GPS and Cellular Radio Measurement Integration

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In many combined GPS/cellular radio receivers, the cellular radio segment is not used to aid the positioning process. Recently proposed Assisted-GPS systems use the communications channel to improve receiver time-to-first-fix and the GPS tracking sensitivity. However, the cellular radio signals can also be used for locating the receiver. Studies using the GSM mobile communication system have shown positional accuracy comparable to that of SA-degraded GPS. To achieve maximum performance (accuracy, availability, integrity and reliability), both sources of positioning information, GPS and cellular, should be regarded as sensor inputs to an integrated navigation system. In this way the benefits of both systems can be fully exploited to produce an optimal navigation solution.

KEY WORDS

1. GPS 2. Cellular Radio 3. Positioning 4. Integration

1. INTRODUCTION. The performance of GPS has been extensively analysed and documented over a wide variety of applications and operating environments. Usage in urban areas is particularly problematic due to potentially long periods of signal blockage. Advances in GPS receiver design have to a certain extent alleviated this problem via the use of techniques that provide very fast signal re-acquisition. Nonetheless, if the signal is blocked it cannot be used, and hence GPS as a sole-means navigation source in an urban environment is unacceptable from the point-of-view of fix availability and continuity for many classes of user. Therefore, the efficient combination of GPS with other sources of positioning data to improve performance is an attractive proposition.

One of the biggest growth areas for GPS utilisation is in road telematics applications where vehicle position data are combined with road traffic information to provide services such as route guidance, emergency services (breakdown, police assistance etc), and local information. Although the GIS-orientated data may reside locally within the navigation system – for example, on a CD-ROM – the real-time requirement for the road traffic information requires the existence of a communication channel between the in-vehicle unit and the service provider. Such a communication channel may be, although not necessarily, provided by a cellular radio-based system.

To provide product differentiation and additional sources of revenue, mobile radio network providers and handset manufacturers are offering an increasing number of valued-added services. An important group, Mobile Location Services, provide user information with location-dependent content and enable implementation of features such as location-sensitive billing. The ability to locate the position of the handset is therefore a key requirement in implementing such services. Various methods, with

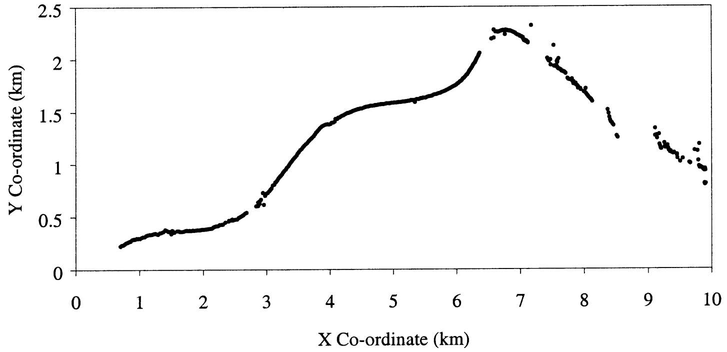

Figure 1. GPS Urban Performance Trial.

varying degrees of accuracy, exist for positioning the handset using signals inherent within the cellular communications system. Either way, users of cellular radio systems are equally likely to be users, or potential users, of positioning systems and vice-versa. Indeed, in some countries legislative issues make the combination of cellular systems and positioning capability mandatory.

This paper reviews the use of the GSM cellular radio system (Mouly and Pautet, 1992) for the purpose of positioning the handset and its integration with GPS. However, the techniques discussed are also generally applicable to other cellular radio systems. Different measurement methods are discussed, together with the required information interchange between the cellular network and the mobile station and what initialisation or calibration stages are necessary. Several different implementations are assessed to demonstrate trade-offs between complexity of the system and modifications to the user equipment and network infrastructure. The accuracy of the measured observables is discussed and assessed via the use of simulation. The impact of the geometry of the base stations around the mobile station and the number of base stations in the solution is presented. The combination of measurements from a cellular network and a GPS receiver into a unified solution is discussed. The potential performance improvement achievable by combining GPS and cellular radio measurements, particularly in locations where GPS performance is typically degraded (for example, city centres), is demonstrated.

2. GPS URBAN PERFORMANCE.

GPS is a line-of-sight system, and the degradation in performance in urban areas due to obscuration of the satellites is well known. Figure 1 shows a trial over a 10-minute journey, position fixing at 1-second intervals, through a region of varying character.

The first-half of the journey offers, in general, good visibility and so allows a nearly continual trail of position fixes. In the second-half of the journey tall buildings, flyovers and underpasses severely restrict the number of satellites that can be tracked to the extent that, for significant periods, position fixing from GPS alone is not possible. Figure 2 shows the position fix *type* (3-dimensional, 2-dimensional and no fix) that was obtained at each sample point.

As can be seen, during the second-half of the journey the ability to fix position was severely curtailed and, even when it did occur, it was essentially limited to 2-dimensional positioning. Over the whole trial, the position fix distribution is summarised by Table 1.

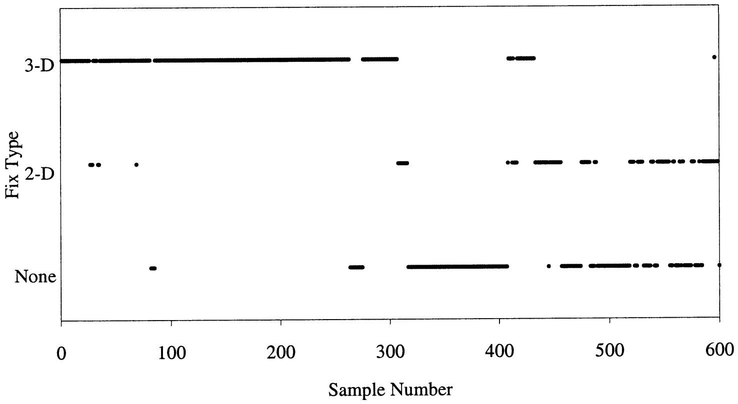

Figure 2. GPS Trial Fix Type.

Table 1. GPS Trial Fix Distribution.

Fix type	Percentage of total
3-D	62
2-D	12
None	26

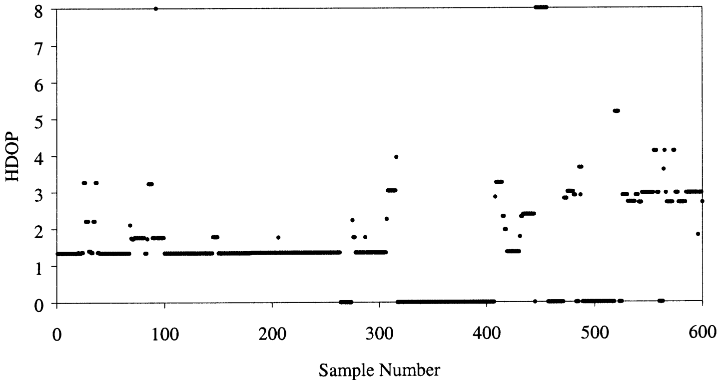

Figure 3. GPS Trial HDOP.

Of course, not only does the number of tracked satellites have to be considered whilst assessing the position fix quality, but also the geometry of those satellites around the receiver. Figure 3 and Figure 4 show the horizontal and vertical dilution of precision (HDOP and VDOP) respectively for the satellite constellations tracked during the positioning trial.

Hence, during the later half of the trial even when position fixing is possible, the dilution of precision is high and so degrades the fix accuracy. The potential impact of combining the GPS position fix data from Figure 1 with additional ranging measurements from cellular base stations is assessed in Section 5.

3. CELLULAR POSITIONING. Cellular positioning methods are based upon determining the Mobile Station (MS) location with respect to the network Base

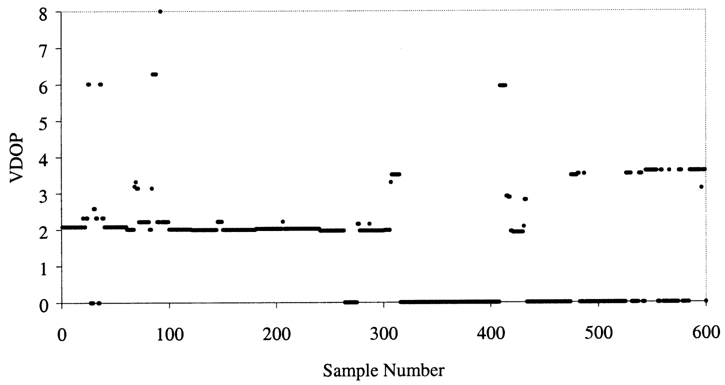

Figure 4. GPS Trial VDOP.

Stations (BSs). Two basic schemes are used. The down-link method whereby the MS makes measurements of signals received from the BSs, and the up-link method whereby the network makes measurements of signals transmitted by the MS. The positioning method employed impacts upon the information interchange, the required system modifications and, of course, the accuracy of the derived position estimate. The ease with which positioning capabilities can be added to a cellular system can also be dependent upon the willingness of the network operator to co-operate in the chosen scheme.

3.1. *Ranging Measurements.* An MS to BS range measurement occurs as part of the normal functionality of GSM so that the relative signal timings of the system elements can be adjusted to adhere to the GSM TDMA specifications. However, GSM is inherently optimised to support reliable communications, not precision positioning services, and the timing information available as a by-product of the system does not yield ranges of particularly high accuracy. Hence, for some applications, additional functionality is required to either, or both, the MS and BS to produce ranging measurements of the desired quality. For a CDMA system the ranging can occur against the CDMA code itself, in a manner similar to GPS. In TDMA based systems, synchronisation information present in the BS transmissions used by the MS to synchronise to the TDMA structure, can be used as epochs against which timing measurements are made.

The BS transmissions received by the MS will be a combination of direct (possibly) and reflected (multipath) signals and, of course, multipath will be prevalent in city centres. Therefore, the measured signal transmission times will be degraded by the level of multipath. However, the equaliser present in the MS – used to reconstruct the transmitted signal from the received components – should help to reduce the impact of multipath. It should also be noted that MSs will be set up to maximise performance in terms of voice and data links and such a configuration is not necessarily optimal for positioning purposes. The measurements of range (signal transmission time) will include errors from several sources such as:

(a) Timing accuracy of the MS,
(b) Errors in the BS timing,
(c) Errors induced by the method used to determine the BS timing (or relative timing).

Since the BSs will be, broadly speaking, all in the horizontal plane of the MS, then only a 2-dimensional or horizontal position of the MS can be derived reliably. The position accuracy will be degraded by the HDOP of the base stations being used in the solution.

$$\sigma_{\text{Position}} = \text{HDOP} \times \sigma_{\text{Measurement}}$$

In a city centre where the cell number is dense, the number of BS transmissions available to the MS should be sufficient such that the HDOP of the BS constellation is not prohibitive. However, in other areas where the volume of traffic is less (larger cell sizes), the number of BS transmissions available to a MS will decrease with potentially an increase in HDOP.

3.2. *Cell Identity Method.* In its coarsest mode, cellular positioning can be based upon simply taking the position of the MS as the position of the BS in the cell in which the MS is currently camped. Hence, the maximum position error will be the cell radius. (This is not necessarily true in all cases. Some cell structures may be based upon base stations using a directional antenna with illumination occurring from the cell edge.)

Cell radii vary due to the different cell densities required to support the expected volume of users. In GSM, the maximum cell radius is 35 km, but in major city centres, with a high cell density, the radius may be at the level of 1 km or smaller. Therefore, if this level of accuracy is acceptable, the only additional function that is required is to relate a BS identification to a physical location.

In a regular positioning application this function would be carried out at the MS. In an inverted positioning application, the MS may just transmit the identification of the base station of the cell in which it is currently camped to the central monitor site, which in turn relates the information to a physical location. Of course, any cellular radio network already monitors at some level (either to a single cell or a group of cells) where a MS is located for the purpose of cell handover and for paging the MS with an incoming call. The Cell ID method is also known as COO (Cell-Of-Origin). COO has the advantage that intrinsically it requires no modifications to either the handset or the network.

3.3. *Timing Advance Method.* The TDMA scheme employed by GSM requires that a BS receives transmissions from MSs correctly aligned to the BS time slots. The timing tolerance in the GSM specifications is ± 1 bit period ($48/13\ \mu$s). For a 35 km cell, the maximum round-trip (BS-MS-BS) signal propagation time is about 233 μs and therefore it is necessary for the MS to advance its transmissions to compensate for this delay. The required Timing Advance (TA) is determined by the BS measuring the round-trip propagation time and then instructing the MS by sending it a coded TA between 0 and 63 (in units of a data bit). Hence, this produces a timing advance range of 0 to 233 μs. The required accuracy in the TA results in a relatively poor range accuracy (in the context of positioning the MS) typically of the order of 500 m. Also, the TA determination algorithm will be based upon maximising signal strength, which does not necessarily correspond to the shortest signal path length. To determine an unambiguous MS location, ranges from a minimum of 3 BSs will be required so that circular trilateration can be applied as shown in Figure 5.

Normally, TAs will only be determined from the BS in which the MS is currently camped. To get TAs from other BSs will require the MS to be forced to attempt a handover to neighbouring cells. Apart from forced-handovers, the sequential nature of the timing measurements between the BS group will introduce further positioning

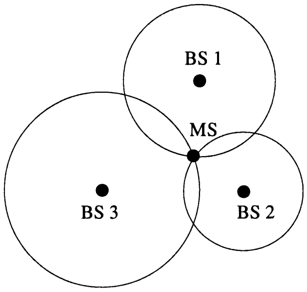

Figure 5. Circular Trilateration.

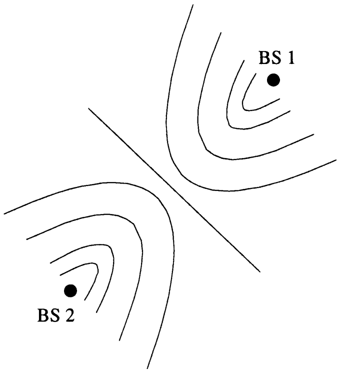

Figure 6. Hyperbola of Constant Range Difference.

inaccuracy, particularly if the MS is moving at high velocity. Clearly, the TA method requires non-trivial modifications to the handset and is also intrusive to the normal operation of maintaining a voice or data call.

3.4. *Circular Method.* If the MS knows when a transmission occurred from a BS, it can then measure the actual signal propagation time. By correlating with the training sequences in the transmitted bursts, ranges to several BSs can be formed. The MS position can then be determined by circular trilateration as shown in Figure 5. It is likely to be impractical for the BS transmissions to be physically synchronised and hence to perform circular trilateration would require the availability of BS timing offsets. These may be monitored and disseminated by the network provider or alternatively supplied by dedicated monitor units deployed within the region of coverage. Of course, the measurement scenario may be reversed with the BSs making received time measurements of a signal transmitted by the MS. In this mode, the circular method is commonly referred to as TOA (Time-of-Arrival). Either way, implementation of the circular method is likely to require modification to both handset and network, or at least augmentation to the network, and again is intrusive to the normal handset operation.

3.5. *Hyperbolic Method.* If the absolute times of transmission from the BSs are unknown, but the relative time offset between BS transmissions is, then position hyperbolae can be formed by measuring the reception time difference between pairs of BSs. Such a measurement is usually referred to as the Observed-Time-Difference (OTD). Each hyperbola represents a locus of constant range difference as shown in

Figure 6. Three pairs of BSs allow the MS to be positioned using hyperbolic trilateration. The whole process of the MS extracting OTDs and performing a positioning solution is commonly referred to as E-OTD (Enhanced-OTD).

The Hyperbolic method can be inverted. Rather than the MS making measurements on the down-link, the BSs can make measurements of the up-link. Each BS can measure the time of arrival of bursts transmitted by the MS. Again, since the time of transmission from the MS is unknown then the BS measurements are formed into OTDs and hyperbolic trilateration is used for the position fix. In terms of power conservation the latter method is, of course, preferable. The hyperbolic method suffers the same implementation issues as the circular method in that relative timing offsets caused by BS unsynchronisation need to be known, together with significant handset and network modifications, together with issues of intrusiveness over normal handset operation.

3.6. *Angle-of-Arrival Method.* Angle-of-Arrival (AOA) or DOA (Direction-of-Arrival) based positioning uses a phased-array antenna at the BS to produce directional information of the MS from the BS. This may also be coupled with range information to increase the number of observables, and hence increase the positioning accuracy. Alternatively, the number of BSs required to obtain a position fix may be reduced (single BS solution). The downfall of AOA is that the changes required to existing network infrastructure could be prohibitive.

3.7. *Assisted-GPS Method.* Assisted-GPS (A-GPS) uses the cellular network to assist the GPS receiver. Timing information and satellite data provided by the network can enhance the performance of the receiver by reducing the time required to obtain a position fix and increasing the tracking sensitivity. A-GPS methods alleviate, to a certain extent, the problems associated with tracking GPS satellites in harsh environments. However, a further benefit can still be obtained by utilising both GPS and cellular measurements within the navigation solution.

4. GSM ACCURACY ANALYSIS.

The accuracy analysis presented here assesses the MS timing error via the use of a GSM simulator and the impact of the BS geometry by examining the HDOP of a typical cell structure.

4.1. *Timing Error.* The MS timing error was assessed by recording the bit timing error of the MS using the GSM simulation scenario TU50 (Typical Urban, MS speed 50 km/h). Figure 7 shows a histogram of the bit timing errors (expressed in metres)

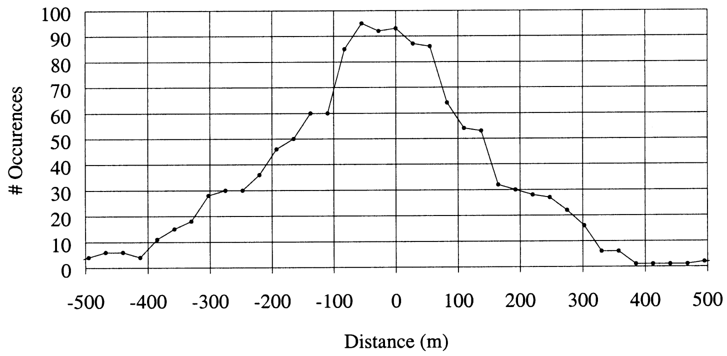

Figure 7. MS Bit Timing Errors (TU50 scenario).

Table 2. OTD Positioning Accuracy (m).

Environment	Accuracy – 67% of time No MPR or weighting	 MPR and weighting
Bad urban	283	206
Urban A	157	101
Urban B	87	58
Suburban	42	58

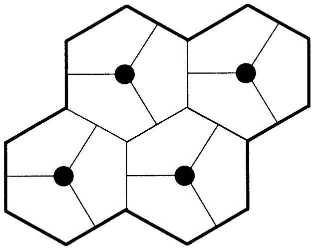

Figure 8. 4/12 Frequency Reuse Pattern.

over 1300 samples. The standard deviation of the data in Figure 7 is 184 m, although it should be remembered that the MS had not been optimised, or any special algorithms employed, to maximise ranging accuracy (such as filtering applied to the data).

Several publications by members of the subcommittee T1P1-Wireless/Mobile Services and Systems of the T1 organisation have assessed GSM position accuracy using simulations covering a range of environments and measurement methods. These tests have included the use of measurement weighting and multipath rejection (MPR) algorithms. Typical results using an OTD method are shown in Table 2 (Villier and Lopes, 1998).

For the simulation, data in a 4/12 frequency reuse pattern were used as shown in Figure 8. In the urban simulation, the cell size is 1·5 km and in the suburban environment 4·5 km. The ranging measurements were achieved by cross-correlation against the GSM synchronisation bursts (in packets of 20 per second). Five base stations were used in each position fix and an MS speed of 50 km/h was employed.

From the results in Table 2, it can be seen that a significant improvement occurs from the application of measurement weighting and multipath rejection, except in the suburban environment simulation. This is attributed to the multipath rejection algorithm being optimised for the harsh urban environment, with a consequence of a degraded suburban performance. Hence, either the degradation is accepted or a more environmentally adaptive algorithm is applied.

4.2. *Base Station Geometry*. The geometry of the BSs used in the location solution impacts upon the positional accuracy due to the well known Dilution of Precision (DOP) factor. Since the user and the BSs are essentially all in the same, horizontal plane, the HDOP is of most interest. Figure 9 shows the HDOP pattern for a three cell reuse pattern. At each point the HDOP is evaluated to the three nearest BSs.

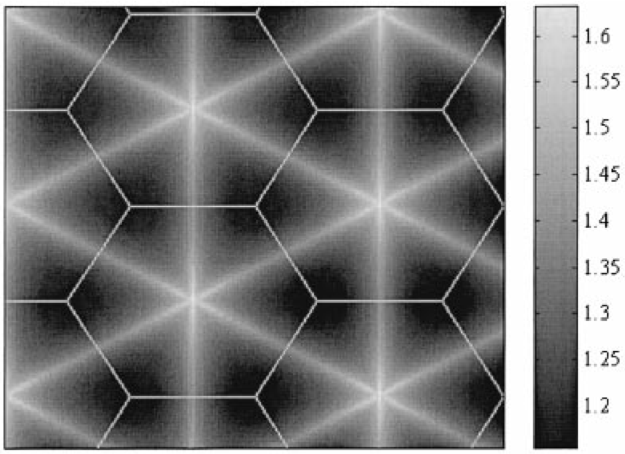

Figure 9. Three BS HDOP.

As would be intuitively expected, for three BSs the HDOP is minimised when the MS is located at the centroid of the triangle and maximised when the MS lies on the line joining a BS pair. In general, particularly in urban environments with a dense cell structure, the MS may be able to range to more than three BSs at a time. However, since a minimum of three BSs are required to perform a cellular position fix, then this should be taken as a worse-case scenario. Figure 9 indicates that, if an accuracy of 100 m is desired, then for a maximum HDOP of 1·6, a measurement accuracy of approximately 62·5 m is required. Fortunately, there is cohesion between the geometric placement of BSs to give satisfactory cellular capacity and coverage and the resultant DOP for the purposes of positioning. However, network providers wishing to facilitate the use of cellular systems for positioning may wish to consider the placement of their BSs in the context of the DOP that MSs will experience.

5. GPS AND CELLULAR INTEGRATION.

The integration of GPS and cellular systems can be considered at two levels:

(a) Integration at a measurement/data level,
(b) Integration at an infrastructure level.

5.1. *Measurement Integration.*

Many of the currently proposed systems that combine GPS and cellular systems only do so at the level of exchanging information (cellular assisted GPS), using the cellular system as a communications channel and using GPS as a precision time source. Whilst these systems can give improved positioning performance, they do not attempt to combine GPS measurements with the cellular ranging measurements into a single navigation solution and so cannot be considered optimal.

In an urban environment, the GPS signals that get blocked tend to be lower elevation satellites and conversely those that can be tracked are clustered near to the zenith or perhaps lie in the plane of the street along which the receiver is moving. Consequently, if there are enough satellites to form a navigation solution the geometry of the constellation will tend to yield a high HDOP. This is unfortunate, since for a land-based user the horizontal position components are likely to be of greatest interest.

As has been seen, for a cellular-based positioning system the opposite is true since the BSs and MS are essentially in the same horizontal plane, yielding low HDOP but typically a poorly defined vertical position component. Therefore, in terms of geometry, the combination of GPS and cellular BS measurements will result in a much improved DOP for a 3-dimensional position fix. The combined solution also allows for all data to be incorporated into the position determination algorithm rather than rejecting data, and so useful information, for reasons such as not enough visible satellites or not enough available BSs.

The mathematical practicalities of combining the measurement data obviously depend upon the exact nature of the data being provided for the solution. GPS provides range and range-rate measurements for a circular positioning solution, whereas the cellular system may provide a selection of BS range, BS range differences, MS TA data plus possibly derivatives of the various range measurements. Equally, the nature of the error sources and the statistical characteristics of the measurement data will be different for the different systems and must be accounted for if an optimal solution is to be produced.

5.2. *Infrastructure Integration.* Since cellular systems are not inherently designed to support positioning services, the incorporation of such functionality can occur in a number of different ways and is also influenced by the requirements of the application concerned. The issues of concern include data flow, information interchange, time synchronisation, power conservation, and the impact of positioning capability on the normal communications functionality of the system and, of course, implementation costs.

One of the fundamental application questions is: 'where is the knowledge of the MS location required?' Not only does this impact on the information flow but also on issues such as where the position solution calculation is performed and what types of measurements are made. However, whatever the system, if measurements with respect to BS locations are made then it will be necessary for either the MS, or a third-party interested in the MS location, to know the BS positions. Of course, such information is not needed or not usually made available by network operators since the BS locations are not needed for a cellular system to operate.

The relative time synchronisation of the BSs is also important in the implementation of positioning capabilities. In a circular trilateration mode, it is necessary for the transmission of the BSs to be known to a common time to enable range measurements to be corrected for BS time offsets. In a hyperbolic trilateration mode, the time differences between BS stations is required so that the offset can be separated from the measurement. Again, such time synchronisation information is not normally made available by the network operator and so may have to be measured by a dedicated monitor station located at a fixed, or known, location.

Another fundamental question is: 'where are the range measurements (or other type of measurement) made? Are the measurements made at the MS or at the BSs?' To minimise network disruption the ideal scenario is for any modifications to occur at the MS. This will also allow regular MSs to operate as normal. However, placing the onus on the MS introduces many issues such as an increase in power consumption and possible interruption to the normal MS voice and data services.

An inverted positioning system, such as a system where the position solution is determined not at the MS but at some other location, could be based around the BSs making measurements of the MS transmissions which, if the MS transmission time is unknown, could be differenced and hyperbolic trilateration used. However, such a scheme again impacts on the MS power conservation, and has possible consequences on the normal MS usage, if the MS has to transmit signals specifically for positioning purposes.

5.3. *Integration Simulation.* In an attempt to assess the impact of combining GPS and cellular BS ranging measurements in a single position solution, the position fix data of Figure 1 were combined with simulated cell locations (cell radius 1·5 km) as shown in Figure 10.

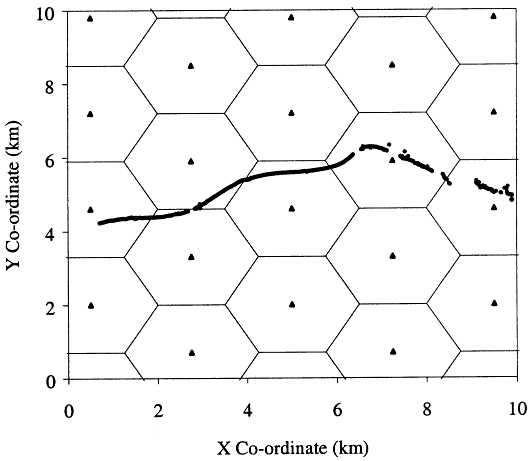

Figure 10. Simulated Cell Locations.

At each position fix, the horizontal and vertical dilution of precision was re-evaluated by combining the visible satellites at each point with the three nearest BSs. The resultant HDOP and VDOP are shown in Figure 11 and Figure 12 respectively.

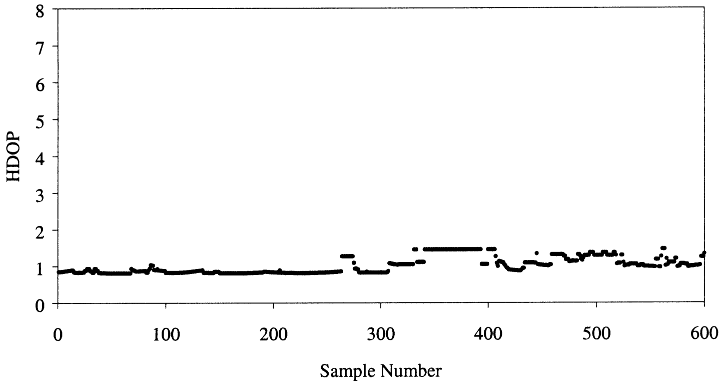

Figure 11. GPS/Cellular Simulated HDOP.

The addition of the BSs mainly aids the horizontal component of the solution and so the HDOP shows the most improvement (comparing Figure 3 with Figure 11 and Figure 4 with Figure 12). At those points where at least one satellite was visible, a 3-dimensional position solution may be attempted. However, the geometry may still

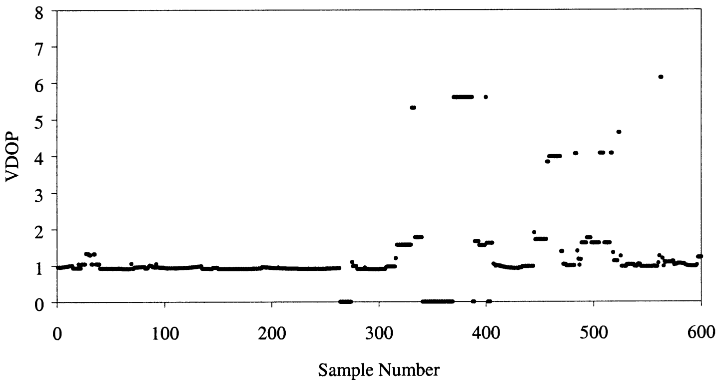

Figure 12. GPS/Cellular Simulated VDOP.

Table 3. GPS/Cellular Simulated Fix Distribution.

Fix type	Percentage of total
3-D	93
2-D	7
None	0

yield a high VDOP, in which case a 2-dimensional solution would appear to be more prudent. Since it was assumed that three BSs would be available at every point, it will therefore be possible to perform at least a 2-dimensional navigation solution at every location. In regions of high cell density, an MS may be able to obtain measurements from several more BSs, although at a lower received signal strength. The new theoretical position fix distribution obtained by including measurements from three BSs together with the available GPS measurements is detailed in Table 3.

For land-based applications, where horizontal positioning is probably of greatest interest, the question may be asked: 'Of what benefit is the retention of the GPS data when the cellular data may suffice?' For maximum accuracy, availability and continuity, all observables, GPS and cellular, should be used in the solution. In non-urban areas, there may be insufficient BSs to provide cellular positioning alone. For maximum accuracy, a 3-dimensional solution is preferable to one in which the receiver height is assumed fixed. In general, particularly in the case of differential GPS, the range measurements from GPS will be significantly more accurate than those obtained from within the cellular network. A redundancy of measurement data also aids the integrity of the solution.

6. CONCLUSIONS. The use of cellular systems for the purpose of positioning is an area that has generated great interest. Under a range of environments, and with suitable data processing, cellular-based systems can produce positioning accuracy similar to that of SA-degraded GPS. However, issues such as coverage limitations make cellular positioning systems unsuitable where unrestricted positioning capabilities are required. Cellular system also, essentially, only provides horizontal positioning. The combination of GPS and cellular technologies, particularly with SA removed, affords improved positioning capabilities over a range

of operating environments that neither system alone can achieve. The optimal integration of GPS and cellular positioning systems occurs through combining the measurements into a single integrated navigation solution to exploit all the available information fully. The GPS/cellular combination also provides improved transmitter geometry in areas where signal blockage may occur. Since cellular systems are designed for communication rather than positioning, a number of infrastructure modifications are required to enable the cellular ranging measurements to be used in a position solution. Depending upon the exact functionality required by the application, modifications to the MS, the BSs, and other parts of the cellular network may be necessary. The cellular communications link can also be used to provide assisted GPS where information such as satellite positions, differential corrections and timing data can be used to enhance the performance of a basic GPS receiver.

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