

# WPI Precision Personnel Locator System

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## BIOGRAPHY

Dr. David Cyganski is professor of Electrical and Computer Engineering at WPI where he performs research and teaches in the areas of linear and non-linear multidimensional signal processing, communications and computer networks, and supervises the WPI Convergent Technology Center. He is an active researcher in the areas of radar imaging, automatic target recognition, machine vision and protocols for computer networks. He is coauthor of the book *Information Technology: Inside and Outside*. Prior to joining the faculty at WPI he was an MTS at Bell Laboratories and has since held the administrative positions of Vice President of Information Systems and Vice Provost at WPI.

Dr. R. James Duckworth is an Associate Professor in the Electrical and Computer Engineering department at WPI. He obtained his PhD in parallel processing from the University of Nottingham in England. He joined WPI in 1987. Duckworth teaches undergraduate and graduate course in computer engineering focusing on microprocessor and digital system design, including using VHDL and Verilog for synthesis and modeling. His main research area is embedded system design. He is a senior member of the IEEE, and a member of the ION, IEE, and BCS and is a Chartered Engineer of the Engineering Council of the UK.

Dr. William R. Michalson is a Professor in the ECE Department at WPI where he performs research and teaches in the areas of navigation, communications and computer system design. He supervises the WPI Center for Advanced Integrated Radio Navigation (CAIRN). His research focuses on the development, test, and evaluation of systems, which combine communications and navigation. He has been involved with navigation projects for both civilian and military applications with a special emphasis on navigation and communication techniques in indoor, underground or otherwise GPS-deprived situations. Prior to joining the faculty at WPI, Dr. Michalson spent approximately 12 years at the Raytheon Company where he was involved with the development of embedded computers for guidance, communications and data processing systems for both space borne and terrestrial applications.

## ABSTRACT

This paper describes the latest developments of the Worcester Polytechnic Institute (WPI) Precision Personnel Locator (PPL) system [1-7]. This RF-based system is used to track first responders and other personnel in indoor environments and assumes no existing infrastructure. Recent developments in a variety of areas, including creating new signal processing algorithms, RF and digital hardware, and antenna design, have enabled demonstration of indoor location to better than 1m accuracy in difficult environments with a multi-carrier signal of 60 MHz bandwidth. Current work is directed at demonstrating sub-meter indoor positioning accuracy.

## INTRODUCTION: PRECISION PERSONNEL LOCATOR SYSTEM

The core technology that must be realized and perfected to achieve precision indoor location is precise ranging (distance estimation) between one or more base stations and a mobile locator device. This ranging technology is the basis for GPS technology in which satellite base station transmitters permit establishment of the location of mobile receivers and is also the basis for cell phone location systems in which tower located base-station receivers estimate the location of mobile hand-held cell phone transmitters.

However, in the past, several primary factors have obstructed realization of this important capability in the indoor environment: insufficient signal strength, lack of precision and multi-path degradation of GPS indoors; FCC spectrum non-compliance of ultra wide band systems; and/or the need for pre-existing infrastructure; failure of simple pulse distortion models in actual through-building and multi-path propagation conditions. In contrast, work to date on the proof-of-concept system described here has demonstrated the means to provide these capabilities within the bounds of practical constraints and allowed development of design rules for future design efforts.

Our solution is based upon the use of an unmodulated wideband OFDM-like signal which we have named



with respect either to the auto-generated coordinate system, or to a user preferred coordinate system. This may be registered to electronic building floor plans if such plans are available and/or may be GPS registered if GPS signals are available at the command console. The command console may also provide other services such as displaying the tracks of all locators so that a map of available pathways in the building may be automatically generated by the movements of personnel in lieu of building plans.

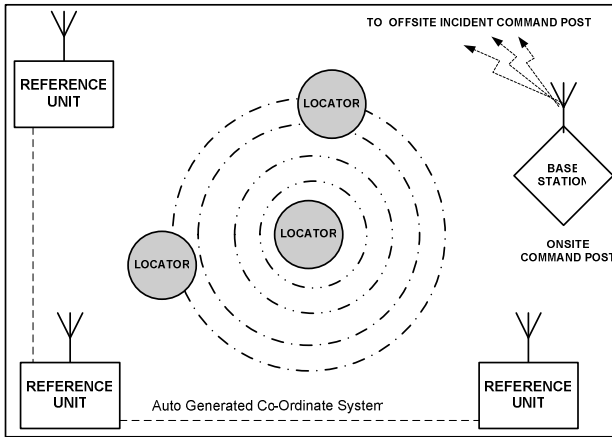


Figure 2: System Architecture

Figure 3 shows each of the main system components in more detail. The locator devices worn by the first responders are shown at the top of the figure. The system supports up to 100 locators. The locator contains two main sections, the data channel handling the overall control of the locator and supporting such functions as the distress feature and diagnostics, and the ranging waveform electronics generating the MC-WB signal. The signals from the locators are received by the reference units deployed outside the building. The reference units communicate with the Base Station containing the command and control console to display the location of the locator devices.

Each of the main system components are described in more detail in the following sections.

#### Locator

The Locator unit carried by the first responders contain two separate sections, a data channel section and a MC-WB ranging waveform section. A block diagram of the data channel section is shown in Figure 4.

The data channel is part of the Locator and contains a microcontroller responsible for the overall control and management of the Locator system. Some of the functions controlled by the microcontroller are:

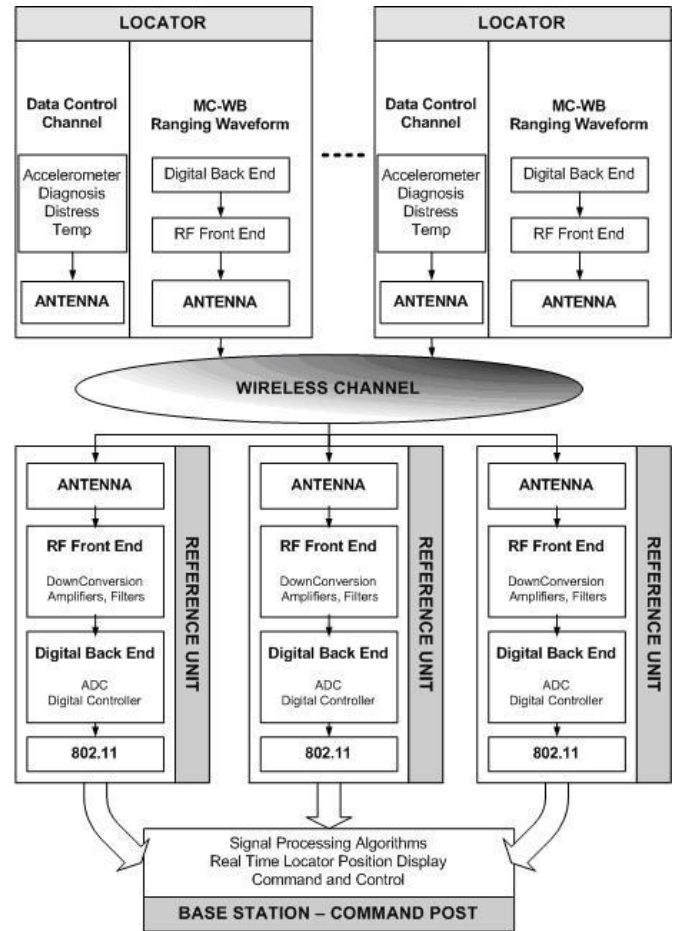


Figure 3: Overall system block diagram showing main components

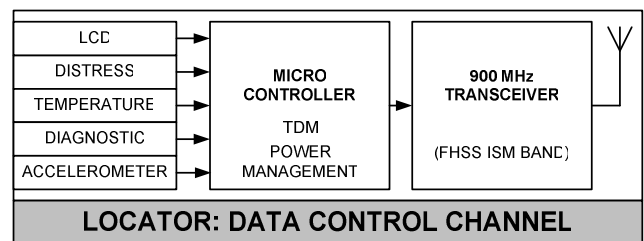


Figure 4: Locator Data Channel Section

- Overall diagnostic and health monitoring
- Overall power-management of locator hardware to maximize battery life
- Implementation of a Time Division Multiplex scheme for transmission of the ranging waveform
- Detection of non-movement using a 3-axis accelerometer
- Transmitting of first responder distress signal
- Transmitting other locator information (temperature, battery condition)

The data channel transceiver operates as a frequency hopping spread spectrum system in the 900MHz Industrial Scientific Medical (ISM) band.

The photograph below shows the current prototype version of the Data Channel hardware.

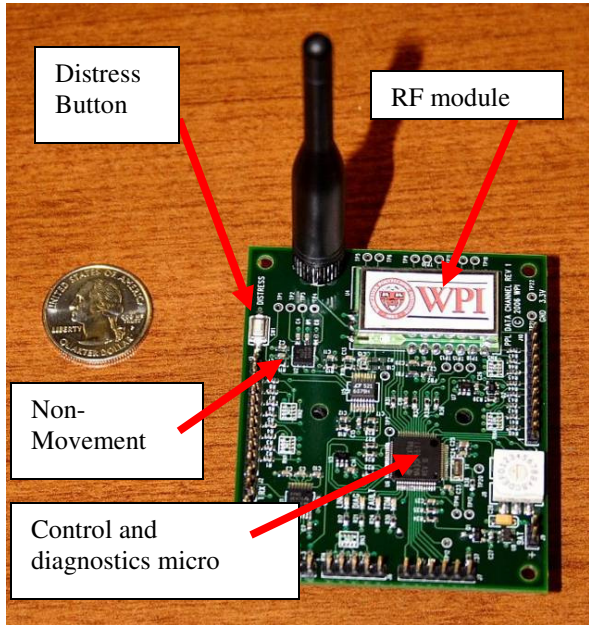


Figure 5: Prototype of Locator data channel hardware containing distress button, accelerometer, temperature, diagnostics, etc.

The second section of the Locator unit is the ranging waveform electronics. The system design is quite simple from the RF point of view, minimizing the RF hardware and taking a “software radio” approach to the maximum extent possible. A block diagram is shown in Figure 6. The ranging waveform is generated in an FPGA which in turn drives a DAC. The baseband output of the DAC is then up converted to create the RF signal.

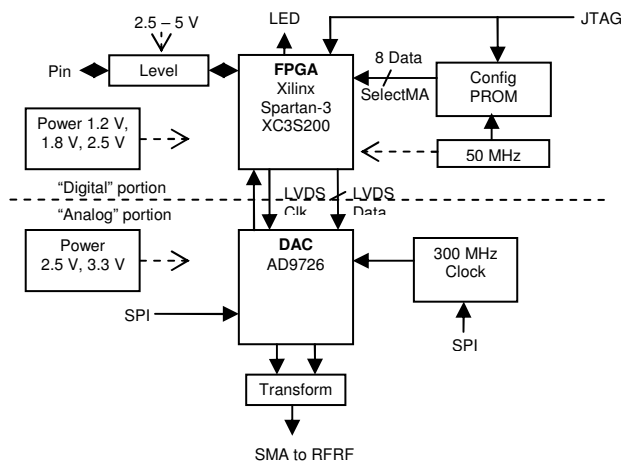


Figure 6: Ranging Waveform section of Locator

Careful attention was paid to the design and operation of the Locator unit to minimize power and so extend battery life as much as possible. Figure 7 shows most of the major system components and their contribution to power consumption. The Locator can operate for over 72 hours in operational mode at an incident site or for many weeks in sleep or standby mode.

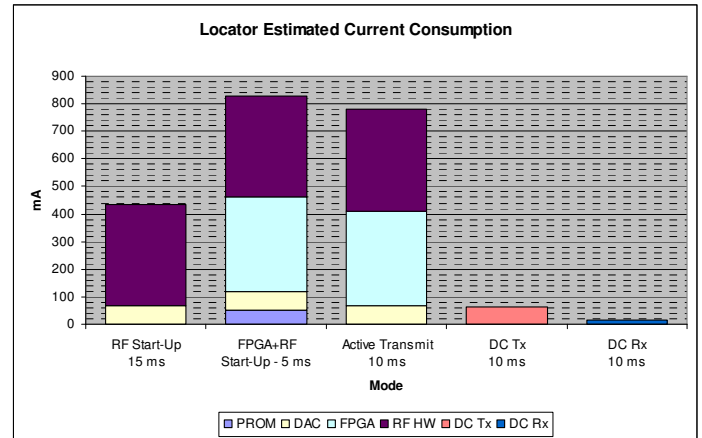


Figure 7: Estimated current consumption of Locator unit

The data channel and ranging waveform electronics and associated antennas are designed to be packaged together into a lightweight, rugged, locator unit as shown in Figure 8. Also shown is the proposed wideband PIFA antenna.

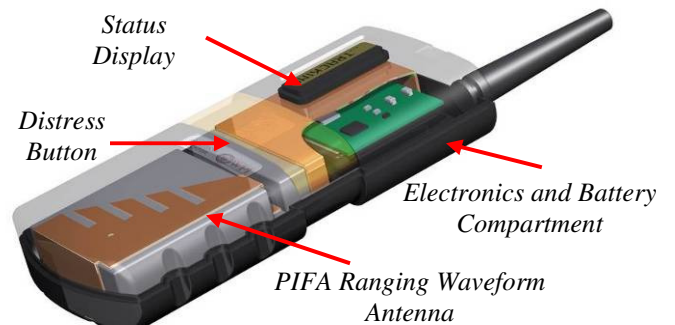


Figure 8: Locator concept drawing and photo of prototype PIFA antenna with circuit board

Although the experimental results in this paper describe operation with a Multi-Carrier signal of 60MHz the Locator hardware described in this section was designed to provide up to 150MHz wide signals. A spectrum capture showing a 120MHz wide signal with 50 carriers is shown below:

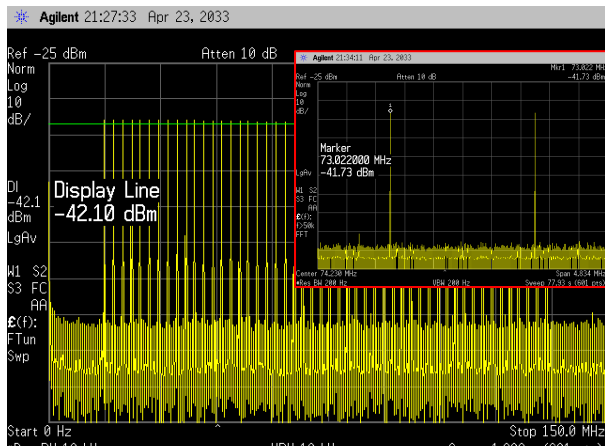


Figure 9: Locator generating 50 carrier MC-WB signal – the inset shows two of the carriers.

Another important test was to show the control and data channel can communicate up to 100m through a typical building structure. The picture below shows the locator was placed in two locations, A, and B, outside the building while a second locator was moved through the three floors of the building to confirm the devices could communicate with each other.

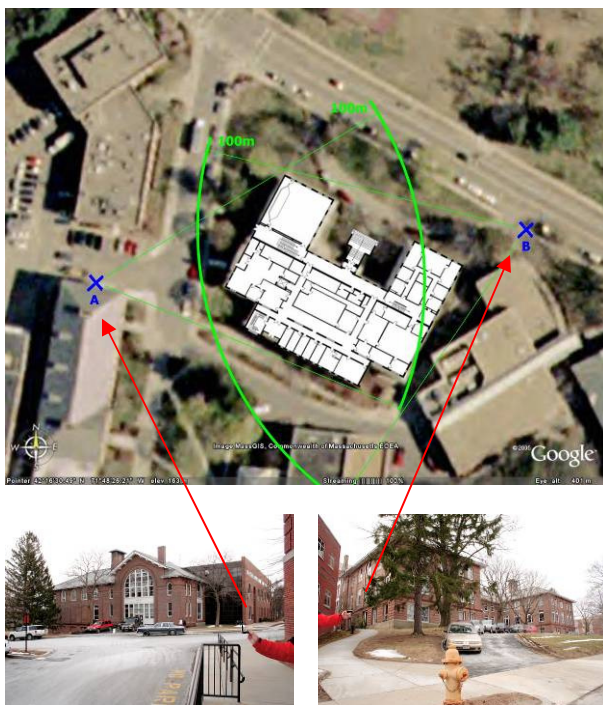


Figure 10: Range testing of Locator

## Reference Units

The reference units are deployed around the building or incident site. They receive the ranging waveform signals from the locators in or around the site to be monitored. The main sections include an RF front end, a high speed ADC, a digital controller board, and an 802.11 transceiver. The incoming ranging signals are sampled and processed and then transmitted to the base station. A block diagram of the Reference unit is shown in Figure 11.

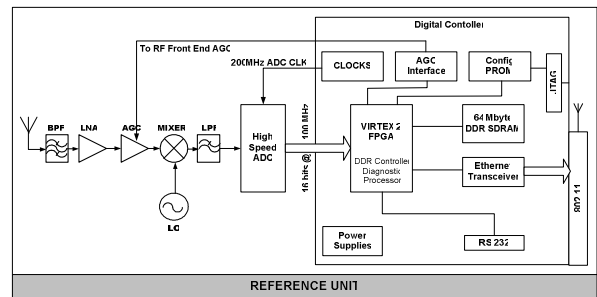


Figure 11: Reference unit block diagram

The Reference unit digital section also uses an FPGA with the FPGA programmed to capture and analyze the ranging waveforms from the locator units.

## Base Station

The base station is responsible for receiving the processed ranging signals from the reference units. Signal processing algorithms are used to determine the 3D location of each of the locator units. This information is combined with the locator information (distress, non-movement, diagnostics, etc) received over the data channel and then displayed on the command console.

## Antenna

The antenna performance, at both the Locator and Reference units, is critical to any RF-based positioning system. Furthermore the physical environments at these two ends are quite different. The antenna designs used for the locator are discussed below.

### Locator Antenna

The locator unit is equipped with a linearly-polarized, wearable, UHF patch antenna. We have designed and tested two versions, appropriate for current and future spectral configurations, with center frequencies of 440 and 700 MHz and with the bandwidth of at least 10% of center frequency.

The antenna for the locator needed to be relatively small in size, at most one quarter wavelength ( $\lambda_0$ ), to not require a matching network (have low loss), to have an almost

omni-directional radiation pattern, and to be amenable to placement in close proximity to a body without compromise of its characteristics. These restrictions indicated that a form of patch antenna was most appropriate. A quarter wave patch antenna of the PIFA (Planar Inverted F Antenna) style is a natural candidate for our task since it is approximately  $0.25 \lambda_0$  [8, 9] in size.

The ground plane is larger – approximately  $0.5 \lambda_0$  in one dimension, however this is not a factor for the present work since the allocated space can be used for housing the transmitted hardware. Furthermore, the size of the PIFA can be further reduced by using various techniques discussed below without reducing the operating bandwidth.

Further miniaturization of the PIFA was achieved using several approaches established previously for L- and S-bands: capacitive loading [10], tapering the patch [11], and using slots for a longer current path [9] along the patch edges have been chosen.

*Planar Inverted F Antenna (PIFA) Concept*

Figure 12 shows the configuration of the PIFA. It consists of a linearly tapered top plate (radiating patch), ground plane, feeding wire (probe feed), and a shorting plate. The height of the top plate above the ground plane is fixed ( $\sim 0.04 \lambda_0$ ). The patch, ground plane, and the shorting plate are made of copper foil and are supported by high-density polystyrene foam (3 pcf) from Dow Chemical Company. The dielectric constant of the foam was measured using the suspended ring resonator method and is approximately equal to 1.06.

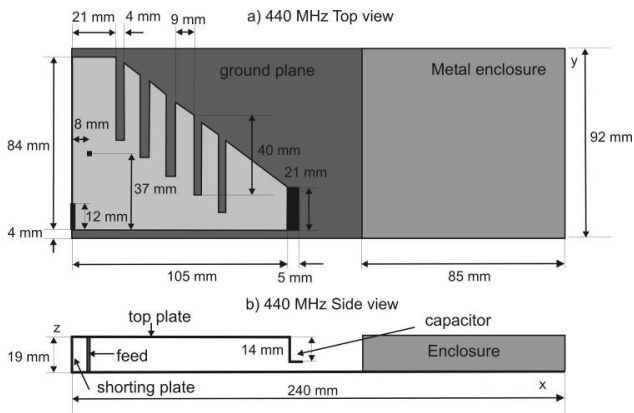


Figure 12: Design of 440 MHz Planar Inverted F Antenna (PIFA).

Figure 13 shows the return loss predicted by simulation and measured for two constructed antennas. We see that a 17% of center frequency bandwidth has been achieved. Radiation patterns as determined by simulation show that the antenna radiation is almost omnidirectional with the maximum directivity gain of about 2.7 dB at zenith; the

polarization isolation in the upper half-space is above 10 dB.

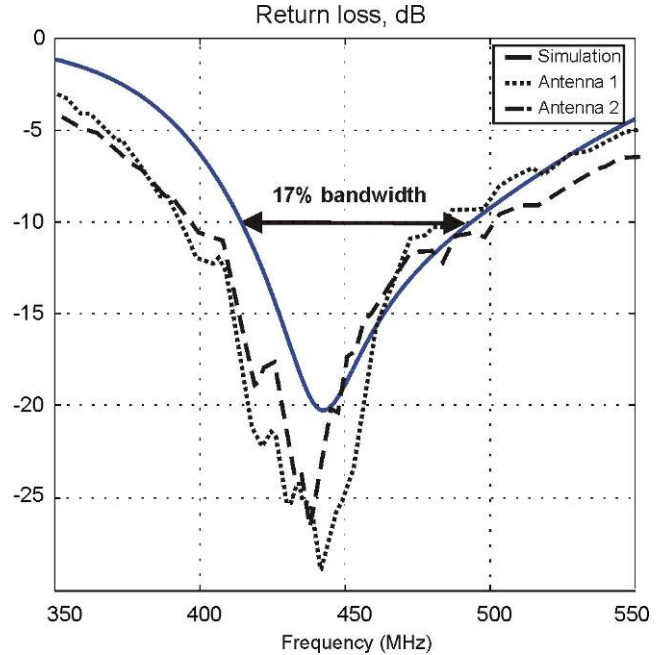


Figure 13: Return loss, simulated and measured for the unloaded PIFA optimized at 440 MHz

*Reference Unit Antenna*

We have experimented with various antenna configurations for the reference units. A corner reflector antenna with variable corner angle was the simplest candidate for the reference unit antenna and we have used these for many of our outdoor and indoor experiments. It has a wide bandwidth and a controllable radiation pattern. It also has good front-to-back isolation, which is significant for cutting the unwanted interference and multipath from the outside environment. At the same time, the antenna is linearly polarized when the driving element is a dipole. This circumstance limits the antenna application scenarios to certain positions of the locator antenna as problems arise when the firefighter is in a prone or recumbent position resulting in a change in polarization. Furthermore the reflector based antennas are not compact and have structures that are easily damaged.

We are currently using a simplified reflector design while developing another compact patch antenna concept that addresses these two issues. The current reflector design comprises a driven element, a supporting balun/impedance match structure and a  $\lambda_0$  square rear reflector panel. The tests shown in this paper were conducted with a vertical dipole driven element and wideband balun while future tests will be conducted with a recently completed circularly polarized driven element and associated balun. We are currently testing concepts for a circularly polarized patch antenna that will meet all our requirements.

## Precision Location Signal

As previously described, our ranging waveform is a Multi-Carrier Wideband (MC-WB) signal. Our experiments to date have used MC-WB bandwidths ranging from 25 to 60 MHz. Future versions of our hardware will allow us to test bandwidths as high as 200 MHz, for evaluation in extreme multipath environments. The signal generally consists of  $N$  unmodulated sub-carriers spanning the bandwidth of operation  $B$  Hz, and (in the simplest implementation) spaced at  $B/N$  Hz. See Figure 14 below. The regular spacing implied above is not necessary, and in fact these sub-carriers can be made to fall at arbitrary points in the spectrum chosen to avoid other-service interference and fulfill regulatory requirements.

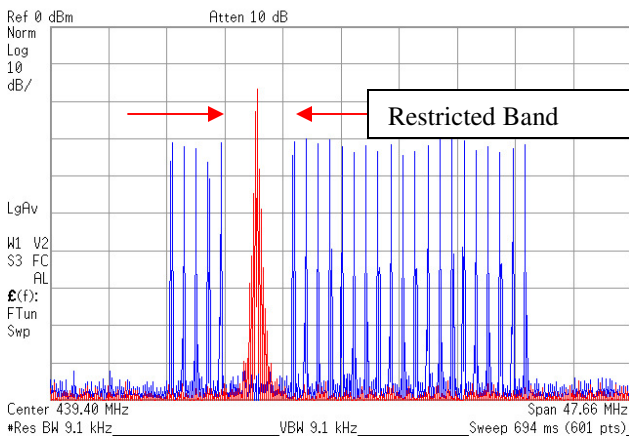


Figure 14: The MC-WB signal (blue) consists of unmodulated subcarriers that may be placed in allowed bands to avoid restricted frequency bands (red).

The 60 MHz wide MC-WB tests shown in the following section used 103 carriers with a center frequency of 440 MHz. The total driving point power was 5 mW, (approximately, 50  $\mu$ W per carrier) resulting in an ERP in the highest gain direction of 10 mW, which is 3dB below our FCC experimental license limit of 20 mW.

Precise and multi-path compatible location is obtained by applying novel multi-carrier range recovery techniques derived in past work at WPI as described in [1, 3, 4, 7] based upon state space estimator approaches to modern spectral analysis first outlined in [12]. Fusion of these range outcomes was previously conducted by using standard multi-lateralization techniques [13] but has now been replaced by a new approach to be described in a future paper.

## PRECISION PERSONNEL LOCATOR SYSTEM TEST RESULTS

Previous published results had been achieved with a 30 MHz wide multi-carrier signal in the 420 to 450 MHz band using linearly-polarized receiving dipoles. Initial work was performed under a Special Temporary Authorization (STA) from the FCC. An experimental license was recently granted that permits both greater bandwidth and use of a wider range of frequency bands for testing. We have modified the RF and other hardware to operate with this new 60MHz wide signal.

We have been successful in demonstrating our system in realistic environments with an average accuracy of approximately 1 m. One of the experiments involved locating a free-standing transmitter (battery powered with no cables to the rest of the system) inside a brick and steel-beam building (Figure 15). The room inside the building in which the transmitter was placed was used for laboratory experiments and had many metal benches, cabinets, ducts, conduits, machinery and other objects that would contribute to a high multipath environment.



Figure 15: The interior view of the indoor test conducted in WPI's Kaven Hall

The receiving antennas were located outside the building and covered an approximate area of 20 m by 15 m as shown in figure 16. As shown in the figure, thirteen antennas were placed around three sides of the Kaven Hall building. In Run 1 these antennas were placed immediately in front of the brick walls, with care to disallow any antenna from having a view of the inside of the building through a window. Throughout this run, the transmitter was placed at known positions at “chest height” above the floor of the laboratory room. This position placed the transmitter below the outside grade and under the plane of the receiving antennas.



Figure 16: The exterior view of the indoor test. Base antennas surround the building wing on three sides.

Figure 17 indicates the difference between the known transmitter positions and the estimated position obtained by the PPL system versus bandwidth. While the locator system generates real time position estimates (approximately once every 2 seconds) all raw data is captured and saved so that results such as depicted in this figure, in which the bandwidth is varied by truncating the spectrum of the captured signal, can be generated.

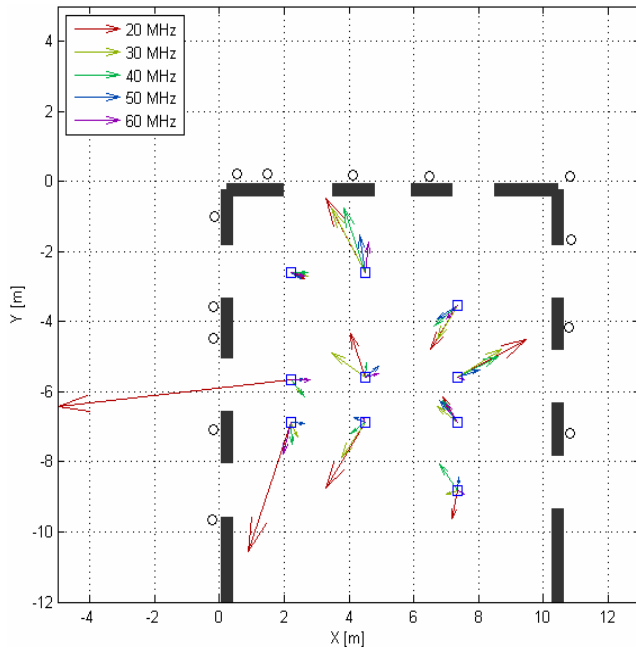


Figure 17: Vectors indicate the difference between known transmitter locations and the estimates determined by the locator system as bandwidth is varied from 20 to 60 MHz

As is clear from Figure 17, increasing bandwidth translates into increased accuracy and increased immunity from outlier results due to multipath effects. With the full 60 MHz bandwidth applied, the average absolute distance error was 0.5 m versus 1 m at 30 MHz. Reprocessing of

the above data with an improved algorithm which is currently being evaluated has improved the 60 MHz performance in this case to an average absolute distance error of 0.37 m.

Figure 18 shows the effects of moving the antennas back from the positions used in Figure 17. Incidentally, in this figure, all data was captured with the transmitter elevated to the same height as the receiving antennas, a position that resulted in increased multipath as the transmitter and receiving antennas all fall on a plane perpendicular to the most prominent reflecting surfaces in the building. Due to terrain constraints, it was not possible to move the antennas on one side of the building through the same range of displacement as the others. One can identify a trend in this figure in which initially there is an improvement in performance as the antennas are backed away from the wall corresponding to increased direct path signals propagating through the windows of the building. For a sufficient back-off the performance degrades due to loss of signal levels.

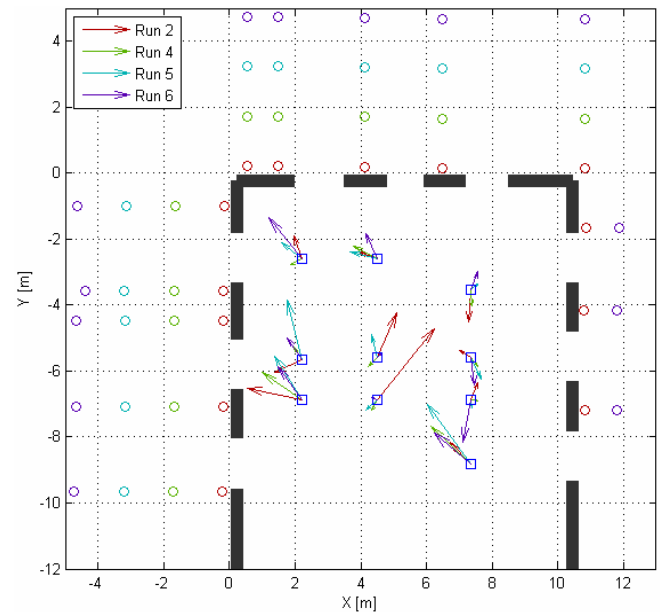


Figure 18: Vectors indicate the difference between known transmitter locations and the estimates determined by the locator system as the external antennas are progressively stepped back from the building

## CONCLUSIONS

This paper documents significant progress towards the important goal of precise (sub-meter) three-dimensional personnel tracking in the indoor environment with no pre-installed infrastructure. We have achieved better than 1 m accuracy in high multipath environments with a 60 MHz bandwidth signal. At this time we are making further hardware and algorithmic improvements which we expect to drive our accuracy up, and more importantly allow even greater distances and amounts of multipath to be

accommodated. The hardware and antenna changes will also enable us to perform our tests in a 600 to 800 MHz band granted to us by an experimental authorization from the FCC.

## ACKNOWLEDGMENTS

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