Constraints on accurate positioning of mobile environmental sensors

G. Maniatis[1,2], T.B. Hoey[1], J. Sventek[2], R. Hodge[3]

[1]School of Geographical and Earth Sciences, University of Glasgow; [2]School of Computing Science, University of Glasgow; [3]Department of Geography, Durham University
Telephone: +44 141 330 2000
Email of corresponding author: g.maniatis.1@research.gla.ac.uk

1. Introduction

The availability of GNSS positioning techniques with global coverage offers considerable potential for localization in GIS. The widespread use of GPS provides users with high precision and relatively high accuracy in real time within a global reference frame. To realise the potential of automated, wireless environmental monitoring systems in inaccessible dynamic environments, location often needs to be known with high accuracy and at high frequencies. For example, the movements of a landslide or a river pebble are rapid but episodic and tracking the periods of motion requires positioning at high frequencies. While this may appear a problem that can be resolved readily by deployment of a dense in situ network of transmitters, so enabling position to be determined by triangulation with in-built redundancy where more than three transmitters are used, the speed of movement and consequent need for very high precision, mean that limits on the precision of time information provides a significant constraint. Here we investigate the origins of this problem and evaluate potential solutions in the context of a mobile sensor designed to track particle movement in natural systems.

While the problem addressed is generic, our specific application here concerns sediment transport in river or coastal environments. Sediment transfer over distances of 10 to 1000 m is considered, representing a range of settings (from small streams to the most active parts of large rivers or gravel beaches).

The global reference frame of GNSS poses two limitations for the applied technology: a) the locality problem - fixing the position of a sensor provides a challenge of finding the optimal resolution of the positioning grid to provide desired spatial accuracy; and, b) the mobility problem - as the sensor moves, tracking its position is subject to a number of movement-related constraints (such as the minimum detectable movement, the speed of the movement, and whether movement is continuous or episodic) and is a function both of spatial accuracy and of temporal accuracy and precision.

The locality problem can be approached using network-based solutions: building a local sub-grid in each sector of the global grid with optimal spatial configuration increases spatial resolution and maximises accuracy in particular deployments. The mobility problem is less readily resolved and the only viable solutions are currently restricted to special cases of the full range of the possible movement-tracking cases. The most difficult of these cases demand high-frequency positioning in locations that cannot be connected directly to the global grid due to technological or physical limitations. For example, underwater tracking where there is a need to track complex movements (whether of mammals, underwater robots or UAVs in oceans, or sediment grain movement in shallow fresh-waters) in a medium where the most readily applied technology can only be made operational, if at all, after extensive modifications.

Tracking of sensors that are, at least temporarily, submerged, is our focus here. The demand for oceanic tracking triggered the development of acoustic (Sonar) and optical wavelength (IR) based techniques as an alternative to radio frequency (RF) based approaches, since the latter are difficult to apply underwater at commonly used frequencies. Underwater RF localization has been explored theoretically and experimentally for both marine and fresh waters and is physically possible at low frequencies (from the VLF band of 3-30kHz for sub-sea applications to the VHF band of 30-300 MHz for river systems) which are incompatible with the operational range of contemporary GPS (1176-15575 MHz, UHF band) [Che et al 2010].

Aside from the problem of RF propagation in water, the key constraint affecting the use of GPS in our application is its precision. GPS is a radio signal localization technique, specifically Time of Arrival or Time Difference of Arrival. GPS operates by monitoring the delay of a radio signal in a triangulation scheme due to distance differences between the nodes of this scheme. Since radio waves propagate at the speed of light ($3 \times 10^8 m.s^{-1}$), the delay between Earth and a typical GPS satellite is c. 100 milliseconds. For the scale of this application (meters to kilometres) the required delay is of the order of nanoseconds, a temporal resolution/precision achieved by processors with clocks above 1GHz. The energy demands of these processors currently make them inefficient for mobile applications, where less powerful but more efficient processing units are typically deployed with clocks up to 16 MHz (thus capable of processing at a temporal resolution of order 10 μs).

Two approaches can be taken to resolve these issues: a) firstly, alternative signal-based localization techniques can be developed. The power signal changes as a known function of distance and time and this can be measured using a Radio Signal Strength Indication, RSSI, value. Although theoretically feasible, this approach is at an early stage of development and a number of technological challenges remain, mainly related to signal inconsistency caused by environmental variability (signal attenuation, fading, refraction) and to the non-standardization of the on-board radio boards (each radio chip deploys different circuitry and is calibrated under different conditions) [Chen et al. 2010]. b) secondly, localization can be considered as an inertial navigation problem; i.e. consider a system with known initial position, movement away from which is resolved through continuous monitoring of accelerations and orientation changes (often referred in the literature as dead-reckoning localization) . The basic challenge these techniques face is error accumulation, mainly due to low precision time references (which need to be both real-time and external to the system) since all subsequent positions are determined in reference to an initial position. Delays that are insignificant for static or slowly changing systems (such as the very small time difference between a sensor making a measurement and these data being stored in a digital memory) accumulate quickly for large monitoring times [Bao et al. 2014].

2. Conceptual Description of the proposed system

To address the level of position resolution needed to resolve the movement of individual sediment grains and record the scheme of forces that define this movement, we propose a micro-location system that combines radio signal-based localization with INS-dead-reckoning localization techniques.

Specifically, we assess the feasibility of a system in which a mobile sensor logs acceleration and orientation data while simultaneously transmitting a radio signal to a local network. The design criteria of such a system can be divided into two categories: the criteria related to physical sensing and the criteria relevant to the accurate positioning of the sensor.

2.1 Physical Sensing-Sensor design criteria.

These criteria are the accuracy and the resonance of the dynamic data that will be sensed and logged by the mobile sensor-transmitter. These criteria are strongly related to the understanding of the sediment transport processes in our application and frame all the specific characteristics of the sensor (computational, electrical and physical).

The scheme of forces in which the sensor must survive and operate is defined by local accelerations in a range from 0 to ±100 g. This range is reported in the relevant literature [Vatne et al. 2008] as an ambiguous measurement which currently includes both translational accelerations related to sediment movement during gradual discharge fluctuations and also rapid shocks applied on individual grains during rapid flow changes and (most probably) grain-grain interactions.

The magnitude of these forces defines the specifications for the mobile sensor (from the capabilities of the on-board processor and the memory capacity of the logging system to the robustness of the sensor-enclosure [Maniatis et al. 2013]). The required measuring range for the acceleration-impact sensor (magnitude of an order of 100g and sampling frequency of c. 100Hz) is itself a technological challenge in a context of long-term mobile real-time sensing [Frank 2003].

2.2 Localization-tracking related criteria.

The criteria of this type correspond to the accuracy and the representativeness of the positional information extracted from the system defining the specifications of both the mobile transmitter and the network used for localization.

This aspect of the system is designed in respect to the mode of movement that needs to be resolved (individual grain movements with a stochastic character) and the high force-impact underwater environment. At a sensor –transmitter level we propose the INS- dead-reckoning approach, using gyroscopes and magnetometers to define orientation changes during the movement. The final multi-sensor will simultaneously log accelerations (three accelerometers), changes of angular velocity (gyroscope) and the direction of a constant reference point (the centre of the earth using the magnetometer). This information allows the resolution of the 6 degrees of freedom of the sensor-movement according to the INS methodology. The logged data can be acquired post-event (through a USB interface for example) but can also be sent wirelessly to the local network through a radio transmitter in real-time.

At a local network level, we propose a system of antennas-receivers in order to apply radio-signal based localization techniques and reduce the error accumulated in the logged data. The basic constraints for the radio signal transmission are: a) the fact that the transmitter will be (at least temporarily) submerged; and, b) it must take place at a frequency adequate to permit real time correction of position through the definition of multiple reference points. This frequency is defined by the range of the possible displacements of the mobile-transmitter and can vary from very low values (≤1 Hz for zero, or very slow, displacements) to frequencies that challenge the limits of radio-based localization and correspond to rapid displacements at the high end of the occurring forces (close to the 100Hz sampling frequency considered for the accurate sensing of large impacts).

3. Initial Assessment of positional accuracy.

The scale of the monitoring system does not permit the direct use of GPS. As a result we consider the localization principal applied in the GPS for the local network we design. This multilateration technique uses the Time of Arrival (ToA) of the transmitted radio signal to the different receivers or the Time Difference of Arrival (TDoA) between two (or more) receivers to calculate the distances between the transmitter and the receivers which are typically located at pre-defined reference points. Distances are calculated using the propagation velocity of the signal and a linear propagation model (propagation velocity= speed of light= distance*time of signal propagation). A minimum of three linearly independent distances are needed to locate the transmitter (with 3 Cartesian coordinates) in the reference frame defined by the receivers (trilateration) [Munoz et al. 2009].

The core of this approach is the assumption that the time differences (occurring at a scale of nanosecond for distances of meters to km) can be detected by the receivers. For our specific application we face a technical limit since the relative instrumentation and controlling software applications are typically capable of synchronization at an order of micro-second [Verdone et al 2010]. To demonstrate this limit we set up a simulation of localization using a random walk in three stages:

Stage 1: At first we model a 2-D unbiased scaled random walk where the four receivers are located at distances appropriate to our application (100 m). The transmitter is capable of performing of 1 meter step per iteration. Each iteration corresponds to a time difference of one second thus the sensors moves with a constant velocity of $1 m.s^{-1}$ towards four predefined directions (North -South along the y axes and East-West along the x-axes) one of which is chosen randomly for every individual step. Our interest is to record the time of arrival of a signal with a propagation velocity of $3 \times 10^8 m.s^{-1}$ received by four receivers located at predefined locations which form an area of $100x100 m^2$ (L x W) [Figure 1.1]. The localization error records the absolute difference of the location of the transmitter as recorded by the random walk algorithm and the location detected by the multilateration algorithm [Figure 1.2].

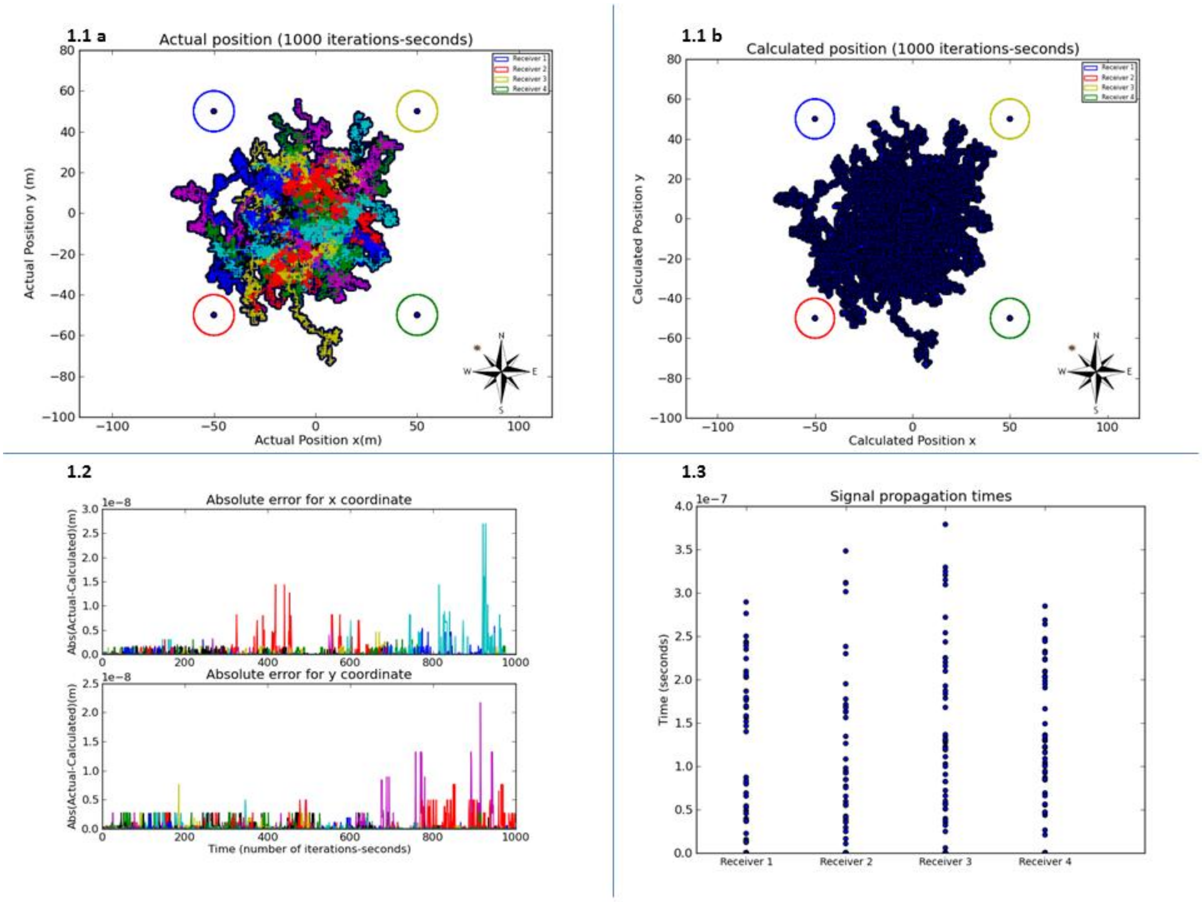

Figure 1. : Simulation of 60 unbiased random walks and positioning using multilateration method (radio-localization principal). The simulation is scaled: 1 unit corresponds to 1 meter (m) and each iteration represents a time difference of 1 second. The moving objects represent sensor-transmitters moving in a coverage area defined by a grid of four receivers located at a predefined positions (Figure1.1a). The transmitter is capable of moving towards four predefined directions (N, S, W, E), one of which is chosen randomly for every iteration. The sensor moves 1 unit-meter every iteration-second (representing a velocity of 1 m.s$^{-1).}$ Figure 1.1b shows the calculated positions after the application of the multilateration algorithm**. Figure 1.2**.Absolute positional error. The localization error is calculated as the absolute difference between the position recorded from the random walk algorithm (actual position in Figure 1.1 a.) and the position detected from the mulilateration algorithm. Fig 1.2 b. **Figure 1.3** Signal propagation times transmitted from the moving sensor as recorded by the 4 receivers. The signal propagation velocity is 3x10^{8} m.s^{-1}.

Stage 2: The second stage models a more realistic scenario where we bias the 2D random walk to mimic the movement in a river flowing along the x-direction (from West to East). We specifically restrict the movement between two horizontal limits in the y-direction (North and South simulating the banks of a river), we minimize the probability of moving towards the -x direction (West-upstream) and we assign a double distance movement (2 meters per step) when moving towards the +x direction (East -downstream direction /direction of flow). The location of the receivers is set to represent the reception from river banks producing an area relevant to the simulation of stage 1 (length of area is 100m). The signal propagation model and the velocity of the transmitter (distance per iteration step) are identical to the previous stage. The mode of the movement of the transmitter affects the accuracy of the detected position [Figure 2]. The high step velocity (1m.s^{-1}) leads the sensors to move outside the area defined by the positions of the receivers.

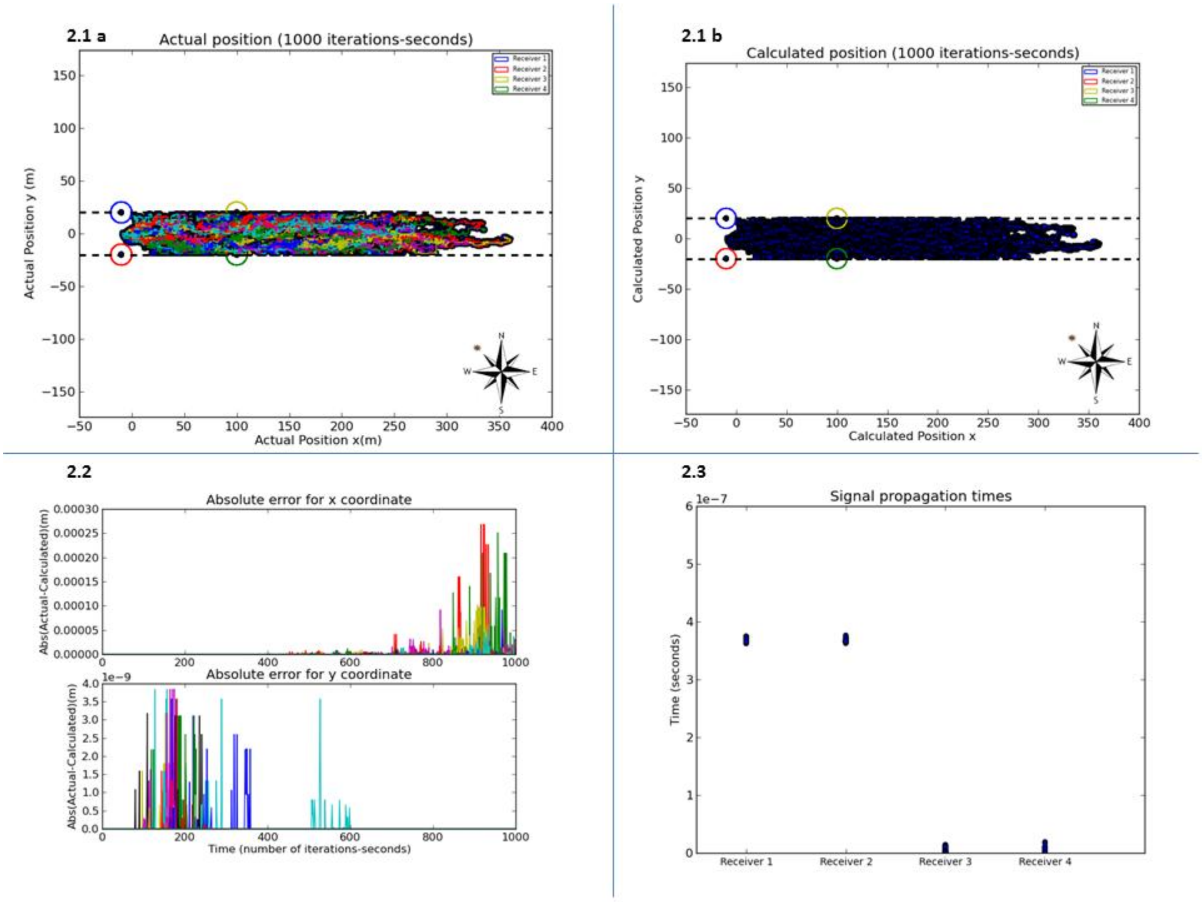

Figure 2. Simulation of 60 biased random walks and positioning using multilateration method (radio-localization principal). The simulation is scaled similarly to Figure1. The mode of movement is different since the random walk is restricted along the y direction (North-South) between two linear limits which represent the river banks (at ±20m). In parallel the walk is biased along the x direction with zero probability for moving West (-x, representing upstream) and a double distance step of 2 unit-meters when moving East (+x, downstream) in order to mimic the movement in a river flowing from West to East. The minimum velocity is 1 unit-meter per iteration-second for the unbiased directions (1 $m.s^{-1}$). Figure 2.1 b shows the calculated positions after the application of the multilateration algorithm. **Figure 2.2**.Absolute positional error. The localization error is calculated similarly to Figure 1. We observe an increase of the error along the unrestricted direction (West-East, x direction) while the error is practically zero for the y coordinate suggesting a decrease in accuracy as the transmitter moves away from the area defined by the position of the receivers. **Figure 2.3** Signal propagation times transmitted from the moving sensor, recorded from the four receivers. Propagation velocity is $3x10^8$ $m.s^{-1}$.

Stage 3: Finally we extend the simulation in stage two by defining a more realistic velocity for the transmitter (0.4 $m.s^{-1}$) and by modifying the radio propagation model so it corresponds to underwater radio-transmission. Freshwater is typically modelled as a low loss medium, and the propagation velocity of the signal is calculated according to the following equation [Equation 1].

$$\upsilon = c/\sqrt{(\mu_r \varepsilon_r)} \qquad (1)$$

Where μ_r and ε_r are the relative permeability and relative permittivity of freshwater. The calculated propagation velocity of the radio signal in freshwater is approximately 3.3 x 10^7 ms^{-1}. For this demonstration we did not consider other parameters that significantly affect signal propagation (such as the water –air interface or the noise added by flow fluctuations). However none of these parameters changes the scale of propagation velocity [Sadiku 2007]. Our focus at this stage is to assess the effect of the delay of the radio signal from the water interference to the timestamps recorded by the receivers [Figure 3].

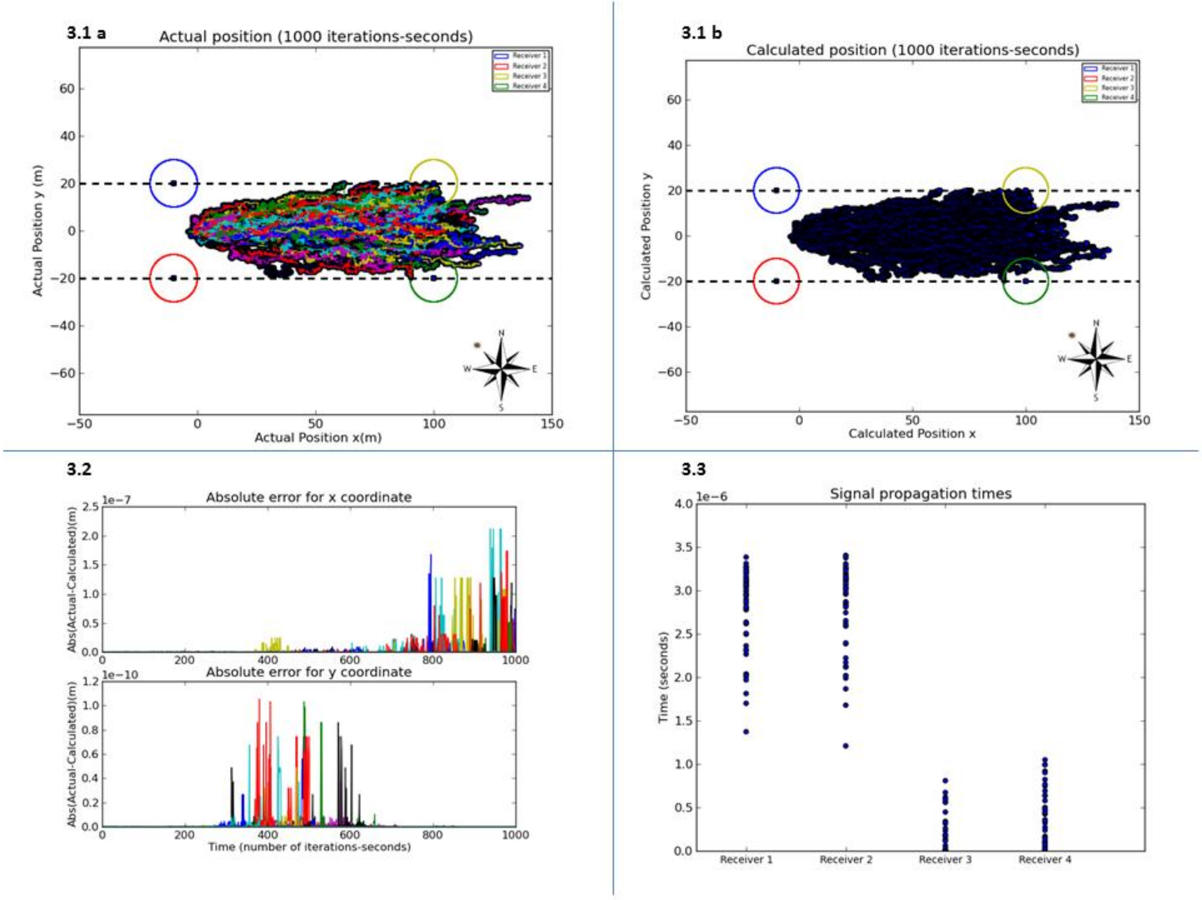

Figure 3. Simulation of 60 biased random walks and positioning using multilateration method (radio-localization principal). The scale and the mode of movement are identical to Figure2. The minimum velocity is set at a more representative 0.4 unit-meter per iteration-second for the unbiased directions (0.4 m.s^{-1}). Figure 3.1 b shows the calculated positions after the application of the multilateration algorithm. **Figure 3.2.** Absolute positional error. The localization error is calculated similarly to Figures 1 and 2. We observe a behaviour similar to the simulation of Figure 2. However the differences are at a scale of 10^{-7} to 10^{-10} unit- meters since the maximum distances are significantly smaller (<150meter-units compared to the 350 meter-units max distance of the previous simulation). **Figure 3.3** Signal propagation times transmitted from the moving sensor, recorded from the 4 receivers. Propagation velocity is set to the value for radio wave propagation in freshwater (3.3 x 10^{7} ms^{-1}). The delay of the signal leads to record propagation times at the order of micro-seconds (Receivers 1 and 2). However a significant number of times still occur at an order 10^{-7} seconds or less (Receivers 3 and 4).

4. Alternative localization techniques.

Two results from the above simulation challenge the feasibility of the GPS technique for this application. Firstly, the time differences for the received signal occur constantly at a scale of equal or smaller to micro-second even for the underwater case where the signal is delayed (Figure 3.3). Secondly we observe an effect of the mode of the movement on the accuracy of the calculated position. For the unbiased random walk the errors along the y and the x direction are comparable and do not reveal an obvious structure that would imply error accumulation. On the contrary, for the biased –restricted walk (simulations 2 and 3) we observe an increasing error along the unrestricted direction (x coordinate) which can be interpreted as a loss of accuracy when the transmitter moves close or over the limits of the coverage area defined by the receivers.

The above considerations lead us to assess alternative radio-based localization techniques. These techniques are based on the measurement of the strength of the received signal with specific metrics (such as the Radio Signal Strength Indicator) in an attempt to replace the propagation velocity-distance model used in the GPS framework with a radio signal strength-distance model. The calibration of this model is an open research challenge and previous applications are typically restricted to indoor short –range environments [Park et al. 2014]. However the method has increased in performance the recent years and it has the potential for long-range application since the latest studies suggest a stabilization of the metrics (decrease of variability) at distances greater than 10 meters which can permit the robust modelling at those scales [Asadpour et al. 2013]. Other experimental radio -localization techniques suggest different types of modulation, or different time synchronization metrics (relevant to Doppler shifts that can occur at the specific RF band) but are not currently applicable for freshwater environments [Hattab et al 2013].

5. Conclusion and Future Work

Here we present an a example case that can challenge the reliability of the positional data stored in a GIS. Despite the special characteristics of the environment we are interested into, similar constrains are relevant to all the mobile applications of similar scale and implement real-time radio-based positioning (GPS measurements). The error existing in the data from this type of localization needs to be carefully considered since it stays inherited to all the possible complex transformations performed during the data analysis-manipulation process of high-level geo-location applications.

For the specific application we work on three separate research challenges.
At first, the success of our approach is dependent on the robustness of the calibration of the radio signal – distance relationship which remains an open research topic [Chakraborty et al. 2009]. We work on providing a robust signal strength-signal model for underwater radio transmission while assessing possible alternative techniques.

Secondly, to maximise the use of information gathered from mobile environmental sensors and combine this with positional data it is necessary to provide a common mathematical framework where both of these measurements can be synchronized and interpreted. Optimising the positioning system in terms of accuracy and computational efficiency depends on *a priori* understanding of the mathematical framework to be used to analyse the data. There is a need to formally combine very different mathematical approaches to extract information and perform useful predictions about localization even at an experimental stage. In the combined and scalable system that we introduce, the deterministic description of Euler transformations for rigid body movement in 3D-space [Akeila et al. 2010] is combined with the position estimate from purely stochastic techniques, such as Kalman filtering and other Monte-Carlo related descriptions [Zanella et al. 2012]. This framework will also permit the nesting of the local wireless network within a global coordinate system and will have general applicability.

Finally we try to enhance the understanding of the physically sensed data and use them in the contemporary fluvial morphodynamics and sediment transport processes context. Our interest is, through a sequence of fluvial experiments and mathematical simulations, to provide robust calibration data and test the hypotheses used in the predictive and description models and are relevant to the local dynamics at grain scale [Hodge et al 2011].

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