

Inverse Diffraction Parabolic Wave Equation Localisation System (IDPELS)

Troy A. Spencer¹, Rodney A. Walker¹, Richard M. Hawkes²

¹ Cooperative Research Centre for Satellite Systems (CRCSS), QUT University, Brisbane, Queensland, Australia
e-mail: ta.spencer@qut.edu.au; Tel: + 61 7 38641772; Fax: 61 7 3864 1517

² Navigation Warfare, Electronic Warfare and Radar Division, Defence Science Technology Organisation (DSTO), Edinburgh, South Australia, Australia

Received: 22 April 2005 / Accepted: 13 July 2005

Abstract. While GPS is a relatively mature technology, its susceptibility to radio frequency interference (RFI) is substantial. Various investigations, including the Volpe Report (Volpe, 2001) which was the result of a US Presidential Decision Directive (PDD-63) assigned to the Department of Transportation (DOT), have recommended that methods should be developed to monitor, report and locate interference sources for applications where loss of GPS is not tolerable. With GPS becoming an integral utility for developed society, the significance of research projects that enhance and expand the capabilities of GPS RFI localisation is highly important.

In response to this requirement for GPS interference localisation, a novel technique called "Inverse Diffraction Parabolic Equation Localisation System" (IDPELS) has been developed. This technique exploits detailed knowledge of the local terrain and an inverse diffraction propagation model based on the Parabolic Equation method (PEM). In wave-propagation theory, an inverse problem may involve the determination of characteristics concerning the source, from field values measured at a certain point or certain regions in space. PEM is an electromagnetic propagation modelling tool that has been extensively used for many applications. This paper will present simulation and field trial results of IDPELS. Simulation results show that this technique has good promise to be useful in locating GPS jamming sources in highly-complex environments, based on networks of GPS sensing antennas. Results also show that the method is capable of locating multiple interference sources. Trials concerning the practical application of IDPELS are also provided. With measured lateral field profiles recorded with a single moving sensor platform in a van, results indicate IDPELS to be a pragmatic localisation technique.

Key words: Parabolic, Inverse Diffraction, Propagation, Localisation

1 Introduction

An area that has received considerable research and development in recent times is the mechanism that discovers the spatial relationship between objects. This process is referred to as *localisation* and has been extensively applied. Areas where localisation can be applied include autonomous mobile robot navigation (Adams, 1999), local neural networks (Weaver et al., 1996), E-911 (Biacs et al., 2002) and airborne electronic warfare (EW) systems (Stimson, 1998).

After World War II, there was extensive research and development of radar-directed weapon systems and secure communication systems. This saw EW-based receiving systems, particularly Electronic Support Measures (ESM) evolve to provide the location of an enemy's signal source (Sherman, 2000). The development of such EW intelligence functions occurred for several reasons. One reason for ESM localisation is because the correlation of source location with the electronic order of battle (EOB) can aid in identifying the signal being analysed. Another reason for ESM localisation concerns the ability to assist in real-time threat assessment. Real-time threat assessment provides an increase in situational awareness (SA) for both people and various on-board electronic systems (Vaccaro, 1993). With real-time situational awareness, effective prompt responses can be performed to avoid or minimise the impact of an opponent's attack. By having localisation and real-time information, both of these factors will assist

the mitigation of hostile electromagnetic aggression against GPS.

GPS which is used as a supplemental means of navigation by avionics systems also has a wide range of other important uses (Spencer et al., 2003). These diverse uses range from network time synchronisation, criminal investigations or even for archaeological discoveries. With the unabated penetration of GPS into civil infrastructure, the possible loss of GPS service could have damaging consequence to users (Baker, 2001). Since the inception of GPS as a supplemental means of navigation, the FAA became an organisation with a primary interest in ensuring the integrity and availability of GPS signals. While early FAA programs focussed on RFI prevention, it latter became clear the GPS would require a significantly greater real-time RFI source localisation capability (Geyer et al., 1999). Other RFI localisation research has shown that a network of sensors can provide an instantaneous estimate in relation to the direction-of-arrival (DOA) of RFI signals (Jan et al., 2001). The continuous real-time estimation ability of a network is a significant benefit compared to a single moving sensor platform. This capability is a substantial factor that should be considered in the design of RFI localisation systems. Consequently a network-centric framework should be chosen for the implementation of this novel localisation technique. For a network to provide highly accurate and real-time position estimation, the configuration of the network will be a significant factor to consider. Investigations concerning the orientation of networks that can be self-configurable or adaptive have also been undertaken (Bulusu et al., 2004).

The importance of GPS availability and its susceptibility to intentional interference has provided the motivation for this interference localisation research. The IDPELS research program has been developed with the objective of ensuring the integrity and availability of GPS signals required by aviation navigation systems and users.

2 Localisation

In performing localisation, there are various approaches that can be undertaken, each of which uses various parameters. Trilateration and Triangulation are two basic geolocation approaches that can be performed with networks. The respective parameters that are required for each of these geolocation approaches are *range* and *direction-of-arrival* (DOA). The estimation of these parameters is found to be a classical process with radar, sonar and geophysical exploration (Vanderveen, 1997).

With trilateration, possible techniques for estimating range can be based on signal strength or the transit time of the signal. Prevalently range based on transit time has been employed due to the greater accuracy that is

available. By finding the intersection of three range measurements, the location of the source is able to be unambiguously estimated. Localisation being performed with trilateration and triangulation is graphically presented in Figure 1.

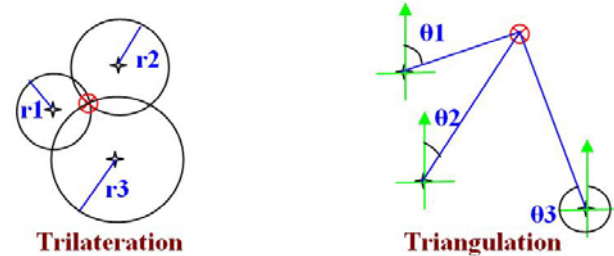


Figure.1 Geolocation using Range and DOA

In a hostile environment, localisation should be performed passively. This is to ensure the enemy can't apply retrospective electronic counter measures (ECM). This means there would only be one-way transmission, i.e. from the interference source. While the signals time of arrival (TOA) is simple to measure, there is no way of knowing when the signal was transmitted. This makes finding the transmission time infeasible. Only cooperative systems such as GPS are able to perform trilateration with one-way transmission.

Triangulation requires the DOA parameter to be used. A network consisting of two sensors is able to estimate the location of the source. Localisation based on DOA has been extensively applied in EW. This is because a hostile emitter can not easily alter the DOA parameter. As a result of the reduced susceptibility to ECM, DOA has become an invariant sorting parameter in the deinterleaving of radar signals for ESM (NAWCWD, 2003). This provides a strong foundation for IDPELS, which can determine the DOA parameters.

The inability of trilateration to resolve the transmission time in a hostile scene can be overcome by using Time Difference of Arrival (TDOA) localisation. The TDOA method requires the difference in a signals arrival time between baseline sensors to be measured. With this measurement, a *line-of-positions* (LOP) indicating where the source can be found is provided. This LOP is known as an Isochrone. The isochrone is an infinite hyperbolic line containing all possible locations where the emitter may be found (Boetcher et al, 2002). Various isochrones, corresponding to different TDOA are displayed in Figure 2. For localisation to be performed with TDOA, multiple baselines are required. The sources location will be at the intersection of the isochrones.

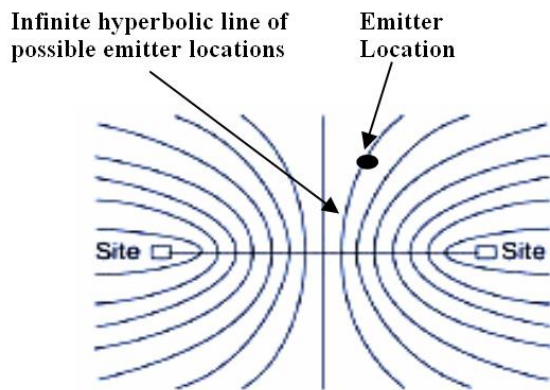


Figure.2 Hyperbolic Isochrone LOP

Another precise localisation techniques based on LOP intersection is the Frequency Difference of Arrival (FDOA) technique (Adamy, 2003). A desirable property of FDOA concerns the dynamics of network sensors. Here a similar difference with TDOA between baseline sensors is found, but with frequency and not time. The result of FDOA is a three dimensional surface defining all possible transmitter locations. By taking a planar cross-section, the curve is called an Isofreq. A set of isofreq curves for various frequency differences is shown in Figure 3, where the baseline sensors are moving in the same direction. As with TDOA, multiple baselines are required for the emitter location to be determined with FDOA.

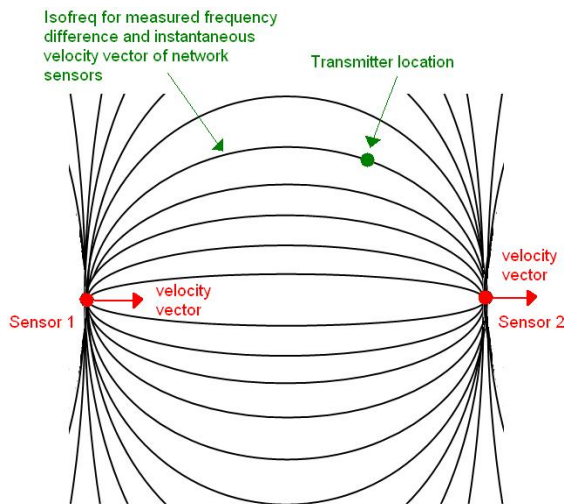


Figure.3 FDOA Isofreq LOP

While FDOA can be based on moving localisation sensors, the computational load associated with moving interference sources will most often be too large. FDOA is therefore generally used only on stationary or slowly moving targets. In practise, localisation systems will typically use multiple platforms. This allows multiple solutions to be considered. A system that combines TDOA and FDOA measurements can determine the precise localisation of an emitter location with a single

baseline, which is displayed Figure 4. The multiplicity of combined TDOA and FDOA solutions produces more accurate results over a wider range of operational conditions. IDPELS could enhance current localisation systems by providing multiple solutions.

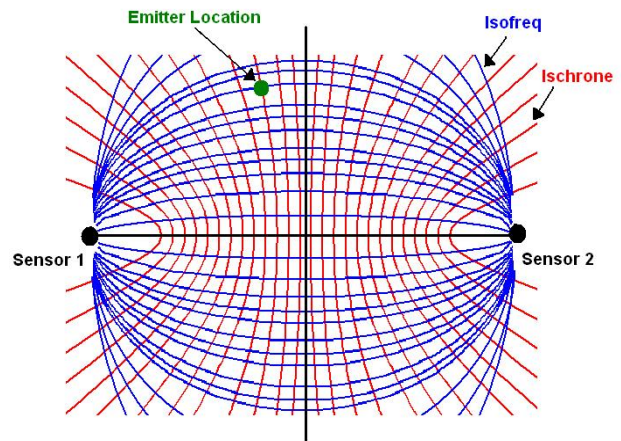


Figure.4 Single Baseline Localisation

There are also localisation techniques that are intended for an urban environment. Intended for picocell and microcell multipath scenarios, the database correlation method (Wolfe et al., 2002) compares a signals path-loss with a look-up table. Depending on the urban layout, the workload for adequate resolution in the look-up tables could be considerable. While any technique that contributes to interference signal localisation in an urban environment should be considered valuable, this database correlation method is not functional in hostile scenarios. In urban EW, there is no method to determine the hostile interference transmission power level. As a result, no path-loss calculations can be made. This renders the database method unsuitable for RFI localisation in an urban EW scene.

With IDPELS localisation being based on the DOA parameter, several common DF techniques will be briefly reviewed. The simplest DF method uses amplitude comparison and a mechanically rotated narrow-beam antenna. While highly accurate DF can be yielded, the probability of signal interception is relatively low (Tsui, 1986). To overcome this low probability of interception (LPI), an array can be configured to provide 360° coverage. This coverage is displayed with a four-quadrant amplitude DF system in Figure 5.

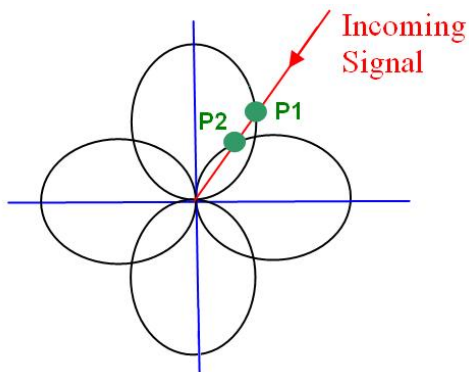


Figure.5 Monopulse DF System

By identifying the greatest (P1) and second greatest (P2) received power levels, the DOA can be determined. While amplitude comparison systems are frequency independent and able to cover wide bandwidths, the DOA estimation has a high probability of being contaminated by multiple signals simultaneously received. These systems also require calibration with signals that have known DOA information. Another common DF technique employed in EW is Phase interferometry shown in Figure 6.

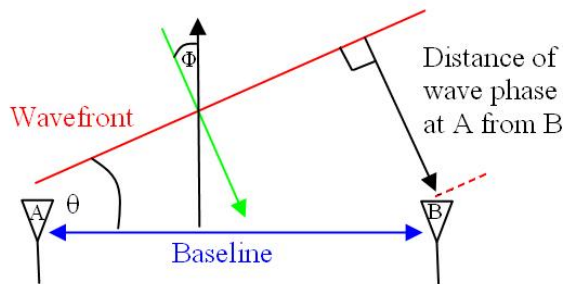


Figure.6 Phase Interferometry

Application of interferometry is however restricted to narrow-band signals. By measuring the phase difference between baseline sensors, the DOA can be determined via trigonometry. In most interferometric systems, the baseline is between 0.1 and 0.5λ . A baseline less than 0.1λ does not provide enough accuracy and if over 0.5λ ambiguous results are provided. There are many other DF finding techniques that could have been analysed, however a tutorial of many existing DOA estimation methods is provided by Godara (1996). A special class of these DF techniques that has high-resolution capabilities will conclude this discussion on localisation techniques.

The high-resolution DF methods are the subspace class of spectral estimation techniques that determine a signals DOA by computing the spatial spectrum and finding the local maximas of the spectrum. Subspace techniques require the noise and signal subspace to be extracted from the covariance matrix of signal observations. Eigen-analysis can be used on symmetrical matrices, or Singular

value decomposition (SVD) can be applied with asymmetric matrices. Both of these techniques will elliptically fit the observed covariance matrix (Therrien, 1992). Subspace based DF methods have the ability to surpass the limiting behaviour of classical Fourier-based DF methods. They are also referred to as super-resolution algorithms. The first subspace method was developed by Pisarenko (1973), which is referred to as Pisarenko Harmonic Decomposition (PHD). It should be noted that PHD does not directly estimate DOA, instead it determines frequency and power of real sinusoids in additive white noise. PHD is based on Caratheodory's theorem which is an indication of the required data-set size for dynamics of desired parameters to be captured (Sidiropoulos, 2001). The extension of PHD to DOA estimation was made by Schmidt (1982) with Multiple Signal Classification (MUSIC). One of the limitations associated with MUSIC is that the number of sensors must be greater than the number of signals present. The Joint Angle and Delay Estimation (JADE) method developed by Vanderveen (1997) can overcome this limitation, provided that signal fading is constant. JADE is based on multiple channel estimates and is best suited for TDMA systems where training signals are available. While blind estimation is possible with JADE, it is considered to have an undesirable intensive computational load. The simplicity of IDPELS in comparison with JADE in performing localisation is significant.

3 Research Objectives

From the localisation methods previously discussed, there are different limitations associated with each. These limitations range from the jammer/sensor dynamics to intensive computational loads. As noted with the combined TDOA/ FDOA method, multiple solutions and simplicity is the ultimate goal of localisation methods. The primary objectives of the IDPELS development were twofold;

- To investigate if an inverse EM propagation model can be used to provide an accurate localisation solution.
- To determine if an improved localisation can be made if detailed knowledge of the local terrain is known.

The new solution can be combined with other methods to provide multiple localisation solutions. Where networks already exist, the integration of IDPELS is also intended to be relatively simple, provided the receiving sensors are available. All that is required for the extra solution is the software for inverse diffraction propagation. The application of IDPELS with a moving single sensor is

also a possible configuration option if a network configuration is not possible.

4 Methodology

The principle methodology of IDPELS is based on applying inverse diffraction to the Parabolic wave equation propagation model (PEM). Fundamentally IDPELS involves measuring a received signal profile using a large antenna array or from a moving vehicle. This received field profile is then inverse propagated over the terrain profile. The source location is then identified by determining the field convergences. This classifies IDPELS as an inverse problem. With the development of IDPELS being based on the PEM and inverse theory, these two areas will be briefly reviewed.

The classification of inverse problems was defined by Keller (1976). Keller defines two problems as *inverses* of one another if the formulation of each involves all or part of the solution of the other. One of the problems has been extensively studied (forward problem), while the other is not so well understood (inverse problem). From a mathematical perspective, the decision of what is direct or inverse can be arbitrary. However in reference to physics (i.e. astronomy, mechanics, geophysics, wave propagation, etc) the decision of which problem is forward or inverse is not as arbitrary. Turchin et al. (1971) define forward problems in the physics domain as a process that is oriented along a cause – effect sequence. A corresponding inverse problem is associated with the reversed, effect – cause sequence. This means that a forward problem involves determining what observation will be made, given various parameters of the systems. An inverse problem will determine the unknown parameters of the system, from the observation made with respect to the system. Another important link that should be considered with forward and inverse problems is the model identification problem (Aster et al., 2004). The combination of these three factors of *Inverse Theory* is shown in Figure 7.

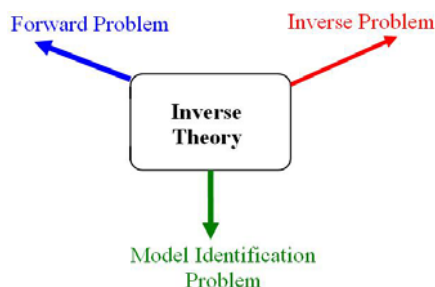


Figure.7 Inverse Theory

Models concerning the physical properties or processes of the systems are generally already known. Over history there have been many mathematicians and physicists who discovered and identified models for many different

systems. Various examples of such people include Gauss, Faraday, Maxwell and Einstein. The model used for IDPELS is the numerically efficient PEM which has been extensively researched and developed (Lee et al., 2000). With wave-propagation theory, a possible forward problem could be the computation of a field radiated by the source. A corresponding inverse problem could involve the determination of the source position from the knowledge of the radiated field. The solution of this inverse problem is the intended function of IDPELS, where the applied model is PEM.

The use of inverse theory has been extensively applied in imaging. The X-ray computer tomography (CT) technique developed in 1971 (Hounsfield, 1973) is the first case of medical images obtained as a process involving inverse problems. Other topics that have applied inverse theory include atmospheric sounding, particle scattering or seismology. One inverse problem that is similar to IDPELS is sonar-based and was studied by Zhu (2001). This sonar research was concerned with image reconstruction by back propagating the PEM model with a focus-marching procedure.

PEM being the model employed by IDPELS, was originally proposed by Mikhail Aleksandrovich Leontovich (1944) for long range radio propagation. In 1946, Leontovich together with Fock (1946) were able to provide a planar and spherical PEM solution. PEM involves approximating the elliptic Helmholtz wave equation with a parabolic partial differential equation to reduce the difficulties experienced in obtaining a Helmholtz solution. After the original development of PEM, application of PEM remained significantly restricted till the 1970's when computer technology had advanced to allow numerical solution to be developed. With advances in computer technology, Frederick D. Tappert and R. H Hardin (1973) introduced the parabolic approximation to oceanic acoustic propagation with the efficient Split-Step method that can propagate a signal with the Fast-Fourier-Transform (FFT). Claerbout (1976) later developed a finite difference PEM version for geophysical applications. Eventually PEM returned to radio propagation where propagation over a littoral environment (i.e. sea or flat terrain) was initially considered. With the development of faster algorithms, Kuttler and Dockery (1991) were able to adapt the split-step method (developed by Tappert) for radio propagation. Further application of PEM was made possible with researchers such as Barrios (1994), who tested the Tappert approach on a variety of irregular terrain profiles. Walker (1996) extended PEM for use in GPS propagation studies. Because radio domains are generally large with respect to the wavelength, approximation of Maxwell's solution must be made. With the efficiency and accuracy provided by PEM, it has largely superseded geometric optics and mode theory in

achieving the approximations. Current PEM applications are wide ranging.

Having provided a brief historical background to PEM, the process of applying inverse diffraction within PEM will now be provided. While finite difference or the Fourier split-step technique (FSS) can be used to solve the PEM, discussion will be restricted to FSS as this was the method employed in the code. One of efficiencies offered by PEM over other propagation models is that it is an open boundary problem. The numerical solution for an elliptical wave equation requires all boundary condition to be specified. This situation is not required by PEM. With FSS, the forward propagation provided by PEM involves marching an input field profile as shown in Figure 8.

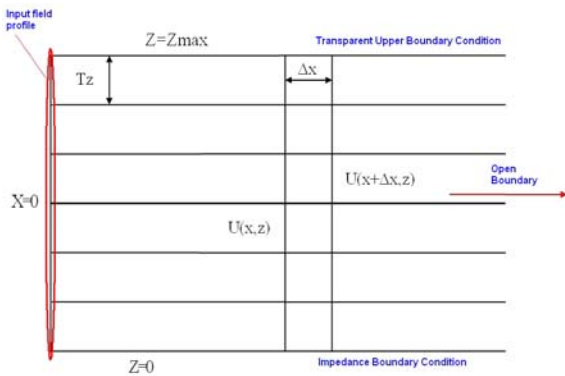


Figure.8 Open Boundary PEM Marching

The initial field profile is transformed into the angular spectrum via the fast Fourier transform (FFT). This angular spectrum is also referred to as the vertical spatial frequency spectrum as it involves the vertical component of the wavenumber. In the angular spectrum a propagator is multiplied with the transformed field profile, which effectively propagates the field to the next marching step. By inverse transforming the angular spectrum that has been propagated, the field at $x+\Delta x$ is able to be determined. The propagator term is also referred to as the Diffraction function, which is multiplied with the angular spectrum. The actual equation employed in PEM may slightly vary depending of factors that are considered in the model. One example could be to account for the atmospheric refractive index. A propagator that has been employed by Hawkes (2003) is shown in Eq. (1) and is based of the Fourier imaging domain method suggested by Eibert (2002).

$$D(p) = \exp \left\{ j\Delta x \left(\sqrt{k^2 - p^2} \right) \right\} \quad (1)$$

where,

- k is the spatial frequency spectrum
- p is the vertical spatial frequency spectrum
- Δx is the distance covered in a propagation step

With the previously discussed forward propagation problem, the diffraction term must be multiplied with the angular spectrum. A high level equation representing this forward propagation is provided by Eq. (2).

$$u(x + \Delta x) = T^{-1}(U \times D) \quad (2)$$

where,

- u is the envelope function of the signal
- U is the angular spectrum of the signal (i.e. FFT of u)

As IDPELS intends to apply inverse diffraction with back propagation in order to resolve the location of the source, it will divide the diffraction term with the angular spectrum. A high level equation representing inverse propagation is provided in Eq. (3).

$$u(x - \Delta x) = T^{-1}(U \div D) \quad (3)$$

Simulation results of inverse propagation with IDPELS are provided in the following section. The final factor that will be discussed with respect to PEM and IDPELS is associated with their upper boundary condition. To ensure there is no reflection of signal from the upper boundary, a windowing function must be applied. With IDPELS, the propagation domain height was doubled for application of the window. Figure 9 provides a display of the gradual signal attenuation in the window domain.

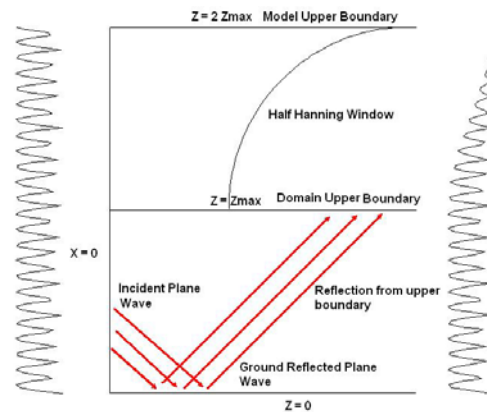


Figure.9 Hanning Window

The chosen window for PEM and IDPELS was the Hanning window. This note is important as it must be considered when viewing the IDPELS display of Figure 13. Further information concerning radio propagation with PEM, is provided by Levy (2000).

5 Simulation Results

Simulation results will be presented to demonstrate the theoretical feasibility of IDPELS to perform geolocation. When analysing IDPELS under simulation, the

generation of a forward propagation field with PEM is a prerequisite. The first example is a simple demonstration of IDPELS where the terrain profile is a single block with a height and width of 20m as shown in Figure 10. The transmission source is chosen to be on the far left-hand side of the block, and 20m above the block. A range of 100m was chosen for field analysis.

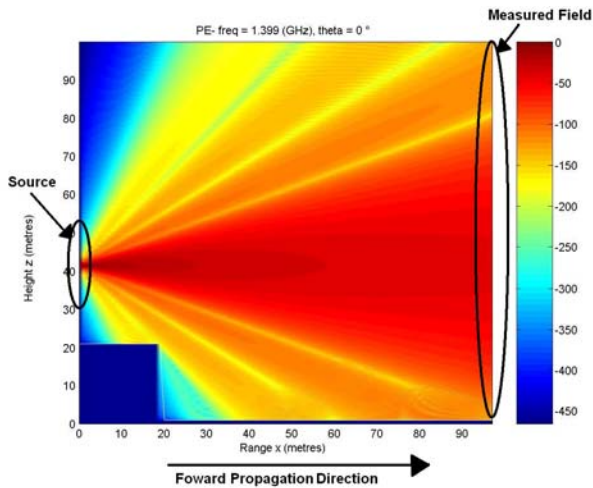


Figure.10 PEM – Block

The corresponding IDPELS result is shown in Figure 11.

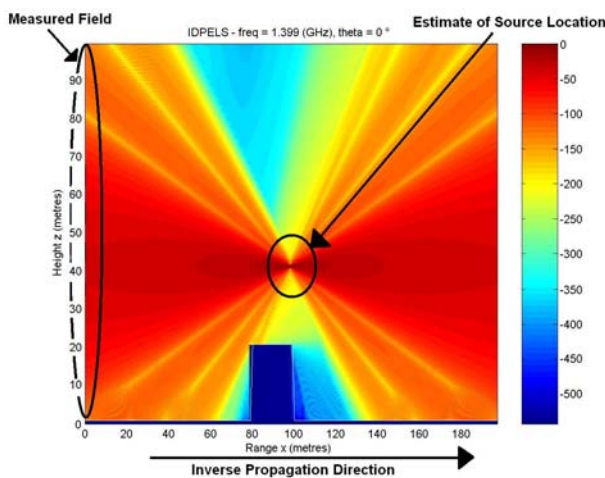


Figure.11 IDPELS – Block

The geolocation capability of IDPELS is clearly demonstrated in this simple scenario with unobstructed line-of-sight (LOS) paths. Where the inverse propagated field acutely converges, this is a highly accurate estimation of the sources locations. It should be noted that the inverse propagation range has been extended an extra 100m. It's also important to recognise that Figure 11 is a reversed view of the forward propagated field. This means the input field profile for IDPELS being on the left-hand side of Figure 11, is the same field profile located on the far right-hand side of Figure 10. This reversed view is present in all other simulated IDPELS

displays. The next demonstration of IDPELS is with respect to a wedge. In this evaluation of IDPELS, the source was chosen to be located 20m above the floor of the domain. A display of the forward propagated field is provided in Figure 12.

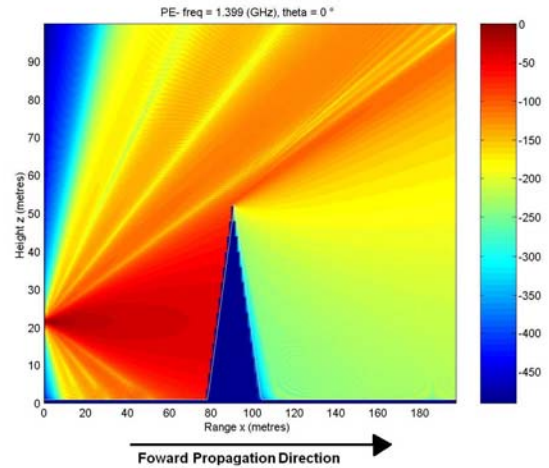


Figure.12 PEM – Wedge

The corresponding IDPELS result is shown in Figure 13.

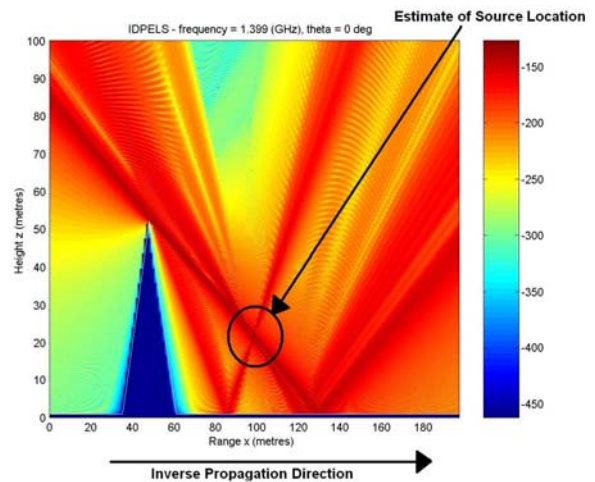


Figure.13 IDPELS – Wedge

This scenario was investigated to consider the feasibility of IDPELS when a *non-line-of-sight* (NLOS) will exist with inverse diffraction propagation. It should be noted that the position of the source at 20m height still allows LOS paths above 88m on the right-hand side of Figure 12. Measuring antenna elements will be required to be positioned at heights greater than 88m in this scenario. With the input IDPELS field profile corresponding to the right-hand of Figure 12, accurate localisation is again provided by IDPELS as indicated by the intersection of the ground reflected beam with the downward directed beam originating from the left-hand side of Figure 13. Please note that visual interpretation must be currently made to determine the location of the source.

With Figure 13 using an input field profile analogous to principles associated with Synthetic-Aperture-Radar (SAR), a further investigation was made with a reduced set of antenna measurements to examine how a network configuration will affect localisation results. A 9-element uniform-linear-array (ULA) configuration is applied to the measure field profile from the right-hand side of Figure 12. The corresponding IDPELS field is shown in Figure 14.

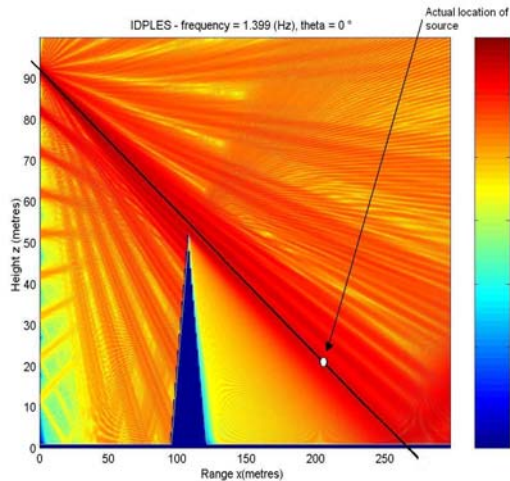


Figure.14 Network Configuration

With the array configuration, there is no definite indication of the interference source location. Only a LOP is provided by the sensor that experienced a LOS to the source. It should also be noted that the sensors with a NLOS to the source did converge to the apex of the wedge that shadows the source. This indication can provide assistance for localisation being conducted in an urban environment.

The next evaluation of IDPELS was to consider its effectiveness against multiple interference sources. A display of three sources simultaneously transmitting interference signals is provided in Figure 15.

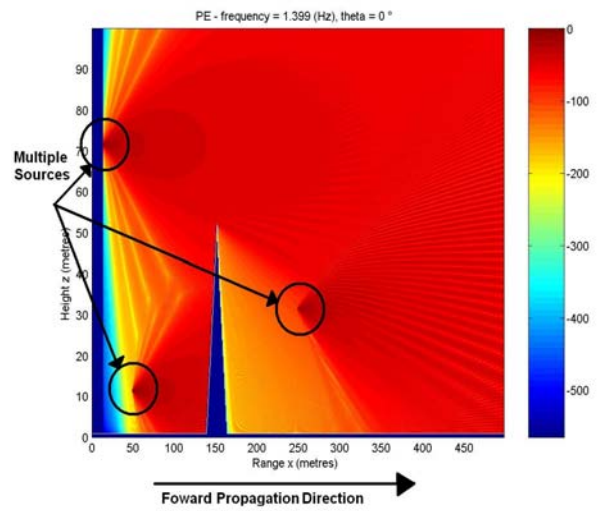


Figure.15 PEM – Multiple Sources

With multiple sources, one source was positioned to be completely obstructed by the wedge. The IDPELS input has no account of this source. Figure 16 shows the IDPELS field generated for the multiple sources in Figure 15.

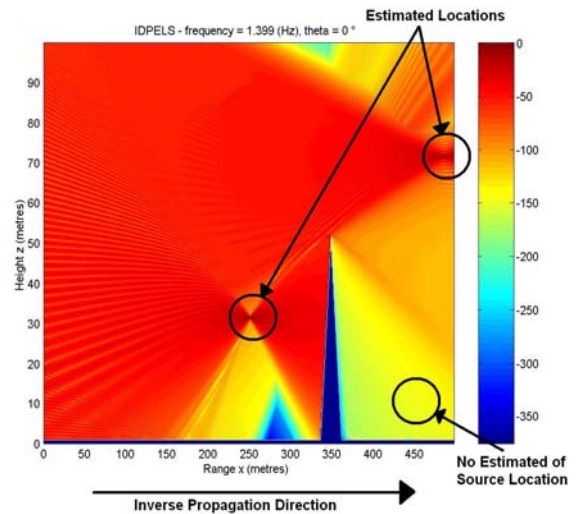


Figure.16 IDPELS – Multiple Sources

All sources with a LOS were able to be localised. This is indicated by the field convergence at their relative positions in Figure 16. The source that did not have a LOS was not able to be localised.

While the geolocation feasibility of a network based IDPELS was not demonstrated in Figure 14, this was due to the NLOS orientation of the source. A demonstration of IDPELS functionality with an array configuration of two antenna array elements is provided in Figure 17.

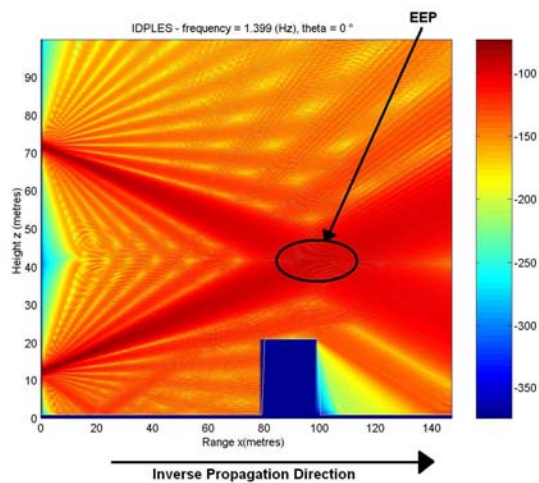


Figure.17 Two-element array configuration

The accuracy of the estimated source location in Figure 17 is subject to a large elliptical-error of probability (EEP) compared with Figure 11. This localisation error can however be reduced according to the array configuration. Factors that govern the localisation error are,

- number of sensors used
- sensor aperture

The localisation error is reduced by increasing either of these two factors. Figure 18 shows this affect where there is an increase in the number of field sensors used, all of which have a relatively larger aperture.

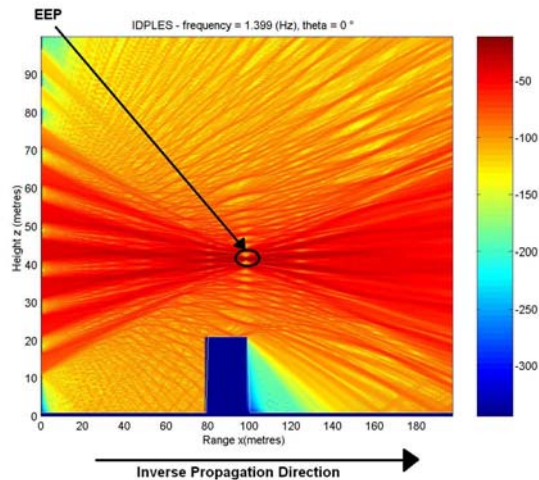


Figure.18 Reduced Localisation Error

6 IDPELS Field Trials

To test the practical application of IDPELS, field trials were conducted in collaboration with the Navigation Warfare, Electronic Warfare and Radar Division of DSTO, Edinburgh, South Australia. The transmission

source was a 1.399GHz tone signal being transmitted from a helix antenna as shown in Figure 19.



Figure.19 Helix Transmission Antenna

Two sets of data were collected. One data set concerns the transmission source approximately 13km east of Truro, SA ($34^{\circ}25'2.85''$ S, $139^{\circ}14'10''$ E) at the base of the Mt Lofty Ranges (Figure 20). The other data set has the transmission source positioned at DSTO Radio Research Station ($34^{\circ}43'26.2''$ S, $138^{\circ}32'15.6''$ E) at St Kilda, SA (Figure 21).



Figure.20 Mt Lofty Base Trials



Figure.21 St Kilda Trials

The input field profiles for IDPELS were recorded based on the SAR analogy. An overview of the signal recording process is shown in Figure 22.

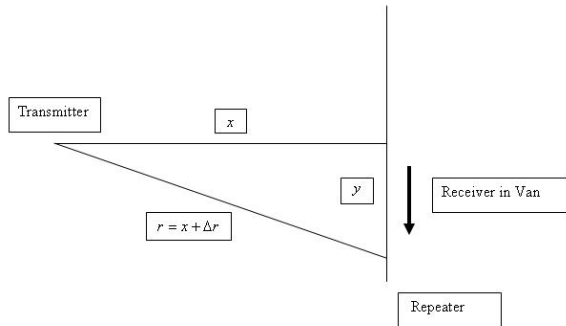


Figure.22 Signal recording process

With Truro data sets, Figure 23 is a display of the IDPELS field where the signal was recorded in a moving van approximately 4.8kms from the transmission site on Baldon road. Figure 24 corresponds to data recorded on Woolshed road, approximately 5.9kms from Baldon rd.

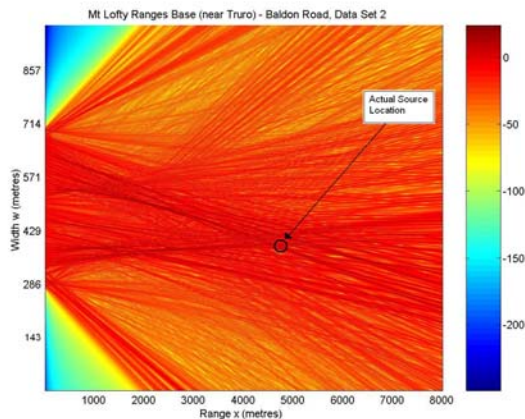


Figure.23 Signal Recorded on Pine Creek Track

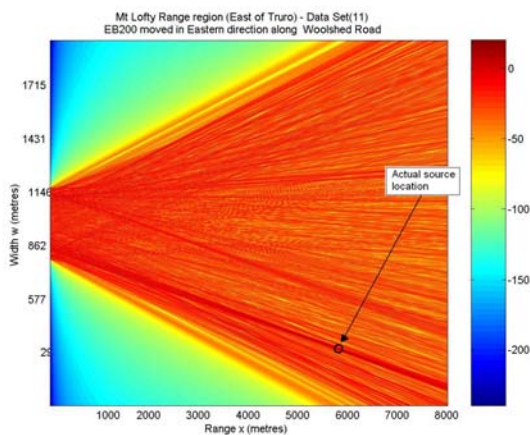


Figure .24 Signal recorded on Woolshed Road

These IDPELS results have not provided a solution as accurate in comparison with simulation results. While data recorded on Pine Creek Track has shown a clear convergence region, Woolshed road data only provided a LOP. Various causes for the solution degradation include noise, clutter, multipath factors and a non-linear phase shift in the recorded signal. A factor that will have contributed to a non-linear phase shift is the road section not being perfectly straight. While scattering and reflection will also have had some impact on the recorded signal, modelling of obstacles was not incorporated into the prototype IDPELS code. This is because the selected region was considered to approximate a littoral environment. A photo of the general terrain profile at the base of the Mt Lofty ranges is shown in Figure 25.



Figure.25 Littoral Mt Lofty Base Region

A photo of the McEvoy road section used to record the test signal is shown in Figure 26. The displayed repeater was used to account for Doppler shift generated by the movement of the van.



Figure .26 McEvoy Road

The displayed IDPELS result concerning McEvoy road shown in Figure 27 has similar visible field convergence to Pine Creek Track. The range of McEvoy rd from the St Kilda Radio Research Station is approximately 3.9kms.

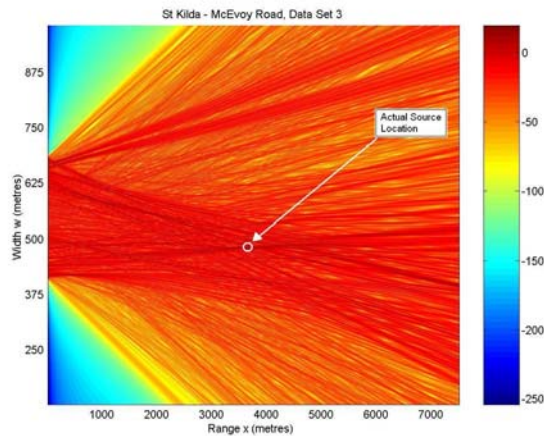


Figure.27 McEvoy Road

The IDPELS field profile corresponding to data recorded on Pt Gawler road is shown in Figure 28. The range to Pt Gawler approximated 10.8kms.

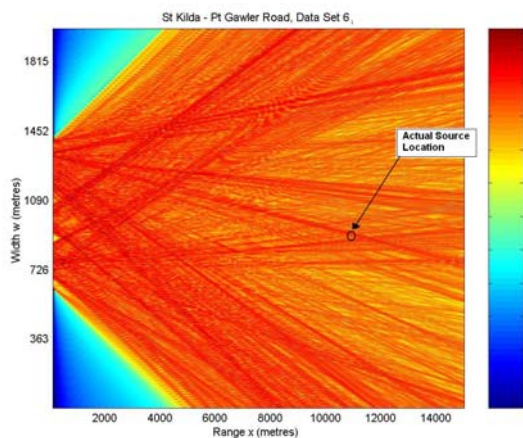


Figure.28 Pt Gawler Road

The localisation result for Pt Gawler road has many field convergent regions. This demonstrates Rayleigh fading where there is no dominant wave component. The terrain profile for this region was also considered to be semi-urban. Van speeds were also greater compared with all data sets. The general driving pattern was initiated with a steady acceleration and maintain at a constant speed. Near the end of the recording session, a steady de-acceleration was applied to being completely stationary. Speeds reached on Pt Gawler road varied between 80 – 100 km/hr, while all other data sets varied between 10 – 30 km/hr.

Conclusion

The simulation results of IDPELS has demonstrated that inverse diffraction propagation is capable in providing a geolocation estimate to multiple sources that have a direct LOS to network sensors. While IDPELS was unable to geolocate a source that only has a NLOS, it could indicate the direction to objects that shadow the source. This could be beneficial in an urban environment. A network configured IDPELS was also shown to improve accuracy with the number of sensors, and sensor aperture.

Field trial results demonstrating the practical feasibility of inverse diffraction propagation were based on a SAR analogy for generation of the input field profile. Trials conducted in regions that approximated a littoral environment indicated the method to be feasible. The trials however also showed that great care must be taken to ensure the phase-shift in the recorded signal profile is linear. Other factors such as multipath propagation and noise also degraded localisation accuracy. It should also be noted that given the experimental nature of the trials, experienced conditions and measurements conducted were not ideal.

For localisation to be performed with novel *inverse diffraction* propagation methods, further research and development is required for an efficient localisation method to be readily available and operational.

References

- Adams M. D. (1999): *Sensor Modelling, Design and Data Processing for Autonomous Navigation*. World Scientific Publishing, Singapore.
- Adamy D. (2003): *Precision Emitter Location by FDOA*. Journal of Electronic Defense – EW 101, January.
- Aster R.C.; Borchers B.; Thurber C. (2004) *Classification of Inverse Problems*. in: Parameter Estimation and Inverse Problems, Academic Press, New Mexico Technology, 1-4.
- Baker C. (2001): *GPS Vulnerability to Interference*. SatNav 2001, Canberra, ACT, Australia.
- Barrios A. E. (1994): *A terrain parabolic equation model for propagation in the troposphere*. Antennas and Propagation, IEEE Transactions on, 42(1): 90-98.
- Biacs Z.; Marshall G.; Moeglein M.; Riley W. (2002): *The Qualcomm/SnapTrack Wireless-Assisted GPS Hybrid Positioning System and Results from Initial Commercial Deployments*. ION GPS 2002, Oregon Convention Center, Portland, Oregon.
- Boettcher P.; Shaw G.; Sherman J. (2002): *A Distributed Time-Difference of Arrival Algorithm for Acoustic Bearing Estimation*. SensIT PI Meeting, Santa Fe, New Mexico.
- Bulusu N.; Heidemann J.; Estrin D.; Tran T. (2004): *Self-Configuring Localization Systems: Design and*

- Experimental Evaluation. ACM Transactions on Embedded Computing Systems (ACM TECS)*, 3(1): 24-60.
- Claerbout J. F. (1976): *Fundamentals of Geophysical Data Processing with Application to Petroleum Prospect*. McGraw-Hill. New York.
- Eibert T. F. (2002): *Irregular terrain wave propagation by a Fourier split-step wide-angle parabolic wave equation technique for linearly bridged knife-edges*. Radio Science, 37(1).
- Enge P.; Jan S-S. (2001): *Finding Source of Electromagnetic Interference (EMI) to GPS Using a Network Sensors*. ION National Technical Meeting Proceedings, Westin Hotel, Long Beach, California.
- Geyer M.; Frazier R. (1999): *FAA GPS RFI Mitigation Program*. ION GPS-99, 12th International Technical Meeting of the Satellite Division of the Institute of Navigation, Nashville Convention Center, Nashville, Tennessee.
- Godara L. C. (1996) *Limitations and capabilities of direction-of-arrival estimation techniques using an array of antennas: A mobile communication perspective*. IEEE International Symposium on Phased Array Systems and Technology, Boston, Massachusetts, USA, 327 – 333.
- Hardin R. H.; Tappert F. D. (1973): *Applications of the split-step Fourier method to the numerical solution of nonlinear and variable coefficient wave equations*. Society of Industrial and Applied Mathematics (SIAM), 15(423).
- Hawkes R. M.; Baker C. P. (2003): *Tropospheric Propagation Model for Land Warfare*. Land Warfare Conference 2003, Adelaide Convention Centre, Adelaide, Australia.
- Hounsfield G. N. (1973): *Computerized transverse axial scanning (tomography). Part I: Description of system. Part II: Clinical applications'*. British Journal of Radiology, 46(1016-1022).
- Keller J. B. (1976): *Inverse Problems*. American Mathematical Monthly, 83(107 – 118).
- Kuttler J. R.; Dockery G. D. (1991): *Theoretical description of the parabolic approximation/Fourier split-step method of representing electromagnetic propagation in the troposphere*. Radio Science, 26(2): 381-393.
- Lee D.; Pierce A. D.; Shang E-C. (2000): *Parabolic Equation Development in the Twentieth Century*. Journal of Computational Acoustics, 8(4): 527-637.
- Leontovich M. A. (1944): *A method of solution of problems of electromagnetic wave propagation along the earth's surface*. Bulletin de l'Academie des Sciences de l'URSS, ser. phys., 8(1): 16.
- Leontovich M. A.; Fock V. A. (1946): *Solution of the Problem of Propagation of Electromagnetic Waves along the Earth's Surface by the Method of Parabolic Equations*. Journal of Physics of the USSR (In English), 10(1): 13-24.
- Levy M. (2000): *Parabolic Equation Methods for Electromagnetic Wave Propagation*. London, Institution of Electrical Engineers. 352.
- NAWCWD (2003): *Signal Sorting Methods and Direction Finding*. in: Electronic Warfare and Radar Systems Engineering Handbook, Avionics Department of the Naval Air Warfare Center Weapons Division, Point Mugu, California, 5-8.1 - 5-8.9
- Pisarenko V. F. (1973): *The Retrieval of Harmonics from a Covariance Function*. Geophysical Journal of the Radio Astronomical Society, 33(347-366).
- Schmidt R. O. (1982): *A Signal Subspace Approach to Multiple Emitter Location and Spectral Estimation*. Ph.D. dissertation. Stanford University, Stanford, California.
- Sidiropoulos N. D. (2001): *Generalizing Caratheodory's Uniqueness of Harmonic Parameterization to N Dimensions*, IEEE Transaction on Information Theory, 47(4): 1687 – 1690.
- Spencer T. A.; Walker R. A. (2003): *A Case Study of GPS Susceptibility to Multipath and Spoofing Interference*. Australian International Aerospace Congress incorporating the 14th National Space Engineering Symposium 2003, Brisbane, Queensland, Australia.
- Stimson G. W. (1998): *Electronic Counter Counter Measures (ECCM)*. in: *Introduction to Airborne Radar*. SciTech Publishing, Inc, Mendham, New Jersey, 457 – 468.
- Therrien C. W. (1992): *Discrete Random Signals and Statistical Signal Processing*. Englewood Cliffs. New Jersey, Prentice Hall Signal Processing Series.
- Tsui JB-Y. (1986): *Parameters Measured by EW Receivers*. in: *Microwave Receivers with Electronic Warfare Applications*, John Wiley & Sons, New York, 81 – 112.
- Turchin V. F.; Kozlov V. P.; Malkevich M. S. (1971): *The use of mathematical-statistics methods in the solution of incorrectly posed problems*. Soviet Physics Uspekhi, 13(681-840).
- Vaccaro D. D. (1993): *Passive Direction Finding and Geolocation*. in: *Electronic Warfare Receiving Systems*, Artech House, Boston - London, 221- 259.
- Vanderveen M. C. (1997): *Estimation of Parametric Channel Models in Wireless Communication Networks*. Ph.D. dissertation. Scientific Computing and Computational Mathematics, Stanford University, Stanford.
- Volpe National Transport Systems (2001): *Vulnerability Assessment of the Transportation Infrastructure Relying on the Global Positioning System*. Office of the Assistant Secretary for Transportation Policy, U.S. Department of Transport, 29 August.
- Walker R. A. (1996): *The Operation and Simulation of GPS Positioning in Harsh Environments*. Electrical and Electronic Systems Engineering, Queensland University of Technology, Brisbane.
- Weaver S. E.; Baird L. C.; Polycarpou M. M. (1996): *An Analytical Framework for Local Feedforward Networks*. International Symposium of Intelligent Control, Dearborn, Michigan.
- Wofle G.; Hoppe R.; Zimmeramn D.; Landstorfer F. M. (2002): *Enhanced Localization Technique within Urban*

and Indoor Environments based on Accurate and Fast Propagation Models. European Wireless, Florence, Italy.

Underwater Targets. Journal of Computational Acoustics, 9(3): 1067-1078.

Zhu D. (2001): *Application of a Three-Dimensional Two-way Parabolic Equation Model for Reconstructing Images of*