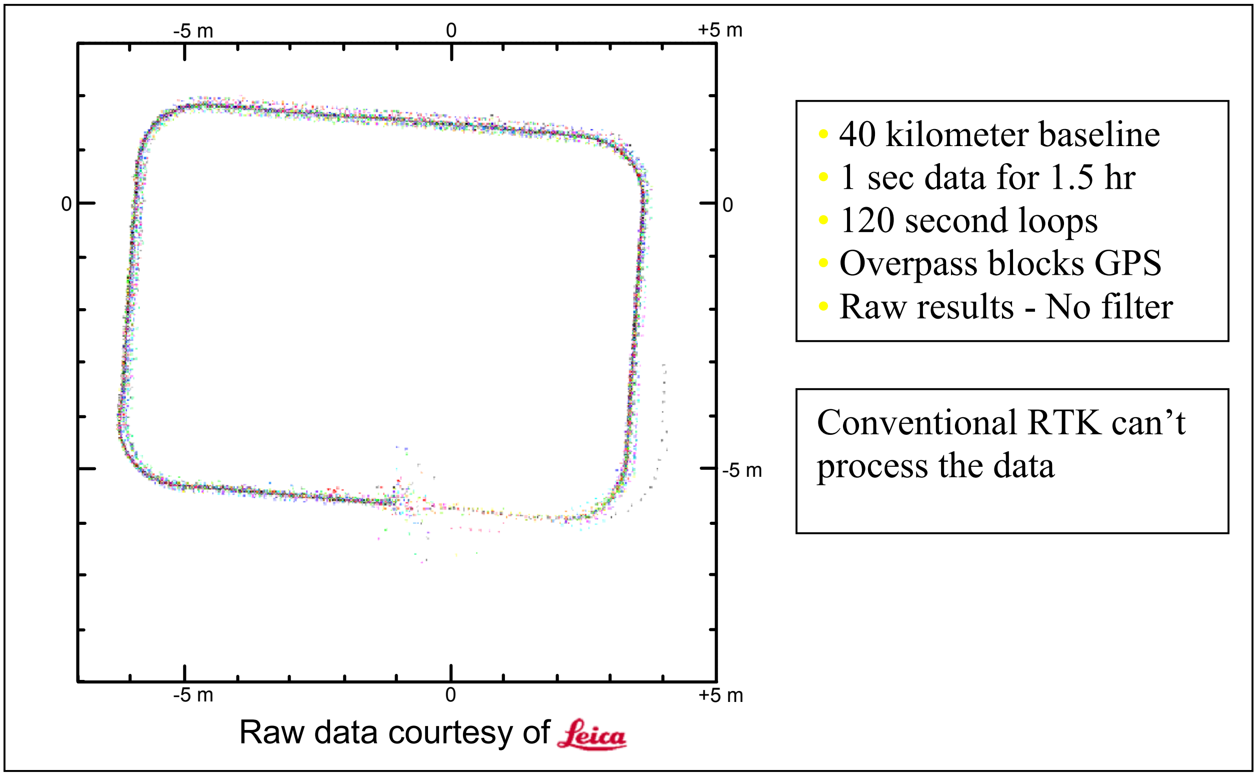

Figure 2. Testing the Epoch-by-Epoch Positioning (EBEP) algorithm illustrating its advantages of not requiring initialization or re-initialization times (compared to conventional RTK systems), and its purported ability to work over extended ranges

These data have provided the impetus for OSD to explore further EBEP performance. In particular, OSD wants to learn how well the algorithm performs for high-dynamic, fighter aircraft applications. This is the purpose of the proposed testing. However, it is becoming more and more difficult to test the performance of high precision TSPI in realistic scenarios. Typically, there are tradeoffs. Realistic scenarios have insufficient truth data, while scenarios that have high-precision truth data are not representative of real world scenarios.

OSD has recently encountered this problem in testing the performance of GPS engines for the JAMI program. The problem was solved by using the following approach:

- High-dynamic scenarios were conducted on a sled track and on a centrifuge.

- The same trajectories were then run on a high-fidelity hardware-in-the-loop simulator.
- The data were compared to validate the simulation facility.
- The simulator was then used to support testing of the hardware for realistic flight scenarios.

The proposed OSD test program will consist of two phases. In Phase I, the Geodetics algorithm will be subjected to a high dynamic sled track at Holloman Air Force Base (AFB), New Mexico. The test will focus on:

- *Precision positioning acquisition performance*. In particular, data will be analyzed to determine if the EBEP algorithm was able to instantly provide precision positioning data the moment the set acquires lock.
- *Precision positioning accuracy*. The data will be compared to truth provided by the instrumented track sensors to determine the accuracy of the Geodetics EBEP algorithm.

Assuming that the live tests go well, the algorithm will then be tested in Phase II with the Eglin AFB Guided Weapons Evaluation Facility (GWEF) hardware-in-the-loop GPS simulator. Representative fighter aircraft trajectories will be simulated. Of particular interest will be the exploration of EBEP algorithm reacquisition time following signal turn-off/turn-on. The test results will be reported in a subsequent paper.

Thomas J. Macdonald is president of MacroVision, Reading, Massachusetts, a company founded in 1998. Previously with TASC for 22 years, he has more than 26 years of Department of Defense (DoD) experience in the development and analysis of advanced navigation, surveillance and radio frequency (RF) communication systems. His particular focus has been on the use of the Global Positioning Systems (GPS) and advanced datalinks for national test and training range applications. This work experience includes 15 years of support to the Director, Operational Test and Evaluation/Resources and Ranges for the Office of the Secretary of Defense (OSD) and 18 years with the test and training community. Macdonald is an advisor to OSD's Central Test and Evaluation Investment program (CTEIP) Office, for which he provides technical expertise for all CTEIP programs that use RF datalinks and GPS-based instrumentation. He is responsible for submitting new program starts, developing system architectures and coordinating the integration/interface of multiple programs. He also supports the tri-service Multi-Service Target Control System (MSTCS) and Joint Advanced missile Instrumentation (JAMI) programs. He is providing technical expertise in the areas of GPS and datalinks designs, and the integration of these programs with several other range instrumentation development programs. He also is a technical advisor and OSD liaison to the Range Instrumentation System Program Office (RISPO), Eglin Air Force Base, Florida. In addition, Macdonald conducts "Advanced Technologies for Test Range Applications" workshops and more than 20 of these workshops have been held on three continents. He has been an invited speaker at numerous ITEA and Associations of Old Crows chapter meetings. He is a past president of the ITEA New England Chapter and is a past vice president for the ITEA Northeast

Region. He is presently on the ITEA Board of Directors and is chairman of the ITEA Educational Committee. Macdonald is also on the Board of Directors of Angel Flight NE, a nonprofit medical air transport association. He received a bachelor of science degree in electrical engineering in 1969; a master of science degree in electrical engineering in 1971; and an electrical engineering degree with a major in RF communications in 1975, all from the Massachusetts Institute of Technology. In addition, he has been an instructor with the graduate school of engineering at Northeastern University for 23 years.

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