Indoor Navigation Test Results using an Integrated GPS/TOA/Inertial Navigation System

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BIOGRAPHY

Alison Brown is the Chairman and Chief Visionary Officer of NAVSYS Corporation. She founded NAVSYS Corporation in 1986 and served as President and Chief Executive Officer until 2006. She has a PhD in Mechanics, Aerospace, and Nuclear Engineering from UCLA, an MS in Aeronautics and Astronautics from MIT, and an MA in Engineering from Cambridge University. She was a member of the GPS-3 Independent Review Team and the Interagency GPS Executive Board Independent Advisory Team, and is an Editor of GPS World Magazine. She is an ION Fellow and an Honorary Fellow of Sidney Sussex College, Cambridge.

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ABSTRACT

NAVSYS has developed a networked radionavigation approach for operating in urban environments where GPS signals can be significantly attenuated or completely blocked. The networked radionavigation approach is based on a Software Defined Radio (SDR) testbed, which combines Global Positioning System (GPS), wireless communications, and Time-of-Arrival (TOA) "Pseudolite" technology to provide location indoors for applications such as first responders, warfighters operating in urban terrain, and location-based services. This system has been integrated with a low-cost Micro-Electro-Mechanical System (MEMS) Inertial Measurement Unit (IMU) to provide an integrated GPS/TOA/inertial man-portable navigation system. The system architecture and test results showing its performance for indoor navigation are presented in this paper.

INTRODUCTION

A Software Defined Radio (SDR) provides a flexible architecture (Figure 1) that allows the same radio components to be reconfigured to perform different functions. NAVSYS has developed an SDR that includes the capability to operate both as a Global Positioning System (GPS) receiver and also as a 900 MHz transceiver operating within the Industrial, Scientific and Medical (ISM) band. Since both the GPS and communications functions reside within common radio hardware, this positioning and communications (POSCOMM) device can use the GPS and communications functionality to provide a positioning capability that leverages both the GPS derived pseudorange and carrier phase observations and also Time-Of-Arrival (TOA) observations derived from the communications channel. The design of the POSCOMM Software Defined Radio is described in this paper.

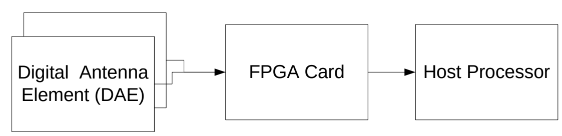

Figure 1 Software Defined Radio Architecture

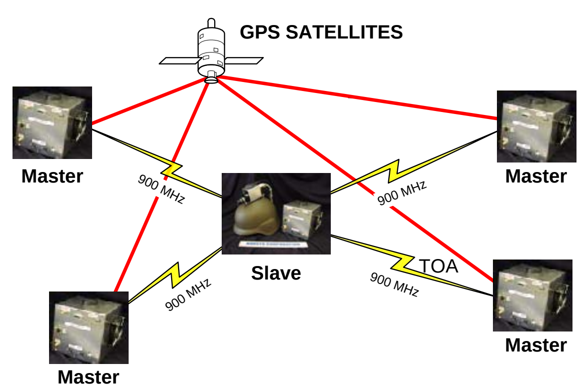

Figure 2 POSCOMM TOA Network[1]

The POSCOMM SDRs are designed to operate in a networked architecture, as shown in Figure 2, where "Master" units are designated as transmitters to provide TOA augmented navigation to "Slave" units operating as receivers in a GPS-denied urban environment. The Master units transmit a TOA message that includes a pseudorandom sequence from which the time of arrival at

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the Slave unit can be precisely determined. A message is also sent which includes the precise time of transmission of the TOA message and the precise location of the Master unit based on the GPS observations. The time-of-arrival differenced with the time-of-transmission provides the Slave unit with a pseudorange observation from each of the Master units' locations. This can be used to solve for the position of the Slave either using the TOA updates alone or using a combination of both the GPS and TOA observations.

We have integrated the GPS/TOA SDR with a MEMS IMU to allow inertial aiding to be applied to the integrated GPS/TOA navigation solution. While the Micro-Electro-Mechanical System (MEMS) Inertial Measurement Unit (IMU) used is relatively low power and inexpensive, the performance is such that the navigation solution degrades within a few minutes if aiding is not available[2]. However, when TOA updates are applied, the inertial navigation solution error growth is damped allowing this inertial unit to support indoor navigation. In this paper, we describe the design for this integrated system architecture and present initial test results on the TOA and inertial navigation.

POSCOMM SOFTWARE DEFINED RADIO

The POSCOMM GPS/TOA/inertial navigation system was implemented using NAVSYS' Software Defined Radio test bed shown in Figure 3[3]. This has been developed using a modular PC/104 configuration to facilitate rapid prototyping and testing of SDR software applications to support advanced positioning and communications functions. Previously, this SDR has been used for demonstrating a Software GPS Receiver (SGR) Application Programming Interface (API)[4], network assisted GPS operation using the military P(Y) code GPS signals[5], and also integrated GPS/inertial operation including Ultra-Tightly-Coupled (UTC) GPS/inertial tracking[6].

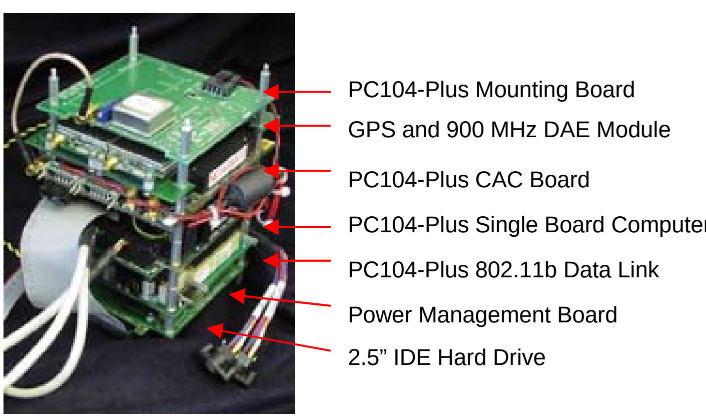

Figure 3 POSCOMM SDR Components

The POSCOMM SDR system is based on low-cost, commercial-off-the-shelf (COTS) hardware and software. The hardware can use any PC-based environment including desktop, laptop, PC/104, or CompactPCI form factors. Signal processing is performed by a Xilinx Spartan-3 Field Programmable Gate Array (FPGA) card and a Pentium-class CPU. The software is portable and developed for real-time flavors of Windows and Linux operating systems. An SCA-based XML schema is used for system configuration.

Figure 4 POSCOMM SDR

The POSCOMM SDR PC/104-Plus stack shown in Figure 3 is packaged in the enclosure shown in Figure 4. The POSCOMM SDR PC104-Plus stack includes the following primary components.

GPS Digital Antenna Element. Received RF signals for both GPS and TOA are converted to digital signals using Digital Antenna Elements (DAEs). The DAEs have a small 1"x4" size and can be easily modified for alternate frequencies and sampling rates and expandability. The DAE is responsible for RF down-conversion and up-conversion as well as high-speed A/D and D/A sampling. Each DAE uses a common sample clock and phase-locked reference local oscillator assuring a coherent sampling environment for all transmitted and received signals.

GPS 900 MHz Digital Antenna Element. This includes a 900 MHz receive and transmit channel that is used for either broadcasting or receiving the TOA-aided data. This could also be configured for use in communicating between the POSCOMM units. The 900 MHz channel was selected as this lies in the unlicensed ISM band. The DAE transceiver can also be configured to work at other frequencies.

PC/104 CAC Card. This NAVSYS designed card includes three Spartan FPGAs and a PCI bridge to the Host Computer. This interfaces directly with the DAE receive and transmit channels through an adapter board, as shown in Figure 5.

802.11b Data Link. The data link provides a transport mechanism for the Network Assist data as well as a remote login capability. In addition, real-time monitoring and navigation display data are transferred over the wireless link.

Host Computer, **Hard Drive, and Power Supply**. These are COTS components that include a PC/104 form-factor Pentium-M Single Board Computer, power supply, and an 80 GB Hard Drive.

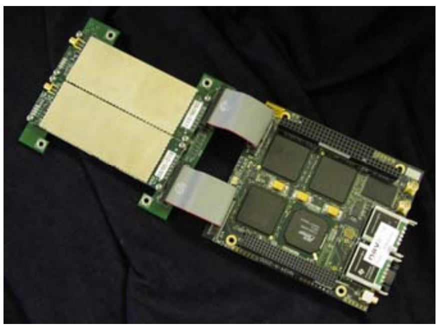

Figure 5 PC/104 CAC to DAE Interfaces

POSCOMM SDR SENSOR HEAD

The POSCOMM SDR is integrated with a helmet mounted Sensor Head as shown in Figure 6. This includes a color digital camera, a MEMS-based IMU, and a dual GPS/900 MHz antenna. The IMU data is used to generate an inertial navigation solution that is updated with the GPS and TOA observations. The position and attitude data from the inertial updated solution is associated with the camera images and is passed back through the network for situational awareness. This imagery can be viewed through a web browser using NAVSYS' GeoReferenced Information Manager (GRIM) (see Figure 7).

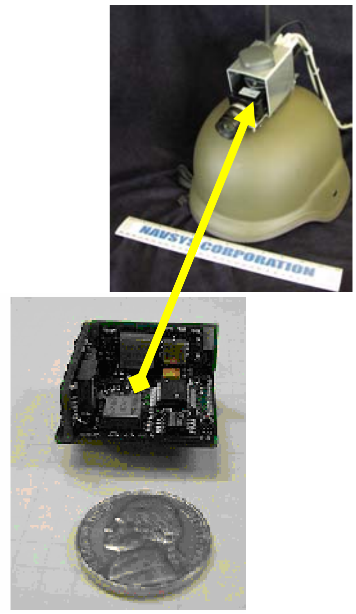

Figure 6 POSCOMM Sensor Head

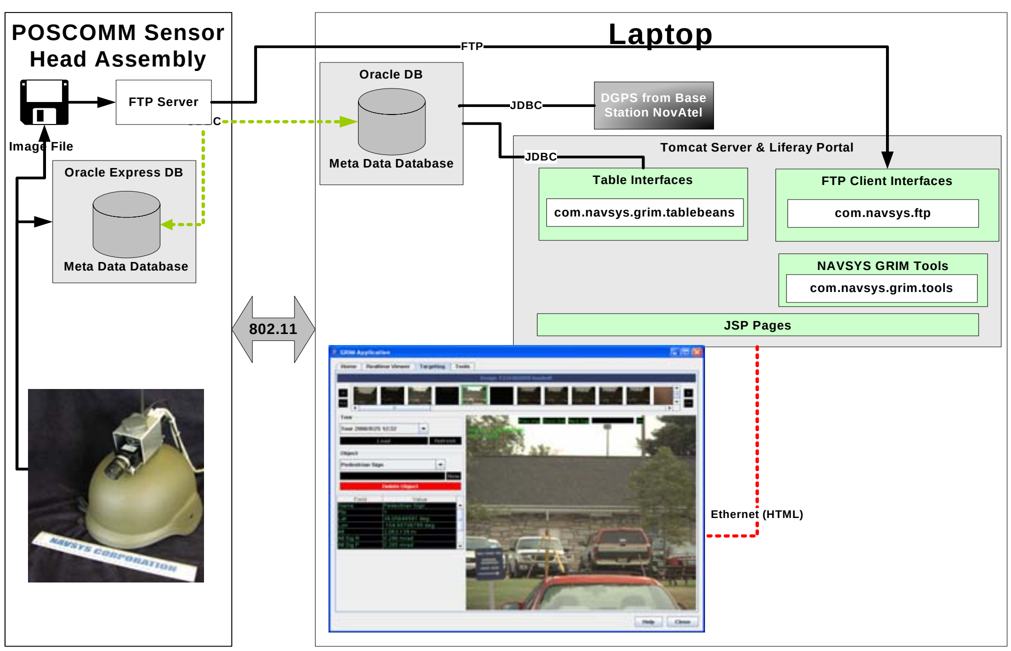

Figure 7 GeoReferenced Information Manager (GRIM) Web Interface

POSCOMM SDR OPERATION

The POSCOMM SDRs are configured through software to operate as either a Master (Transmit) or Slave (Receiver) mode of TOA operation.

Master units are required to be tracking at least one GPS satellite to allow the time of the TOA transmission to be synchronized precisely with GPS time. These units send TOA Assistance messages across the network which tells the Slave units what TOA observations are available for use in aided navigation and also provide the location of the Master units that are providing the TOA aiding.

Slave units will default to GPS tracking if satellites are in view, but do not require GPS tracking to operate. At start-up, the time on each unit is initialized across the network using Network Time Protocol (NTP). On receipt of the TOA Assistance messages from the Master units, the Slave unit will then initiate tracking of the TOA observations which will be used, in combination with any observed GPS satellites, to compute the aided navigation solution.

The SDR architecture allows for a variety of different waveforms to be used to provide TOA assistance. The key feature of the POSCOMM SDR approach is that the design of the SDR DAEs and firmware allows the timing of the TOA transmission to be precisely locked in time to the received GPS signals. For the POSCOMM testing, we implemented a combined Code Division Multiple Access (CDMA), Time Division Multiple Access (TDMA), and Frequency Division (FDMA) approach for sharing the spectrum between the multiple Master Units providing TOA assistance. This provides maximum flexibility in configuring the POSCOMM TOA assistance network to optimize performance and share limited bandwidth for both positioning and communications functionality. The CDMA, TDMA and FDMA parameters that specify the TOA signal characteristics are all defined using configuration parameters and are defined in the TOA ACK Message sent by the Master Units (see Table 1).

Table 1 TOA Acknowledge Message

Field Name	Units	Description
Time	Week secs	GPS time of week of first TOA being transmitted
PRN		ID of PRN code
Period	ms	Interval between TOA signals
Duration	ms	Duration of TOA ranging signal
Freq	MHz	RF Frequency of TOA signal

The GPS/TOA solution accuracy is a function of the following components which are addressed in the POSCOMM SDR design[3].

- Accuracy of the GPS time and position mark at the Master unit.
- Geometry provided by the TOA observations.
- Accuracy of the TOA observations

In the indoor environment, the building can significantly attenuate the received signal power, and strong multipath signals are present. To mitigate the multipath in the TOA measurement, a maximum likelihood estimation (MLE) algorithm is used. This algorithm models both the direct signal and closest multipath signal and detects the direct signal as the result of the maximum likelihood estimation. The MLE algorithm is also used to derive the TOA navigation solution. Field tests were performed at NAVSYS to evaluate the multipath environment and the ability of the TOA tracking loops in such conditions. Test data was collected from units operating both outside the building, where GPS could be used as a truth reference, and inside the building. In both cases, the TOA signals were passing through multiple types of construction.

TOA OBSERVATIONS

The accuracy of the TOA observations is a function of the waveform characteristics, the tracking loops employed, and the environment. The main challenge faced for the TOA ranging signal design is to provide robust and accurate performance in the presence of multipath.

To evaluate the multipath environment and the ability of the TOA tracking loops to handle these errors, four Master units (Figure 9) were set up around the NAVSYS building shown in Figure 8 with the test layout shown in Figure 10. Test results were collected from units operating both outside the building, where GPS could be used as a truth reference, and inside the building. In both cases, the TOA signals were passing through multiple different types of construction. The west end of the building is metal construction while the center and east end is brick construction.

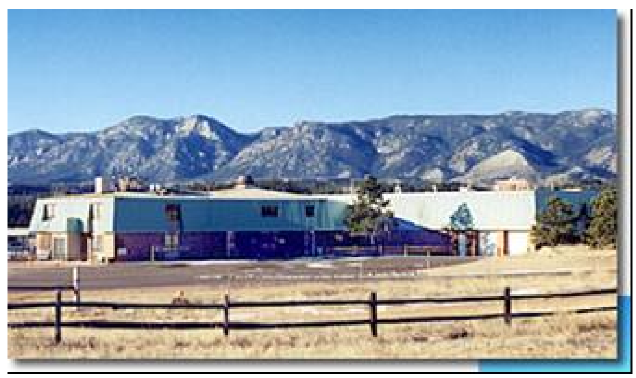

Figure 8 NAVSYS Building (Southwest View)

Figure 9 POSCOMM Master Unit

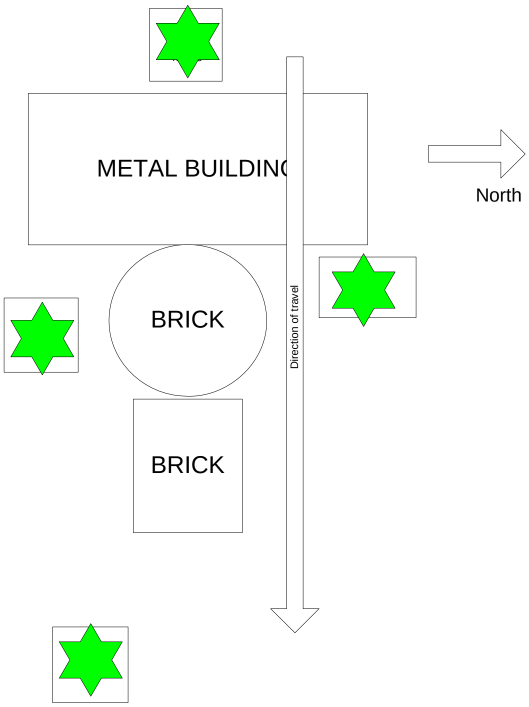

Figure 10 Indoor Test Pseudolite Layout

An MLE algorithm is used to estimate the TOA from the correlation results generated from the 900 MHz received signal correlated with the modulated PRN code. The algorithm detects the peak of the correlation from the closest in signal detected. This will result in detecting the correlation peak of the signal from the direct path from the transmitter rather than a multipath signal that arrived from an indirect path. Figure 11 shows the correlation results from four transmitters when the receiver has a direct line-of-sight to the transmitters. All four signals have a strong detected correlation peak with a received RF signal of around -16 dBm. Figure 12 and Figure 13 show the correlation results from signals received through the NAVSYS building. In these cases, the building can significantly attenuate the received signal power and also strong multipath signals are present, which appear as peaks showing to the left of the direct signal peak. The MLE algorithm used to perform the TOA tracking detects the closest peak in each case shown.

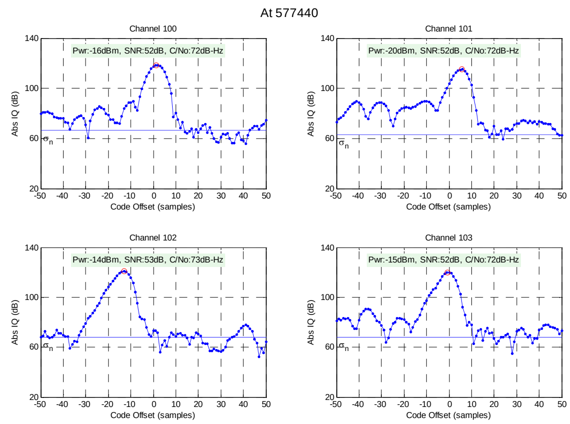

Figure 11 MLE Estimation of Shortest TOA Pseudorange (outdoor testing)

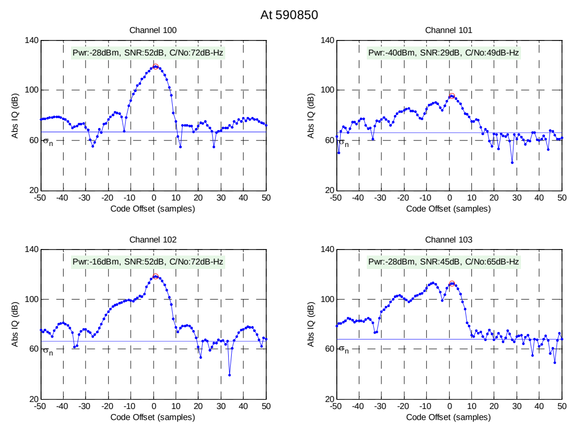

Figure 12 MLE Estimation of Shortest TOA Pseudorange (indoor testing)

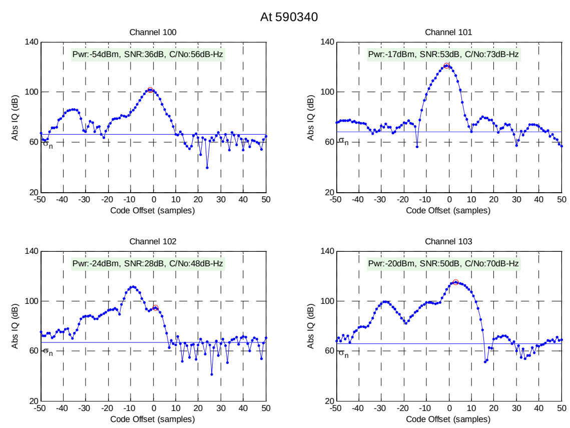

Figure 13 MLE Estimation of Shortest TOA Pseudorange (indoor testing)

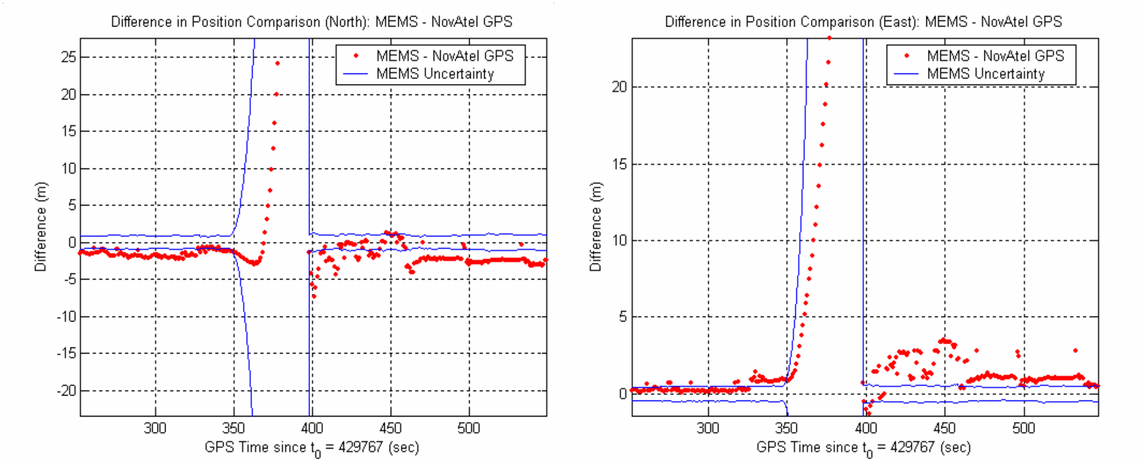

Figure 14 MEMS Inertial Navigation Results

MEMS INERTIAL NAVIGATION

The MEMS IMU being used for the inertial navigation is based on the low cost Analog Devices accelerometers and gyroscopes. These inexpensive instruments exhibit significant drift when operating as an unaided inertial navigation unit. Figure 14 shows the inertial navigation results during a short GPS drop-out. The navigation solution accuracy degrades very rapidly without updates. The POSCOMM approach is to continue to apply TOA updates to the inertial navigation solution which will bound the IMU error growth.

TOA-AIDED NAVIGATION TEST DATA

The TOA-aided navigation solution was first tested in an outdoor environment using GPS as truth data to analyze the performance of a TOA navigation solution. The results are shown in Figure 15. The POSCOMM navigation solution computed from four TOA observations agreed with the GPS truth solution to within 5 meters except for a few excursions. In Figure 16 the indoor test configuration is shown that was used to test the TOA solution. Five transmitters were set up at different sites around NAVSYS' building. This building uses brick construction on the east side and center and is a metal building with brick façade on the west side. The navigation test results are shown in Figure 19. The average position error was on the order was 5.53 m (RMS).

An example of the signal variation throughout the building is shown in Figure 17 and Figure 18. This data is shown for a Master transmitter located on the SE side of the building. The figures show that the received SNR of the TOA signals drops by 40 dB as the unit is moved to the West of the building. These plots also compare the tracking performance achieved with the straight peak detection and the MLE estimation. The MLE estimation technique noticeably has fewer excursions demonstrating its improved performance in tracking the TOA signals in a strong multipath environment.

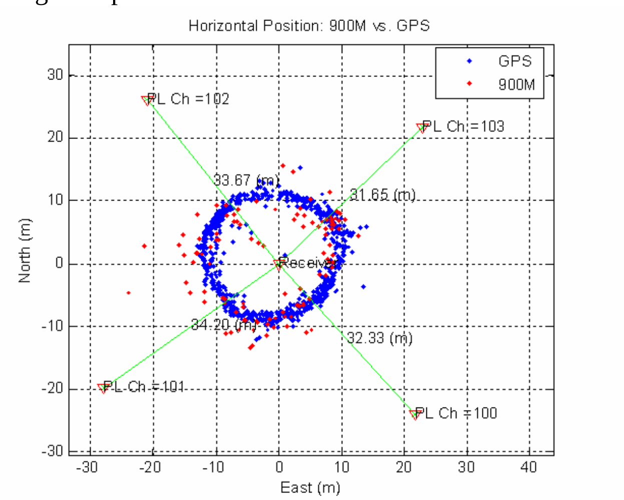

Figure 15 TOA Navigation Solution

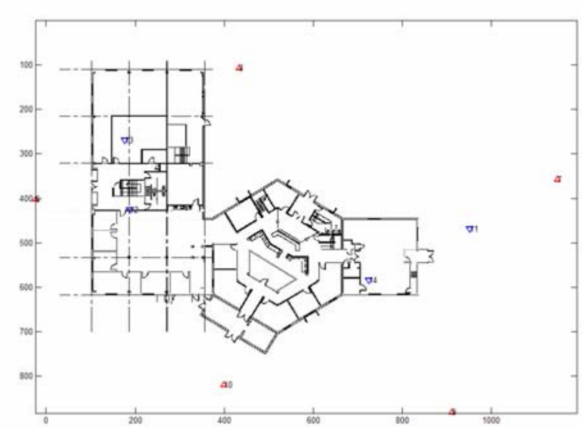

Figure 16 NAVSYS Building Transmitter Sites (Red) and Test Sites (Blue)

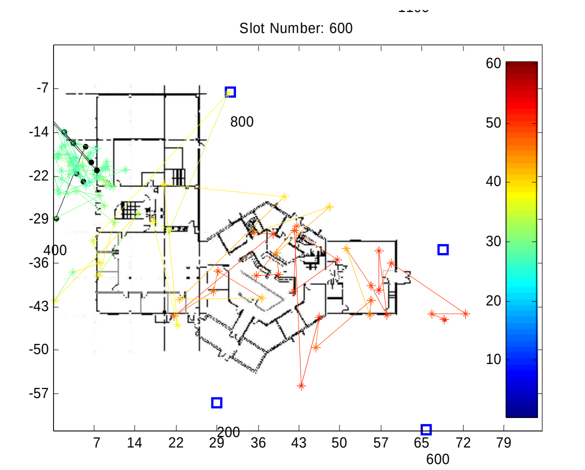

Figure 17 Signal Strength using TOA Peak Detection

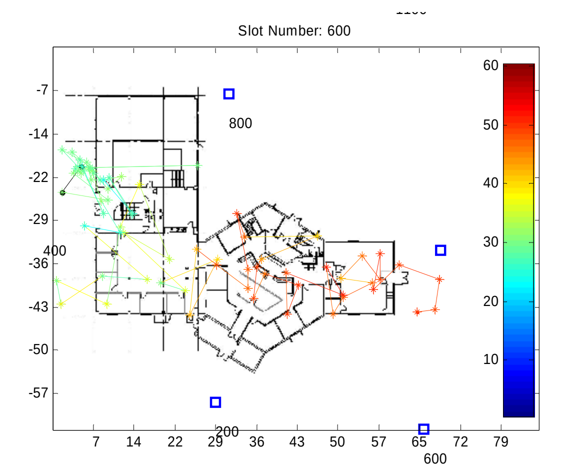

Figure 18 Signal Strength using MLE Detection

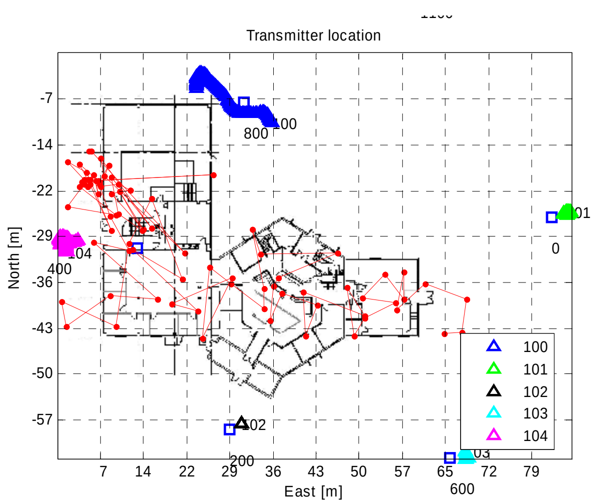

Figure 19 Navigation solution in mobile indoor test

CONCLUSION

The POSCOMM units are being developed to provide a robust urban navigation solution that can provide precise positioning inside buildings where the GPS signals cannot be received. The initial tracking and positioning results shown in this paper show the capability provided by the POSCOMM SDR to augment GPS signal tracking in the challenging urban environment with TOA aiding from an alternative RF source. This technology offers the capability to provide access to GPS-like quality of service both outside and inside buildings. The camera and inertial unit in the POSCOMM Sensor Head also provide the capability for real-time georeferenced situational awareness by networking the POSCOMM units with the GRIM web-based server.

Military applications for this technology include improved military operations in urban terrain (MOUT). Commercial applications include firefighters as well as other First Responders. This project will give firefighters, police officers and emergency officials an electronic vest and eyepieces that will provide their commanders with their location and their vital signs, as well as real-time georeferenced images of their surroundings.

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