A New Differential Positioning Technique Applicable to Generic FDMA Signals of Opportunity

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BIOGRAPHY

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Robert Mason is Technical Director of Terrafix Limited; integrators and designers of navigation and communications systems. A physics graduate from Imperial College London he obtained his PhD in communications and neuroscience from Keele University in 1981 and was involved in design of complex systems at Marconi Space and Defence Systems before joining Terrafix. He is a chartered scientist and physicist and a member of the Institute of Physics. His research interests include novel navigation techniques, software defined radio (SDR) and cognitive systems.

Joseph Harrison is principal radio frequency (RF) design engineer at Terrafix Ltd. He has been with Terrafix for twenty five years and has worked on a variety of design and research projects including mobile network radios, GSM modems and radio modems. Before working for Terrafix Ltd he worked for Marconi Space and Defence and Marconi Secure Radio Systems working on a variety of electronic warfare (EW) and electronic countermeasures (ECM) projects.

ABSTRACT

A differential positioning technique is proposed that is capable of exploiting the many radio frequency (RF) signals that are transmitted using frequency division multiple access (FDMA). The technique is designed to operate on ‘signals of opportunity’ (signals that are designed for purposes other than navigation), and requires no knowledge of the modulation format or signal content. Example FDMA signals of opportunity include amplitude modulated (AM) broadcast signals, frequency modulated (FM) broadcast signals, and television signals. In principle, the system can operate simultaneously on these different types of signals, maximizing performance by exploiting heterogeneous signal qualities and using whatever signals are available at a particular location. As a result, the technology has the potential to provide positioning in Global Navigation Satellite System (GNSS) deprived environments, such as in urban canyons, and deep indoors.

The proposed positioning technique operates by bringing portions of a signal received at reference and user locations together and adaptively correlation testing them. The correlation-testing is used to jointly estimate the differential time offset (DTO) and the differential frequency offset (DFO). In order to improve accuracy the DTO measurements are Doppler-smoothed using the DFO measurements. The DTO measurements are used to calculate ranging measurements that are used to obtain a position.

The concept is experimentally validated on AM broadcast signals in the medium frequency (MF) and low frequency (LF) bands. Preliminary results indicate that the system provides a position solution in difficult environments, such as indoors. It is expected that expanding the system to incorporate more signals will result in significant performance gains.

1 INTRODUCTION

Global Navigation Satellite Systems (GNSS) have evolved to be the positioning system of choice for many applications. However GNSS signals are susceptible to obstruction, interference and jamming. Signal obstruction is a particular problem indoors, underground and in deep urban canyons. Sources of unintentional interference include adjacent-band satellite communications, harmonics of television transmissions and remote locking devices, radar and terrestrial aircraft navigation signals [1].

Deliberate GNSS jamming has historically been a military issue. However the introduction of GNSS-based law enforcement, high-value asset tracking and, potentially, road user charging have made jamming of interest to criminals. Low-cost jammers, covering all GNSS bands, are now easily obtainable via the Internet. Most of these jammers have a very short range; however, some can disrupt GNSS reception over tens of kilometers [2].

A further source of GNSS disruption is space weather. During solar maxima, ionospheric scintillation can disrupt reception of most GNSS signals in polar and equatorial regions at certain times of day [3], while a solar flare can knock out all GNSS reception over the side of the Earth facing the sun [4].

Therefore, to maximize the robustness of a position solution, in terms of availability, continuity and integrity, it is necessary to augment GNSS with one or more dissimilar positioning technologies. These technologies must operate independently of GNSS and be subject to different failure modes.

Navigation and positioning technologies may be divided into two categories: dead reckoning and position fixing [5]. Dead-reckoning technologies measure the distance traveled and direction. Examples include inertial navigation, odometers, magnetometers and Doppler radar and sonar. Positioning using dead reckoning requires a known starting point and the errors are cumulative, so the position error grows with time. However, there is no reliance on landmarks.

In position fixing, the user position is determined by measuring the range or direction to landmarks, or both, at known locations (or by being in close proximity to the landmark). Thus, for a position solution to be obtained, sufficient known landmarks must be available. However, there is no degradation in accuracy with time. Position fixing techniques may be divided into two further categories: radio navigation and feature matching [5]. In radio navigation systems, the radio transmitters normally constitute the landmarks and their radio signals are used for range and/or direction measurement. Signals are identified by frequency and/or aspects of their modulation. Examples include GNSS, Loran and ultrawideband positioning systems.

Feature matching systems use characteristics of the environment as landmarks. Examples include buildings, roads, field boundaries and terrain height. Traditional "map and compass" navigation is an example of feature matching. Automated feature-matching systems must both match features to a database and determine the ranges to and/or directions of those features. Feature-matching sensors include optical and infra-red imaging sensors, laser scanners and radar.

Signals of opportunity is a generic term for radio signals that may be used for positioning, but are not specifically designed or modified for that purpose. These will typically be broadcasting or communications signals. Note that, by convention, signals already used by the user equipment for communications purposes are not classed as signals of opportunity. A key benefit of using signals of opportunity is cost as there is no need to install additional transmission infrastructure. A further benefit, for military applications, is that signals that could identify the presence of a military operation are not required. However, a major drawback is that the transmissions will not have been optimized for positioning. For example, transmitters will typically not be time synchronized and the signal modulation will not have been optimized for ranging accuracy.

Television and radio broadcasts are often used as signals of opportunity because the modulation format of these signals is publicly known and transmitter locations (to a few tens of meters) are publicly available. In recent years, positioning using both digital television [6, 7] and digital audio broadcasting (DAB) [8, 9] signals has been demonstrated. Additionally, a technique that is capable of simultaneosly exploiting cellular, digital television and GNSS signals has been developed [10].

This paper focuses on a generic positioning technique that is applicable to all signals that use frequency division multiple access (FDMA). Example FDMA signals include frequency modulated (FM) broadcast signals, television signals and differential global positioning system (DGPS) signals. In addition, the technique can incorporate communication signals, even though knowledge of the modulation details may be proprietary [10].

The technique does not require time synchronization to be included in the signals, and the system is differential, comparing measurements made at a rover or mobile receiver at an unknown location with a reference or base receiver at a known location. Signals are captured simultaneously at the reference receiver and user locations. Signature parameters of the signals are then brought together for analysis to yield measurements of the differential timing offsets (DTO) (between the two receivers) of each signal. These DTO measurements can subsequently be processed to give the position of the user.

This paper validates the concept on amplitude modulation (AM) radio broadcasts in the medium frequency (MF) and low frequency (LF) bands. A wide range of AM radio broadcasts are currently available in most countries. In the LF and MF bands, the predominant ground-wave propagation mode offers better coverage in remote areas and over sea than higher frequency signals. Signals in these bands are also difficult to jam over large areas as high transmission powers are used to overcome relatively inefficient receiver antennas. However, not all locations are served by a sufficient number and geometry of AM radio broadcasts to generate a position solution. Therefore, a practical signals of opportunity positioning system would use AM signals alongside other signals, such as frequency modulation (FM) radio broadcasts and television. Alternatively, a hybrid positioning system, combining differential AM ranging with differential Loran could be used. This would be useful in areas where there are currently insufficient Loran signals to meet the accuracy and integrity requirements.

AM radio positioning systems previously reported in the literature [11, 12, 13] have used carrier phase measurements to generate a position solution. A sub-25 meter accuracy has been reported for such systems under optimum conditions. However, there are problems. Range derived from carrier phase has an ambiguity equal to the wavelength of the signal (200 - 550 m in the MF broadcast band). To resolve this ambiguity either the user must start at a known position [11] or a large number of signals must be receivable to enable consistency-based ambiguity resolution [12]. Furthermore, it is necessary to calibrate for azimuth-dependent phase biases at the transmitter and ground-wave propagation effects. However, the greatest limitation is that absorption and re-radiation of the signals produces large random phase variations indoors, in deep urban areas and near transmission lines [13]. Consequently, the derived position may suffer from unreliability and rapid deterioration in adverse environments.

2 CONTEXT AND OVERVIEW

This paper explores positioning using DTO measurements obtained by correlating modulation information between the reference and user receivers over intervals of half a second. These measurements are unambiguous and are affected much less by re-radiation effects. However, they are much noisier than carrier-phase derived DTO. The modulation-based DTO measurements may be used in four different ways to form a navigation solution:

1. A snapshot position solution using only single-epoch modulation-based DTO measurements. This is equivalent to a snapshot GNSS solution using differential code measurements only.
2. A snapshot position solution using several epochs of modulation-based DTO measurements that have been smoothed using either time-differenced carrier-phase DTO or differential Doppler shift. This is equivalent to a snapshot GNSS solution using differential carrier-smoothed code.
3. An extended Kalman filter (EKF)-based position solution using both modulation-based DTO measurements and either time-differenced carrier-phase DTO or differential Doppler shift measurements. This is equivalent to an EKF GNSS solution using both differential code and differential carrier measurements.
4. A snapshot position solution using carrier phase-based DTO measurements with a modulation-based solution used to bound the ambiguity resolution search space, enabling the ambiguities to be resolved with fewer signals. This is equivalent to a real-time kinematic (RTK) differential carrier phase-based GNSS solution.

This paper focuses on the second option, which uses multiple modulation-based DTO measurements that are smoother by Doppler shift measurements. The first method has been investigated in [14], and the remaining methods will be described in future publications.

The method presented here for obtaining range information by modulation correlation is potentially applicable to any signal with sufficient information contained within its modulation. It is not even necessary to know the modulation format of that signal provided it may be separated from its neighbors. Consequently, it forms the basis of a potential use-anywhere heterogeneous-signal radio positioning system, which can opportunistically use whatever FDMA signals happen to be available at a particular location.

This paper is organized as follows. Section 3 introduces the concepts of the system; Including a description of the system and an overview of the process of obtaining a position from the measurements. Section 4 presents results obtained from simulations that have been designed to assess the quality, across Great Britain, of positioning that can be obtained from the AM LF and MF broadcast band. Section 5 presents details of a series of preliminary trials. This includes details of the demonstration apparatus and of the system's positioning performance during the trials. Conclusions and future work are presented in Section 6 .

3 SYSTEM DESIGN

3.1 System Concept

The technique is designed to operate on signals that have no synchronization content; hence, any positioning system must be differential: comparing measurements made at a rover, at an unknown location, with a reference, at a known location.

A representation of the system is presented in Fig. 1, which shows a reference receiver, R, a roving receiver, A, and a set of N transmitters, $\{T_1, T_2 \ldots T_N\}$. Also shown in the diagram is a transmission channel that allows information transfer between the reference and the roving receivers.

The transmitters emit a set n of signals that have the potential to be used for position signals that shall be referred to as candidate signals. It is commonplace for more than one transmission to originate from the same transmitter site. Therefore the number of candidate signals tends to be greater than the corresponding number of transmitter sites (in general $n > N$).

Only one mobile receiver and one reference receiver is shown in the figure. However, it is conceivable to extend the system to incorporate any number of rover and reference stations. Moreover, it is possible to blur the distinction in roles of the two stations. For example, stations could offer dual reference/rover functionality, as with network or relative positioning systems [5]. Without loss of generality, only a single rover and single reference receiver are considered in this paper.

Signals are captured simultaneously at the reference receiver, R, and rover, A. Signature parameters of the signals are then

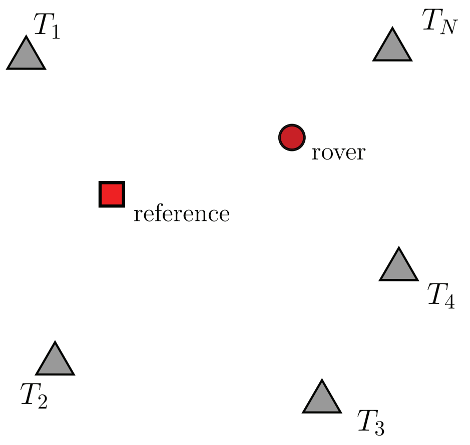


Figure 1: System Diagram

brought together for analysis to yield DTO measurements and subsequently a position.

For real-time operation it is necessary to introduce a transmission channel, or datalink, between the base and rover receivers. The chosen direction of the datalink is largely application driven. For example, for tracking applications the system operator desires knowledge of the user, or participant. In this scenario it is possible to use a datalink that operates from the rover to reference receiver – subsequent analysis being performed at the latter. Alternatively, for navigation applications, a datalink from the reference to the rover can be used – subsequent analysis being performed by the user. This allows the system to operate with an unlimited number of participants. This mode of operation is also suitable for covert applications, where the user does not wish to reveal his or her location by radiating a signal.

3.2 System Architecture

A differential signal of opportunity (SOP) system operates by simultaneously capturing multiple signals. In early SOP systems (see, for example, [11, 12, 15]) the process of simultaneous capture was accomplished by arranging a set of narrowband receiving channels in parallel. For these systems, each narrowband receiver was tuned to receive only one signal at any one time. In addition, reference and rovers were coordinated so that they were tuned to the same sets of signals. For practical reasons the number of receiving channels (and hence the number of signals that could be processed) was extremely limited.

The system presented here adopts an alternative arrangement whereby a single wideband receiving apparatus is employed at both reference and rover. The wideband approach has several advantages over a narrowband approach. Most notably, a wideband receiver is capable of capturing an entire band, or bands, allowing it to simultaneously receive all embedded signals. For instance, the demonstration apparatus, presented in Section 5, is capable of capturing over one hundred channels that lie within the AM LF and MF broadcast bands.

Shown in Fig. 2 is a representation of the system architecture. A description of the elements are as follows:

- **Radio Frequency (RF) front-end,** consisting of an omnidirectional wideband antenna, followed by analog signal conditioning components. The conditioning components allow the desired band (containing many signals-of-opportunity) to pass through, while rejecting out-of-band frequencies. This is followed by gain control used to attenuate or amplify the incoming band.
- **Analogue-to-Digital Converter (ADC),** used to convert the continuous-time analogue signal into a discrete-time representation. The ADC outputs a sequence of digital samples, quantized to levels of finite-precision. The sample rate of the ADC must be high enough to adequately encompass the whole band. This, in general, means that sample rate is at least twice as high as the input bandwidth to satisfy the Nyquist–Shannon sampling theorem.
- **Digital Signal Processing (DSP)** is used to perform discrete-time processes that, ultimately, yield timing information and a position fix. Important functions include the extraction of timing information (Section 3.3), and implementation of the positioning algorithm (Section 3.4). At several stages during DSP operations the SOP transmitter almanac is queried to retrieve supplementary information.

The RF front-end may encompass automatic gain control (AGC) to attenuate or amplify the incoming band to the correct level. The specification of the ADC is an important factor influencing the noise performance of the receiving apparatus. Of particular importance is the dynamic range, which is the ratio between the largest and smallest possible signal amplitude that can practically be received. This must be sufficient so that the apparatus can accommodate the large variation in signal strength that occurs with terrestrial radio signals. This is typically much larger than, for example, GNSS signals when they are received on earth.

Digital signal processing can be implemented in hardware or software. Hardware implementation is necessary for high-rate processes, however, lower rate processes can be successfully implemented in software.

The datalink that connects the reference and rover receivers is also shown in Fig. 2. As explained in Section 3.1, this is used to send encoded signal parameters from the reference receiver to the roving receiver. In the diagram, the position fix is delivered at the roving receiver location. However, for certain certain applications, the direction of the datalink would be reversed to enable the position fix to be calculated at the reference receiver. To avoid confusion, the demonstration system, further detailed in Section 5.1, differs from the design presented here. For example, the demonstration apparatus implements non-real-time

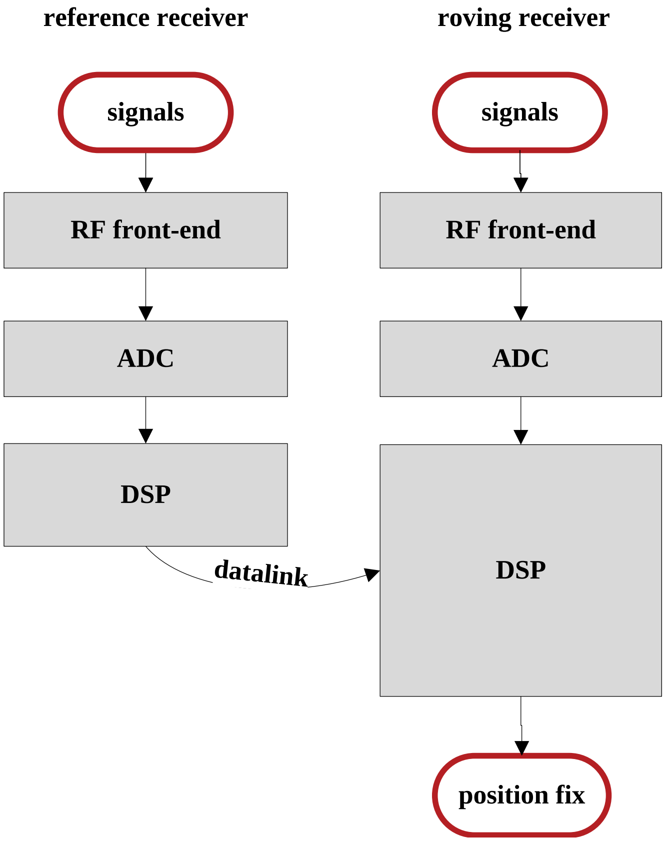


Figure 2: System Architecture

DSP on one PC, post-capture. This bypasses the need for a datalink and reduces hardware requirements.

3.3 Estimation of Differential Timing Offsets

The estimation of differential timing offsets between versions of the same signal that have been received at reference and rover locations is a key part of the DSP operation. It is achieved by forming a cross ambiguity function (CAF) to correlation-test signal portions.

The cross ambiguity function technique is also employed by some GPS receivers for code-correlation. In order to yield measurements, GPS signals are correlated with locally stored *clean* replicas of themselves. This is contrary to the system presented in this paper that, instead of using replicas, correlates signals with versions of themselves that have been received at a different location. In addition, GPS signals are optimized for ranging measurement, whereas, signals-of-opportunity have variable content. As a result, the correlation response of SOPs is sporadic, further challenging reliable parameter estimation [16].

The CAF technique is also used in radar applications; devices that use *illuminators*-of-opportunity to detect and localize targets are of particular relevance. In this case, range measurements are made by correlating signals that arrive directly from a transmitter with target-reflected signals. These systems have many commonalities with SOP systems because of the non-cooperative nature of the illuminators-of-opportunity. TV and radio broadcasts in the very high frequency (VHF) and ultra high frequency (UHF) part of the spectrum are typical illuminators [17].

The steps taken to estimate DTOs are accomplished in DSP. The key functions (including correlation testing) are as follows:

- **Baseband conversion,** used to separate signals into channels and shift them down in frequency to baseband so that they are centered about zero hertz. Part of this process includes mixing the signal with a synthesized complex sinusoid to ensure that the baseband signals have the complex representation (in-phase and quadrature (I/Q) outputs) that is needed for correlation-testing (see for example, [18]). A key role of the baseband conversion is to reduce the sample rate, which eases the processing burden for all subsequent stages.

- **Correlation testing** is used to jointly estimate the differential timing offset (DTO) and differential frequency offset (DFO). It is a multistage process that is used to form a complex ambiguity function (the magnitude of which is searched to find the peak). The DTO and the DFO are estimated from the peak position. Incorporated into the correlation process is an interpolation routine which is needed to obtain sub-sample precision.

- **Time domain smoothing** refers to the processing of multiple DTO estimates (provided by correlation testing) to produce a smoothed output of greater continuity and precision. The procedure incorporates low-pass filtering and outlier detection, and is aided by the DFO observations that are used to estimate the rate of change DTO estimates.

The sample rate reduction that occurs during baseband conversion is particularly important as it eases the computation required for the intensive correlation testing.

A plot of a CAF used to estimate DTO and DFO values is displayed in Fig. 3a. This plot has been obtained from the data acquired by the test apparatus (presented in Section 5). The horizontal plane (the *ambiguity-plane*) extends over the search domain of DFO and DTO values, and its scope is limited by the range of candidate DFO and DTO values. For example, the search extent is large during the initiation stage when the position and Doppler uncertainty is high, but reduces in size as DTO and DFO measurements are made, and consequently uncertainty has decreased. Using a highly restricted search domain is important for real-time applications, as large search areas are computationally hard to address.

Identification of the dominant lobe within the ambiguity function is straightforward, while location of the peak within the lobe is more involved. Because of the large discrepancy between the required DTO precision and the baseband sampling interval it is necessary use a digital-to-analogue interpolation technique. This can be achieved using a reconstruction filter that operates in accordance with Nyquist–Shannon sampling theorem (see, for example, [19]), to calculate exact values of the signals as they would appear in analogue form. The foregoing interpolation technique should be distinguished from *super-resolution* methods, which are also used to improve accuracy in time delay measurements. In particular, super-resolution techniques are used to separate close spaced correlation peaks present due to, for example, multipath or re-radiation [20]. The potential of super-resolution to improve performance of the presented system is yet to be investigated.

Adequate consideration of the length of the signal portions used for correlation is important. If the portions are too short observations are disposed to gross error. This is because the ambiguity function becomes more noisy which can lead to incorrect peak identification.

Time-domain smoothing is also referred to as noncoherent averaging (correlation testing being referred to as coherent averaging). An example of a time series of DTO measurements that have been smoothed is shown in Fig. 3b. This plot has been obtained from the data acquired by the test apparatus (presented in Section 5). For clarity, on the plot the DTO observations, which are plotted on the *y-axis,* have been multiplied by the speed of light. Signals of opportunity are uncooperative and undergo unpredictable changes. In particular, audio modulation is subject to gaps (for instance, between spoken words) and momentary bandwidth contractions. This affects the quality of the sequence of DTO estimates obtained. A smoothing routine is used to excise rogue measurements. Performance can be further enhanced by weighting the remaining DTO estimates according to transient signal metrics, such as amplitude and bandwidth.

3.4 From DTO to Position

As explained in Section 3.3, DTO measurements are formed from a sub-set of the signals received by both the reference and rover – each signal producing one DTO measurement. The DTO measurements, together with the known transmitter and reference receiver locations, are used to determine the position of the mobile receiver.

Multiplying a DTO measurement by the signal propagation speed (approximately the speed of light) gives a measurement of the difference in the pseudo-ranges from the transmitter to each of the two receivers. Adding the known range between the transmitter and the reference leaves a transmitter to rover pseudo-range analogous to that measured by GNSS user equipment [21] . The key difference here is that the rover receiver clock offset is with respect to the reference receiver clock instead of the transmitter clock.

The position and clock offset is determined from a set of pseudo-range measurements using an estimation algorithm and a measurement model (the deterministic part of which is sometimes known as a functional relationship). As ground-wave propagation is dominant for MF broadcasting the rover position can be determined using a measurement model similar to that used for enhanced Long range navigation (eLoran) [5]. Note that vertical position information cannot be obtained from ground-wave propagated signals.

Where the baseline between the rover and reference is short, a Cartesian approximation may be used, enabling a version of the GNSS measurement model [5, 22] with two position dimensions to be used. This latter approach has been used for the work presented here. The relationship between the measurements and the rover position and clock offset is nonlinear, requiring the use of a nonlinear estimation algorithm. For the preliminary results presented here, an iterated least-squares (ILS) algorithm has been used with the reference receiver position used for initialization.

Once an initial position solution has been obtained, the measurement model may be linearized, enabling an extended Kalman filter to be used to process multiple-epoch DTO measurements. However, this is a subject for future research.

In order to make DTO measurements, the signal observation periods (or windows) at the base and mobile receivers must be synchronized. This is to ensure that the observation windows are approximately placed to observe the same portion of signal as it appears at two different locations. In principle, the receiver clock offset term in the position solution may be used to periodically resynchronize the rover receiver clock with that of the reference receiver in order to maintain alignment. However, initial time synchronization must be performed before a position solution is available. One option is to incorporate synchronization pulses in the data link between the rover and reference.

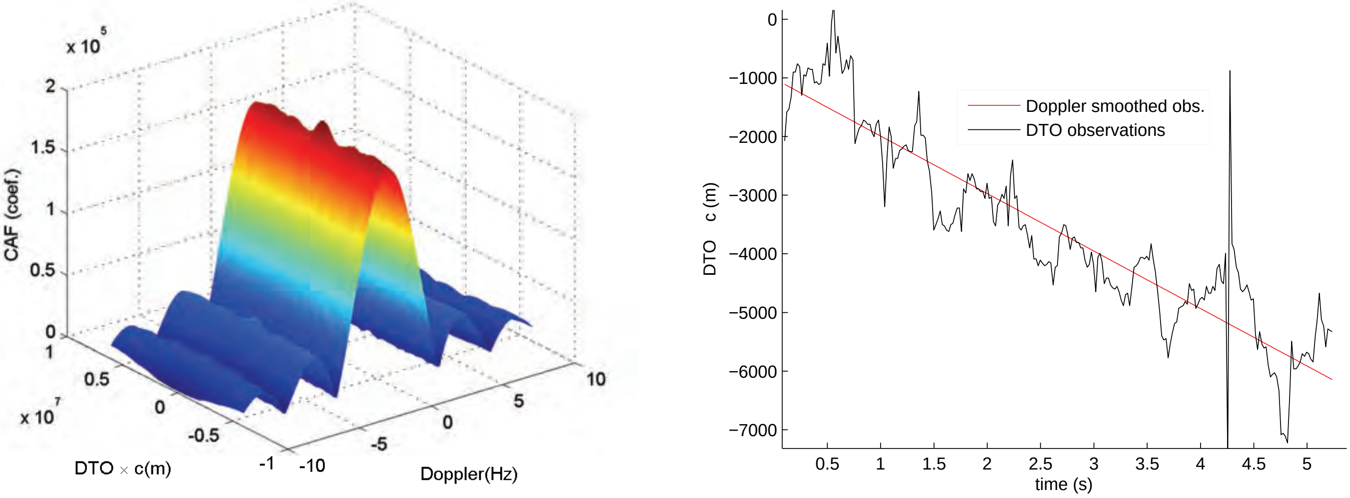
The a-priori position is used to query a signal source almanac database that contains a catalog of signals that offer good positioning potential for that particular location. The almanac database has been developed by considering a combination of factors, such as propagation loss, the extent of cross channel interference and signal geometry, all of which are used to assess the eligibility of a signal for positioning.

4 POSITION QUALITY COVERAGE MODEL

Assessing the positioning quality of AM broadcast signals is motivated for two reasons: 1) to predict suitability and likely performance of the system, and 2) to assist in the a-priori selection of a set of signals for correlation.

Great Britain is in International Telecommunications Union (ITU) region 1. In this region the medium frequency section of the spectrum used for AM broadcasting spans from 531 kHz to 1602 kHz. It is split into 120 uniformly spaced channels of 9 kHz. However, because of channel re-use, there are many more stations than there are channels.

Shown in Fig. 4 are plots of the coverage, according to a simple model, of AM MF broadcast signals across Great Britain. Fig. 4(a) shows a prediction of the number of signals that can be received at any one location. In the population-dense southern region of Great Britain the number of signals received approaches its maximum of approximately thirty, whereas in the sparsely populated northern region, signal reception drops to a minimum of three signals. Also shown on the plot are the transmitter locations (marked with triangles). Incidentally, there are



(a) Cross ambiguity function

(b) Time domain smoothing

Figure 3: Estimation of differential timing offsets (DTOs)

94 transmitter sites and 232 broadcasts [23, 24].

Shown in Fig. 4(b) is a plot of the horizontal dilution of precision (HDOP) across Great Britain. HDOP is a measure of the geometry-dependent effects on precision [5, 22]. In the context of this system, it is the ratio of the DTO variance for the set of chosen signals to the root mean square of the horizontal position error. The HDOP for this chart was constructed for a system that used all available candidate signals for positioning.

The coverage model used to construct the plots shown in Fig. 4 is based on a simple propagation formula [25, 26]. It should be noted that the model makes many simplifying assumption. For example, it has been assumed that the terrain is flat with a homogeneous set of electrical parameters. Moreover, it has been assumed that transmitters issue an azimuthally isotropic signal. It should be appreciated that some of the AM transmissions included are purposefully directional. In addition, the model fails to account for cross-channel interference, which has the potential to render a signal unusable for positioning. Cross-channel interference is particularly pronounced on channels that are used within the United Kingdom for the transmission of single frequency networks (SFN). Additional, potentially important, un-modeled effects include urban fading and sky wave interference.

The model assumes a reception threshold: the cut-off received power level below which the signals are considered unusable. An estimation of this cut-off level has been made using empirical data obtained from the demonstration apparatus. In using empirical data, it is aimed to accommodate for antenna and front end losses that might occur in addition to propagation losses. Details of the demonstration apparatus are presented later in this paper.

5 PRELIMINARY TRIALS

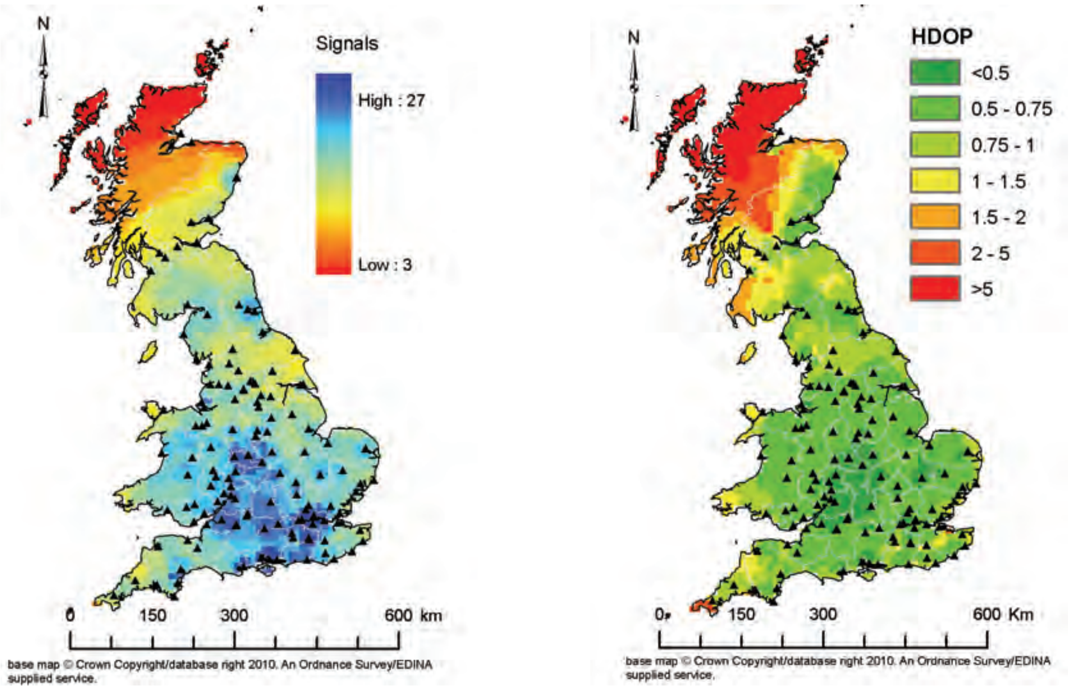
5.1 Demonstration System

A demonstration system has been developed to prove the concept of AM positioning and predict the performance of a real-time system. In accordance with the design presented in Section 3, the demonstration system comprises reference and rover receivers. Both receivers include an RF front-end that is used to obtain a digital snapshot of the spectrum. Subsequent processing is then carried out digitally.

To allow real-time operation the system presented in Section 3 incorporates a datalink. However, to ease implementation, the demonstration apparatus has been designed to operate without a datalink. Instead, the digitized snapshot is stored in memory modules by the reference and rover receivers. Following a trial exercise, the data on the memory modules is downloaded to a PC for further processing.

Due to the absence of a datalink, it is necessary for the demonstration system to employ a method of synchronizing the observation windows used for correlation that does not rely on the transmission of either clock corrections or synchronization pulses. This has been achieved by incorporating a Global Positioning System (GPS) receiver into each of the demonstration system receivers. Timing information derived from the GPS receiver is subsequently extracted and used for synchronization. It should be appreciated that this reliance on GPS is only a feature of the demonstration apparatus and the system proposed in this paper can operate entirely independently of GPS.

Shown in Fig. 5 is a schematic of the demonstration system apparatus that is located at the reference and rover locations. Also, shown in Fig. 6 is a photo of the apparatus (not including the active high-frequency antenna). The apparatus comprises the following parts:



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(a) Number of signals received

base map © Crown Copyright/database right 2010. An Ordnance Survey/EDINA supplied service.

(b) Simulated HDOP

Figure 4: Simulated signal positioning coverage across Great Britain.

- An active high-frequency antenna (Watson) followed by a 1.9 MHz low-pass filter.
- A 14-bit 140 MS/s analog-to-digital converter (Analog Devices AD9254 on an Altera HSMC data capture board) that is used to capture the RF signal.
- Hardware DSP that is implemented on a field programmable gate array (FPGA) development board (Altera Cyclone III 3C120 development board), that writes the ADC data samples to memory and then, once the capture is complete, writes the data to a personal computer via a Joint Test Action Group (JTAG) interface. A processor is instantiated within the FPGA that configures the capture hardware, provides user feedback via a liquid crystal display (LCD) and primes the capture system when a push-button is pressed, ready for capture synchronization via the GPS time pulse. The development board provides the 10MHz sample clock for the ADC.
- A GPS module residing in a Terrafix TVC3000 vehicle computer system, configured to produce a time pulse at the start of each minute, as defined by GPS time. The pulse is used to synchronize the capture of data at two different locations.

A GPS fix of the receiver locations was obtained from the module that was incorporated into the demonstration apparatus. The GPS receiver positions were used to: 1) provide a "true" position of the reference receiver - as required by the position algorithm; 2) provide a location for the rover that could be compared to the SOP derived fix. The GPS receiver used was consumer grade and had an accuracy of approximately ten meters.

5.2 Positioning Experiments

Fig. 7 is a map of the test region, centered around the city of Stoke in the UK. Shown on the map is the location of the reference receiver (marked with a square), and two roving receivers (marked with circles), denoted *A* and *B*. The transmitters (depicted by triangles) used for positioning are shown, however, for clarity, three transmitters (located outside the mapped extent) have been omitted. Land-use across the region was a mixture of urban and rural, with vertical elevation varying by up to a hundred meters.

Both rovers were located outside in the vicinity of light infrastructure such as communication wires. A representative photo (the location used for rover *A*) is shown in fig. 8b. The two separate rover locations used a common reference receiver, placed inside a brick building (fig. 8a). In these photos, the elongated white cylinder is the active antenna of the demonstration apparatus. The baseline distances (i.e. the distance between the reference and rover) were 15.9 km and 5.9 km for location *A* and *B* respectively.

The results presented are those from positioning tests for rover location *A* (Fig. 9a) and rover location *B* (Fig 9b). The individual position fixes are marked with a crosses. It should be noted that the work is ongoing, and the difference in the number of fixes obtained at location *A* compared to that for location *B* reflects this fact. Individual position fixes are accompanied by an error ellipse that represents the region within which there is a

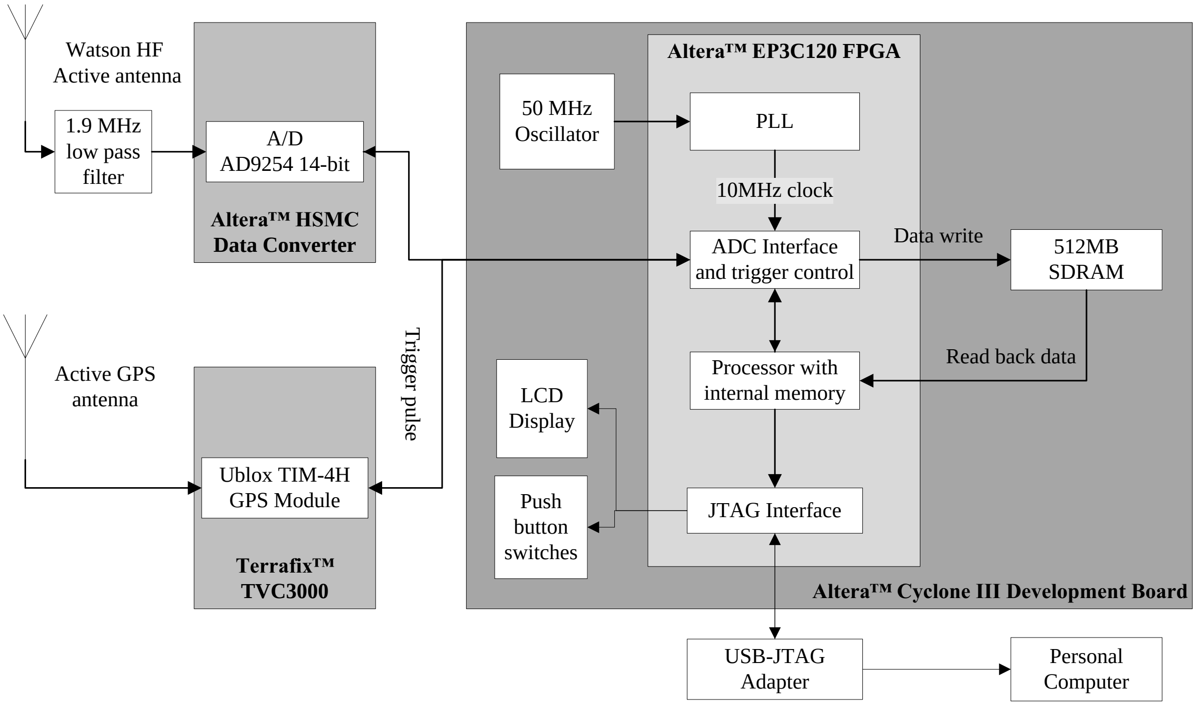


Figure 5: Schematic of demonstration system

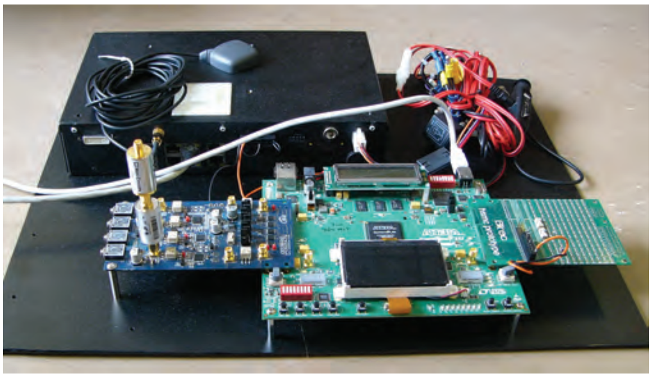


Figure 6: Photo of demonstration system

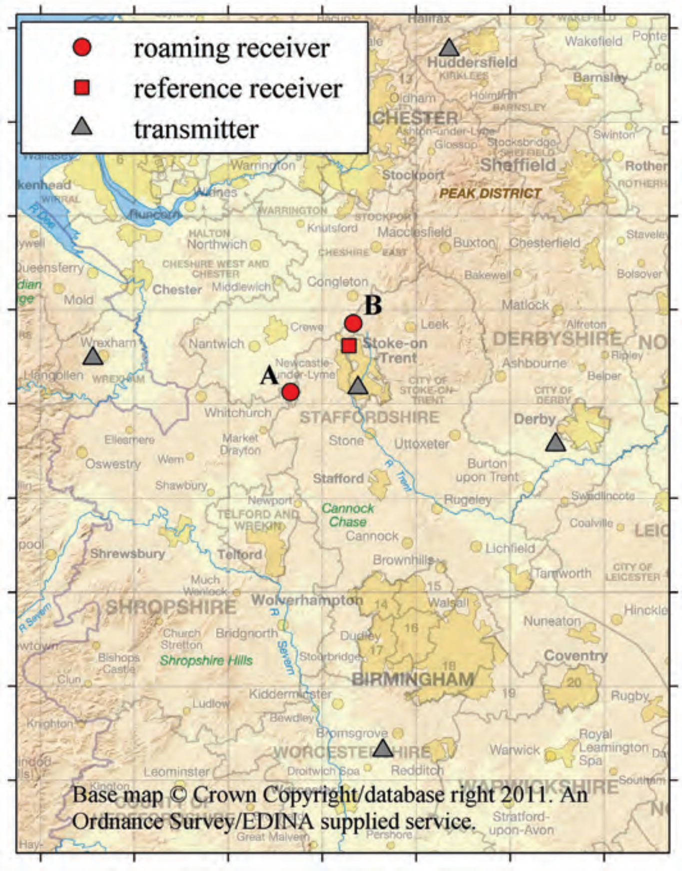
40 percent likelihood of a subsequent measurement appearing, on the assumption that systematic errors and statistical characteristics are constant (see, for example, [27]). The error ellipses have been calculated by estimation of the variance in the pseudoranges that have subsequently been projected into the position domain. To give an indication of the overall performance at each location, pooled results are presented in Table 10. Position statistics have been calculated by vector addition of easting and northing component statistics (not shown in the table). Note that all position errors are calculated using the GPS position fix (accuracy ~10m) as the basis for a true position.

5.3 Discussion on Positioning Results

The groundwave propagation mode is predominant for both Loran signals and for signals in the AM broadcast band. As a result, an AM positioning system is likely to be subject to similar error-mechanisms affecting Loran. Therefore, it is useful to use Loran as a benchmark. In urban-environments Loran receivers often experience positioning errors of a hundred meters [28], and indoors, of several hundred meters [29]. For our experimental setup it should be appreciated that propagation environment is far from ideal, in particular, the reference station was located in a building which has some steel frame superstructure, and the roving receiver was located in the vicinity of overhead power cables. Metallic objects and electric-installations are known to have significant impact upon Loran and AM broadcast band positioning [30, 29][13] and cause biases commensurate with those observed.

The fixes shown in fig. 9 are not clustered together but are highly scattered. This implies that the temporal stability in the range observations is poor. The large variation in the biases are surprising since, unlike GNSS, which uses moving transmitters (mounted on satellites), all elements of the system are geometrically fixed. Characterization of the nature and cause of the bias errors is a topic of ongoing research. However, it should be remarked that temporal variations of 30m have been observed in Loran ranging measurements [30]. It has been suggested that these could be accounted for by fluctuations in power grid consumption causing changing patterns of interference[30].

It should be appreciated that if the biases were highly stable, or the temporal variations understood, it would be conceivable



Base map © Crown Copyright/database right 2011. An Ordnance Survey/EDINA supplied service.

Figure 7: Test region of preliminary trials (scale: 20km per division)

to map the bias errors, and apply corrections to mitigate their effect. It is also possible that results could be improved upon by combining them with carrier phase observations. However, carrier phase measurements in the AM band are also subject to large errors [13].

6 CONCLUSIONS AND FUTURE WORK

The technique presented in this paper is applicable to the numerous RF signals that use FDMA. Example signals include frequency modulated (FM) broadcast signals, television signals and differential global positioning system (DGPS) signals. In addition, the technique can incorporate communication signals even though knowledge of the modulation details may be proprietary.

The technique relies on measuring DTOs between two receivers. This is achieved by calculating the cross ambiguity function (CAF) from the modulated waveforms. Using this CAF it is possible to achieve enhanced performance over methods that first demodulate the signals prior to correlation. This is because, particularly for FM signals, demodulation can markedly lower the signal to noise ratio [16]. Moreover, the CAF technique allows the joint estimation of the DTO and the DFO. The DTO estimation is enhanced by incorporation of the DFO estimate ,and the error mitigation techniques described in Section 3.3, which are tailored for the uncooperative nature of signals-of-opportunity.

(a) Reference receiver location

(b) Rover location *A* (also representative of location *B*)

Figure 8: Receiver locations

In terms of scalability, due to the generality of the technique, the system architecture is capable of accommodating large number of signals without major modification. Specifically, the wideband receiving apparatus allows the simultaneous capture of multiple signals. Further, the generality of the CAF operation dispenses with the necessity for signal specific operations (such as demodulation), which can complicate processing. Further, the software-defined approach allows flexibility for easy real-time signal selection and weighting, both of which assist in the incorporation of heterogeneous signals.

AM broadcast signals have been used to demonstrate proof of concept. Currently, the system is accurate to approximately 500m. As discussed in Section 5.2, possible causes of errors include re-radiation effects due to near-field objects, weather dependent propagation effects, and interference from communication lines. Further investigation is needed to determine whether it is practical to calibrate or mitigate these. The positioning technique developed may also be used to aid ambiguity resolution in carrier-phase based AM positioning. However, it should be noted that carrier-phase based positioning can be unreliable indoors, in urban areas and near power lines [13].

The potential of low or medium frequency navigation system to augment GNSS has been recognized [30, 29]. Currently, Loran-C is the only widely available low-frequency navigation system [30]. However, its coverage has become less extensive in recent years. It is conceivable that a calibrated AM-based system would perform to a similar standard as Loran (but without the need for extensive infrastructure), and help assist in fulfilling navigation and positioning requirements that are needed to supplement GNSS.

The demonstration apparatus captures signals from both the LF, and the MF bands. Signals in both bands are of the same format and propagate predominately by the groundwave mode. However, it is conceivable to design a system that operates over multiple bands upon signals with diverse formats. Employing heterogeneous signals could result in a synergy that safeguards the position solution, particularly in difficult environments. For instance, a system using both AM and FM radio signals could harness the wider bandwidth of FM signals to yield accurate positioning in open-areas, while relying on the penetration of AM signals to enable positioning deep indoors and underground. Of course, incorporation of a greater variety of signals requires special efforts to generate and maintain the signal source almanac[10].

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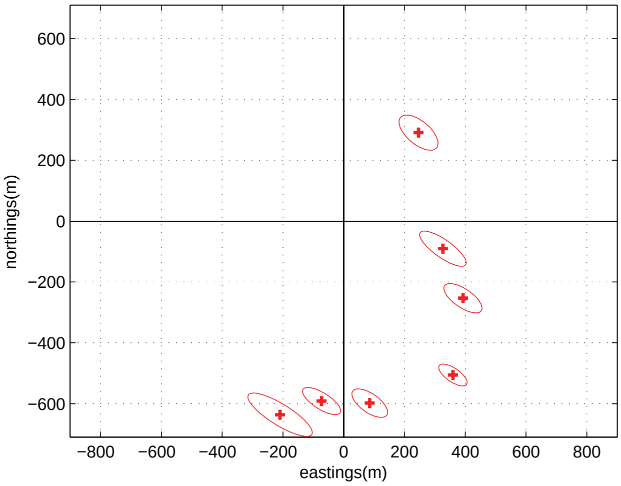
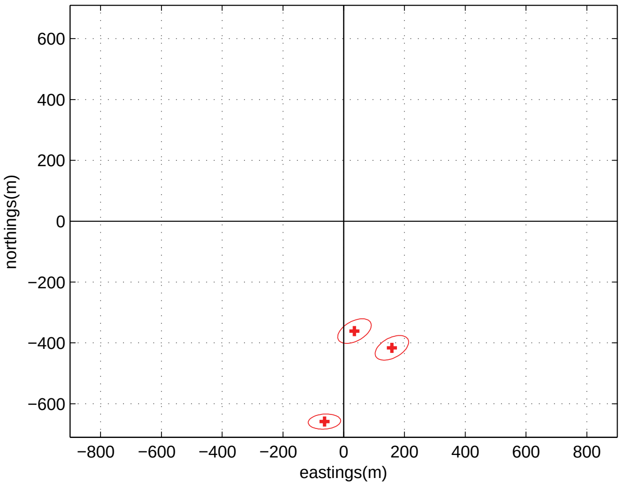


(a) Rover location *A*



(b) Rover location *B*

Figure 9: Scatter plots showing errors in position fixes

Receiver Location	***A***	***B***
Number of fixes	7	3
Baseline length (meters)	15897	4898
HDOP (coef.)	0.70	0.84
RMS error (meters)	479	506
Bias error (meters)	526	481
Standard deviation (meters)	693	193

Figure 10: Summary of positioning statistics

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