

# Chapter 11

## Spatiotemporal Accuracy in Mobile Phone Location: Assessing the New Cellular Geography

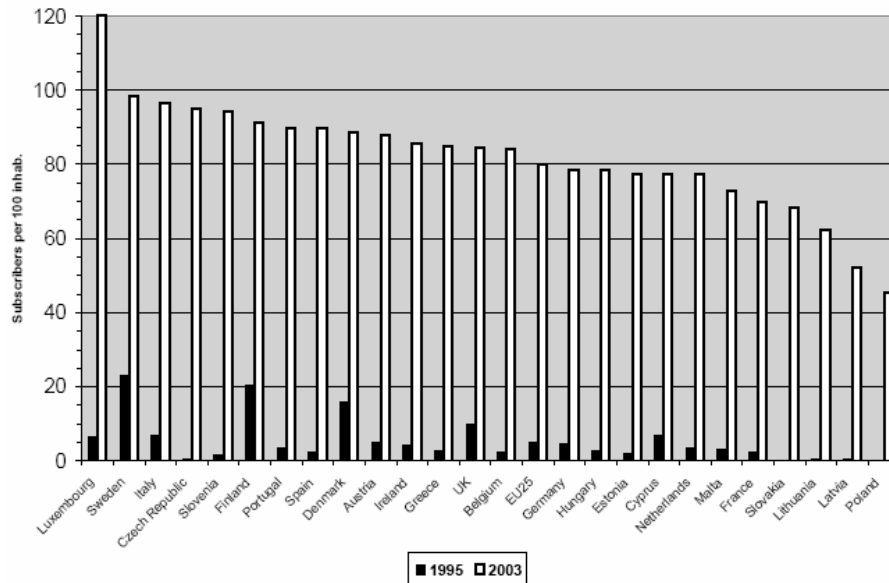
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### 11.1 Introduction

Mobile or cellular phones form part of the everyday life experiences of 80% of the adult population in developed countries and their use is growing (see Figure 11.1, which reports 2003 data). They have quickly become ubiquitous devices that go wherever their users go, surpassing their original purpose of an individual communication system to become a 'wearable computing' device.



**Figure 11.1.** European mobile phone penetration. Number of subscribers per 100 inhabitants 1995 and 2003 (EU-25). Source: EUROSTAT (2005).

Mobile phone *location*, together with the individual identification of its user, can provide a new methodology to understand population mobility in contemporary societies (Miller, 2004). However, from a geographic point of view, most research published on mobile phone location has primarily focused on the spatial information requirements to support Location Based Services (LBS), or its visualisations, at the *individual* user level (Mountain and Raper, 2001; Dykes and Mountain, 2003, 2002) rather than at a *society* level. A recent exception of this is the work of Shoval and Isaacson (2006).

The contribution presented in this chapter is based on the premise that mobile phone location (or its technological successors) ought to become a new spatial reference system, drawing a parallel with the development of the postcode to become the 'New Geography' a decade ago (Raper et al., 1992). The 'New Geography' of the turn of the millennium has been also defined as a 'Mobile Geography' (Amin, 2002; Fisher and Dobson, 2003) where society is no longer seen to be tied to spaces of fixity but rather to move in spaces of flows. The authors of this chapter believe that mobile phone location methodology allows the measurement of the mobility patterns of large groups of people, through the analysis of the 'spatiotemporal signature' of their mobile phones. However, such measurement is limited by constraints of the spatiotemporal *accuracy* imposed by the technology and thus configuring what is here defined as the 'New Cellular Geography' — a geography of cells through which people can be seen moving. In other words, the fact that the location accuracy is so poor makes the mobile geography a cellular geography of movement between coarse cells, and not a precise space of flows.

Assessing those technological limitations in the spatiotemporal accuracy of mobile phone location is of significant importance to social scientists interested in starting to understand the 'New Cellular Geography'. This chapter presents an evaluation of the spatiotemporal accuracy of mobile phone location with the aim of determining its most appropriate scales of application as an automated method to measure and represent the mobility of individuals or large groups of the people in contemporary cities. Measuring and understanding the spatiotemporal accuracy of information about mobile objects is a crucial requirement to build reliable dynamic and mobile GIS, the major theme of this book, and essential in determining the geographical scale of mobility that this technology can measure.

The research carried out and presented here analysed the level of spatiotemporal accuracy of mobile phone location available in the UK in 2004, as an early example of the technology easily accessible to any researcher interested in mobility studies. Furthermore, it also provides a baseline against which future enhancements of mobile phone location methods (i.e. 3rd Generation mobile phones, GPS-enabled phones, or voice-over Wi-Fi technology) can be compared with.

The second section of this chapter presents a brief overview of contemporary concepts of cities as spaces of flows to justify the need for new tools to measure urban mobility. Section 11.3 reviews a series of important issues surrounding

mobile phone location technology, including society and mobile phones, new location uses and requirements, mobile phone location accuracy and privacy issues, in particular focusing on its spatiotemporal accuracy. The fourth section presents the methodology of the research carried out to assess the spatiotemporal accuracy of mobile phone location available in the UK in 2004, while the Section 11.5 summarises the analysis of the results. Finally, the sixth and last section offers some conclusions and drafts out the future developments and opportunities for mobile phone location to become the ‘new cellular geography’.

## 11.2 Measuring the mobile society

*‘In contemporary societies mobility has become the primary activity of existence.’*

(Prato and Trivero, 1985, cited in Thrift, 1996, p. 286)

Contemporary conceptions of cities and urban life give mobility a primary role as the major structuring component, using such metaphors as ‘the space of flows’ (Castells, 1989), or ‘a place of mobility, flow and everyday practices’ (Amin and Thrift, 2002). Cities are no longer seen as a bounded space around a single centre, or as an independent organic structure with well-defined borders, nor as an integrated system following specific rules within an ‘outside world’. Instead cities are today perceived as nodes in a space of flows (Castells, 1996). Cities are thus seen as the relative space of the ‘multiplex city’ vs. the old order of the ‘uniplex city’ resulting from a ‘splintering urbanism’ (Graham and Marvin, 2001) or as a place of mobility, flow and everyday practices (Amin and Thrift, 2002). These and other authors (e.g. Bauman, 2000; Urry, 2003; White, 1992), no longer see cities as spaces of fixity, where order should be sought, but instead as an amalgamation of changing flows, a station in networks of distant socio-economic relationships, a relative space of complexity.

Despite a general consensus in this major turn on the conception of contemporary cities, there are conflicting theories about how contemporary cities should be understood and represented. This chapter does not aim to participate in the current urban debate, but instead proposes and evaluates a new methodology to represent such new conceptions of contemporary cities. There is a need for finding new representations of cities and contemporary urban life but it is acknowledged that the right tools to do it have not been available. As Sudjic summarises it: ‘it is true that in its new incarnation, the diffuse, sprawling, and endlessly mobile world metropolis is fundamentally different from the city as we have known it (...) But the equipment we have for making sense of what is happening to our cities has lagged far behind these changes’ (Sudjic, 1992, p. 297).

This lack of appropriate ‘measuring equipment’ is especially obvious in the traditional methods of social science research that try to map and understand the spatiality of the ‘mobile society’, since they fail to adequately measure its rapidly changing spatiotemporal dynamics. These attempts to understand mobility from the

standpoint of population geography (primarily based on population census), geodemographics, and transportation research (through travel surveys), usually fall short of reflecting the complex reality of each individual's life (Cole et al., 2002).

Therefore, mobile phone location, or in fact any other technology that allows a mobile personal computer device capable of transmitting its location (such as a PDA-GPS – personal data assistants with global positioning system, Wi-Fi laptop computers, RF-ID tags – Radio Frequency Identification tags, etc.), offer a very viable solution to track the mobility of large groups of population with extensive societal coverage already built in.

### 11.3 A review of mobile phone location

This section will look into the technological detail of mobile phone location to help understand the results of the evaluation of its spatiotemporal accuracy, which is presented in subsequent sections. The following five sub-sections will briefly cover a few of the important issues that shape mobile phone location technology; society and mobile phones, new location uses and requirements, mobile phone location accuracy and privacy issues. The focus is thus on the impact of each of these issues on spatiotemporal accuracy, as background against which to interpret the results of the research presented later in the chapter.

#### 11.3.1 Society and mobile phones

During the last ten years, mobile phones have become an integral part of contemporary societies, not only in developed countries, but also in the so-called developing countries, where on many occasions it is the only type of telecommunication technology available to its citizens (Agar, 2003). The number of mobile phones worldwide in 2005 was 2 billion subscribers with an estimated figure of 3 billion subscribers by 2010 (Informa Telecoms and Media, 2005). In most countries mobile phone penetration had widely surpassed the number of fixed telephone lines in 2005.

This phenomenal growth is signalling the inherent essence of the mobile phone versus the fixed telephone; the mobile phone identifies and communicates the person who uses it, while the fixed telephone line connects the household or the company (Cairncross, 2001). It is this personal use and individual identification, together with the ubiquitous possibilities of nearly anytime/anywhere one-to-one communication that has made mobile phones so popular. Their diffusion has been much faster than any other mass technology in the past, to the point of starting to be considered today as an 'extension of the body' (Townsend, 2000).

These are the pivotal points that justify the use of mobile phones as the location technology for the purpose of tracking mobility in contemporary societies, as expressed in Section 11.2, and that can be summarised in the following three major advantages for social scientists:

- ❑ High penetration across most groups in society
- ❑ Accepted status as an 'always-on wearable device'

- The individual identification of its user.

This chapter concentrates in the spatiotemporal accuracy of mobile phone location and therefore other societal aspects of the mobile phone boom will not be covered here (for a review, see Lacohee et al., 2003), nor its technical evolution and future developments. Nevertheless, additional research is needed to identify the social groups that lie in the remaining proportion of society that is not using mobile phones, and establish the major factors in their decision, since they would not be covered by the methodology analysed here (e.g. see Osman et al., 2003).

### 11.3.2 Mobile phone location technology

Mobile phone operators need to know the geographic location of each mobile phone device in the network in order to be able to route calls to and from them, and to seamlessly transfer a phone conversation from one base station to a closer one as the user is moving while talking. This technical need was transformed into a commercial opportunity to increase the *Average Revenue Per User* (ARPU; Adams, et al., 2003), through what are now known as 'Location Based Services' (LBS).

LBS are all those services that use the location information of a mobile device to provide a user with location-aware applications (Fisher and Dobson, 2003). Such location information can be provided by the network operator, the mobile phone device, or a combination of both. The type of LBS applications initially proposed were very broad and creative and raised many expectations in the general public (Schofield, 2004). For example, one was offered the possibility to make requests of the type of 'where is the nearest...?' (ATM, petrol station, pharmacy, etc.), identify friends that walk near by, ask for navigation instructions if we are lost, know where is another person, or receive a promotion from a familiar store as we walk past it (Location based 'spam', see Chapter 3). Nevertheless LBS failed to deliver its promises at the turn of the century, and its huge forecasted market potential did not come to reality basically because the users have yet to find any true value in the few service options available (Zetie, 2004). This is partly because early services have been very restricted due to the poor location accuracy available, and the limited capabilities of both the hand-held hardware (screen size and quality, processing power and storage capacity) and the network data transfer speeds and bandwidth (Mountain and Raper, 2001). These issues are beyond the concern of this accuracy-focused chapter, however, and hereinafter only the location aspect of the much broader 'LBS field' will be considered in this analysis (the 'L' in LBS).

Despite the initial commercial failure of LBS, new legislation recently introduced by the US and the European Union (EU) requiring mobile phone operators to provide an accurate location for calls to emergency services, have acted as a catalyst for increased commercial support of LBS since 2001 (Chen, 2004). Worldwide revenue from LBS is now expected to increase to more than USD \$3.6 billion by 2010, from \$500 million in 2004 (Chen, 2004). Those legal requirements and their implications for location accuracy demands will be discussed in Section 11.3.3. The second characteristic of this LBS 'revival' is that the most successful applications are not those that offer location-aware contents to the mobile device user, but

instead, those that provide the user's geographical location to a third party, together with some other value-added services, especially tracking of children, travelling employees or vehicle fleets (Zetie, 2004). These services have raised new privacy challenges that will be briefly exposed in Section 11.3.5. But all are based upon the ability of the system to report reliable and accurate locations of users, providing the rationale of the work reported in this chapter.

### 11.3.3 New location uses and requirements

The automatic location of persons or mobile objects is a broad research field and commercial market, being LBS for mobile phones just a subset of it. As computers become ever more ubiquitous and multifunctional, mobile computing devices 'need to know' their geographical location in order to perform certain functions (Costa-Requena et al., 2001). This broad field of ubiquitous computer devices is generally referred to as 'wireless computing', and the devices that reveal the location of the person using them (e.g. GPS, mobile phones, RF-ID tags, etc.) have been termed '*Personal Location Devices*' (PLD; Fisher and Dobson, 2003). Therefore, the discussion presented here should be viewed within the much wider subject of wireless computer device location, but has been reduced in this chapter to mobile phone location for simplicity due to the enormous popularity of that device.

A major distinction must be made between applications where the location information is only known by the *personal location device* (PLD) itself, its 'end-user', or the network operator, and those in which this information is passed onto a third party. A third party refers here to an organisation or person who requests the location information of a PLD, being a different entity from either the user of the PLD (1st party) or the network or technical operator of the PLD (2nd party) (Fisher and Dobson, 2003). The current debate and new thrust of mobile phone location applications in the last few years have been particularly centred on these third-party applications.

The situations in which society is ready to relinquish some individual privacy for a greater benefit are typically those where life is at risk, or justice is at issue. The privacy issues of disclosing such information are briefly exposed in Section 11.3.5. In this section the main two new uses of such 'potentially allowed disclosures' will be summarised, since they are shaping the new location requirements and are providing new scenarios for future research in this area: emergency services, and terrorism and crime prevention.

**Emergency Services.** In situations where life is at risk, the most important strand of new location applications fall within the emergency services arena (see also Chapter 12 on the use of mobile GIServices applications in disaster management). The dispatchers of emergency-response organisations recognised the growing problem of not being able to locate calls from mobile phones, which in many countries account for over 50% of total calls to emergency services (Salmon, 2003). The caller is usually not able to provide his/her location accurately to send a rapid response, especially under a panic situation or when outside the area of his/her daily wanderings (Hunt, 2004).

In the US a set of legislation known as ‘e-911’ (for ‘enhanced 911’, the federal emergency number) was approved by the Federal Communications Commission (FCC) as early as 1996, requiring all the wireless communication operators to provide the *automatic location information* (ALI) of callers to 911 emergency services (Federal Communications Commission, 2004). The initiative was to be rolled out in two phases at the end of which wireless operators were required to provide tight location accuracy depending on one of two possible methods to provide ALI; ‘network-based solutions’, where the network calculates the location of the caller, or ‘handset-based solutions’, where the location is provided by the actual handset (requiring GPS-enabled phones). Those accuracies were (Salmon, 2003):

- ❑ For network-based solutions - 100 metres for 67% of calls, and 300 metres for 95% of calls.
- ❑ For handset-based solutions - 50 metres for 67% of calls, and 150 metres for 95% of calls.

The FCC has already fined several operators for millions of dollars for failing to meet those requirements (Weaver, 2003).

The importance of the e-911 initiative lies in the fact that, based on the legal pressure faced by mobile phone operators, the wireless location market has been exhausting all the technical possibilities that were financially feasible to provide an accurate ALI, speeding up dramatically the implementation of true LBS as a side effect (Branscombe, 2003). Similar but later efforts have been introduced in the European Union (EU) under the e-112 directive (European Commission, 2001), proposed in 2001 and finally approved in July 2003 (Branscombe, 2003), whose benefits are just starting to be realised by the emergency services sector in some EU countries (Hunt, 2004).

**Terrorism and crime prevention.** Other examples of the new uses of mobile phone location information by third parties that have already started to be accepted by society are related to the numerous recent measures to tackle terrorism or crime. Mobile phone location information is already being used by the police to track offenders, either in chases or as evidence for trials. Summers (2003) reports six different trials where mobile phone location evidence proved decisive in the conviction of murderers between 2002 and 2003, depicting this technology as ‘the new fingerprint’. The value of this technology for police has been definitely proven during the Madrid and London train terrorist bombings, on 11th March 2004 and 7th and 21st July 2005, in which mobile phones played a major role in activating the bombs or capturing the terrorists (El Pais, 2004; BBC News 2005a).

However, the way that mobile phone location technology worked in 2004 could only *partially* help the police authorities, not only because of the location accuracy problems already mentioned, but more importantly due to the ephemeral nature of the location data that is not systematically stored. In the UK, the Home Office proposed a requirement for mobile phone operators to keep location information for

12 months and SMS for six months (Mathieson, 2003), a proposal which has been extended to the whole of Europe in 2005 (BBC News, 2005b). These proposals present an important challenge to individual privacy (BBC News, 2005c), as well as require a high level of commitment and investment from the operators, sometimes saturated by police requests (The Economist, 2005). On the other hand such datasets pose an enormous potential for the type of geographical analyses this chapter proposes (assuming that some degree of access to aggregated data is allowed), as well as a critical challenge to current ontologies of spatiotemporal representation, GIS data models and database storage and processing capacity.

#### 11.3.4 Mobile phone location accuracy

There are several approaches to finding the PLD user's location employing various technologies and resulting in several geographical accuracies. Until recently, a distinction in the positioning technology of a PLD would clearly differentiate the type of device and its market sector (e.g. mobile phone, GPS or RF-ID tag). As these technologies have been miniaturised they are being combined in hybrid solutions that use more than one of these location methods to calculate its position (such as GPS-enabled phones). Nevertheless, in 2004 the majority of PLDs used were mobile phones (in a traditional sense) and still had a 'stand-alone' basic network positioning method. Therefore, since the interest of the research presented in this chapter was to measure the commonly available mobile phone location technology in the UK in 2004, only network-based location methods will be discussed in this chapter.

Mobile phone location methods (until GPS-enabled phones appeared in 2004) rely on the way operators structure the cellular network of transmitters for finding phones in their service territory and routing calls to them. The basic type of phone positioning is called *Cell-ID* location (Cell Identification), a method that requires little investment and provides poor accuracy since cells vary greatly in size, especially outside urban areas (Spinney, 2003). Accuracy of Cell-ID location depends on the size of the cell where the user is located (the greater the cell size, the less accurate the location estimate), cell size being dependent on several factors: the density of base stations that an operator has in an area, the power of their transmitters, the height over the ground of the transmitters and the obstacles around the base station (e.g. buildings, trees, local topography). As a result, the accuracy can vary from 500 metres to over 5 km (see Section 11.5.1 for the actual results and discussion).

A variation of the Cell-ID methodology is called Cell-ID++, which combines basic Cell-ID positioning, with Timing Advance (TA), and Network Measurement Results (NMR). TA corresponds to a distance estimate from the base station to the handset based on timings, while NMR measures the power of the signal received by the mobile phone from the adjacent base stations (Faggion and Trocheris, 2004). Cell-ID++ just estimates the radius around a base station where the mobile phone is likely to be located.

In order to improve location accuracy beyond Cell-ID solutions, many different methods have been proposed. The 'Angle of Arrival' (AOA) method requires a



minimum of two base stations to determine the angle of arrival of the mobile phone signal, and the network can then work out the handset location by bilateration. 'Enhanced Observed Time Difference' (E-OTD), also called 'Time of Arrival' (TOA) (Zhao, 2002), measures the time difference between signals from three or more base stations to the mobile phone to calculate the distance to each station, and then obtains its position by the trilateration of those distances. All elements in E-OTD must be constantly synchronised. A different method that does not require time synchronisation is 'Time Difference of Arrival' (TDOA) in which the mobile phone position is determined by the network's servers based on trilateration but using time difference measurements rather than absolute time measurements.

All of these methods are very difficult to implement across the network because expensive equipment such as directional antennas, precise clocks or additional location-processing servers at base stations are required (Zhao, 2002). Additionally some of them require special software to run on the handsets, which would mean that it would only work in the most advanced ones. According to Mountain and Raper (2001) in 2001 neither did most of the UK networks provide these conditions, nor were the handsets ready, and even when all factors converge the accuracy was at best 200 metres in urban areas.

In the US the e-911 initiative has caused mobile phone operators to abandon network-based location solutions, due to the poor spatial accuracies of the network solutions described above, as well as the high infrastructure costs required to implement them across an extensive territory. Alternatively, they had rapidly started switching to GPS-enabled phones (Federal Communications Commission, 2004) that can give an accuracy of 20 metres and are much cheaper to subsidise at the handset level rather than invest in the network that would have been soon replaced by 3rd generation technology. New hybrid solutions include methods that combine both network and handset-based location calculation, of which Assisted-GPS (A-GPS) is the most promising and accurate one (Shoval and Isaacson, 2006), but had still not made its way to mainstream mobile telephony by 2005 and therefore will not be covered in the chapter.

### 11.3.5 Privacy issues

*'What counts is not the barrier but the computer that tracks each person's position – licit or illicit – and effects a universal modulation.'*

(Deleuze, 1992, p. 5-7, cited in Thrift, 1996, p. 291)

Mobile phone location has attracted a wide interest in the critical analysis of its challenges to individual privacy, since it allows a person's location to be known by other people. This aspect, termed location privacy, has already been covered in Chapter 3 of this book, and only a few additional issues particular to mobile phone location will be briefly mentioned here.

The right to privacy in the handling of personal data is regulated in most of the countries by personal data protection legislation. These ensure that personal data should only be collected where necessary, should only be used for the purposes for which they were collected, should not to be disclosed to another group or agency without some sort of consent, and should be securely stored (Curry, 1999). Of interest here are the situations of disclosure of such personal information to another group or agency (named in this chapter as disclosure to a third party), and the requirement of specific user consent.

As mentioned in Section 11.3.3, society has already deemed it necessary to relinquish some individual privacy for a greater benefit from mobile phone location, typically in situations where life is at risk (emergency services), or crime has been committed. Fisher and Dobson (2003) propose a typology of seven scenarios for the use of personal location information, and establish whether disclosure of such information to third parties will be beneficial, and therefore should be legally permitted, and those in which it should not and thus should be prosecuted.

The aim of this chapter is to propose the use of mobile phone location technology as a proxy to understand mobility at societal level, and therefore this would require the consent of mass groups of society in order to be truly representative. The proposed approach should then be to ask the potential participants for their consent, ensuring the information is only used for the purpose of understanding urban mobility in aggregated ways. This is a similar scenario as with the information requested in a population census, although there all citizens are obliged to provide personal information on condition that it only be disclosed in a spatially aggregated form (Dale et al., 2000). Nevertheless, as Chapter 3 has already insisted, new legislation should regulate a 'new right to privacy in a geocoded world' (Curry, 1999), so that these beneficial uses are permitted and potential abuses prosecuted, before the technology is made 'blind' altogether, and its potential urban research benefits are lost.

#### **11.4 Methodology for assessing spatiotemporal accuracy in mobile phone location**

This section presents the methodology undertaken to measure the spatiotemporal accuracy of mobile phone location in the UK in 2004. The main objective of the research methodology selected is to illustrate, through meaningful examples, what are the characteristics, limitations and potential uses of different datasets containing current mobile phone location information for a group of users in a metropolitan area.

The main concern of potential users of this technology is the level of spatiotemporal accuracy of the location information that was commercially available in the main European markets at the time this research was carried out (2004). Therefore, the research presented in this chapter is an empirical exploration of the technology available in 2004 through a series of mobile phone location tests that surveyed the movements of a small sample of participants in the UK.

In the UK, the four mobile phone operators with a GSM licence in 2004 were: *O2*, *Vodafone*, *T-mobile* and *Orange*. A fifth operator called '3' held a 3rd Generation licence only (UMTS). Other 'mobile brands' in the market that could seem independent in fact operate using one of the four operators' networks listed above (e.g. *Virgin*). In this chapter the term 'operators' are used to describe the four GSM operators in 2004. In addition to the operators, mobile phone location services can be provided by any third party, under a contract with the operators to sell value-added services using location information. In the UK, at the time of writing (2005), there were around 12 different companies of this type, which will be referred to in this chapter as service providers.

Due to the difficulties of accessing mobile phone location data directly from the operators, it was decided to subscribe to several of those service providers and purchase from them the location service of the participant's mobile phones. Two different services were selected based on price, ease of access to and automation of the location information collection; 'FollowUs' ([www.followus.co.uk](http://www.followus.co.uk)) and 'Childlocate' ([www.childlocate.co.uk](http://www.childlocate.co.uk)).



**Figure 11.2.** Mobile phones and GPS used in Test 2 (photograph: Brenda Valdes).

A series of three different tests of mobile phone location were carried out in order to generate a minimum dataset that would enable the desired analysis to be performed. The mechanics of each of these tests and their objectives will be individually explained below in this section, and the overall results in Section 11.5. All of these tests basically consisted of locating several mobile phones through two of the service providers that offered a commercial option to track mobile phones with the consent of each user. The differences between the tests reside in the aim of each test, their geographical coverage, and the stages in which they were developed, providing different settings for the subsequent analysis of the data.

As a result of each test, a series of 'time-location stamps' (TLS) was collected. The concept of time-location stamps will be used in this chapter to refer to the spatiotemporal information of a single event in which both the geographical location of a mobile device (in a pair of coordinates) together with the date and time at which such a location was measured is stored in the project's database. The aims and methods of each of the three tests carried out can be summarised as follows:

- **Test 1** - Aimed to measure the intra-urban mobility patterns of a group of nine postgraduate students in the city centre of Leicester, UK. The test was carried out by approaching the potential participants through friends, since the sensitivity of information requested (personal location) demanded a minimum level of trust about the researcher that could not be expected from anonymous random participants. An account was opened with the service provider *Childlocate*, where the nine students' mobile phones were initially registered through SMS. The actual location tests were carried out during three consecutive weekdays in June 2004, at various temporal intervals each day and always within non-sleeping hours (typically 9:00 to 21:00h), in order to compare the outcome of several temporal resolutions in the data. The total number of location requests was 159 at an average temporal interval of 2.5 hours. The location requests were manually placed at *Childlocate* Website, one participant at a time. Only seven requests out of the 159 were not successful, therefore yielding 152 valid locations (availability rate of 95.7%).
- **Test 2** - Specifically addressed the need to measure the actual spatial and temporal accuracy of the mobile phone locations provided by the different phone operators, and analyse the differences between them, and throughout the different areas of the city centre of Leicester, in order to determine the factors for variations in accuracy. The test located three mobile phones from different operators (O2, Vodafone and T-mobile), travelling together with a GPS unit (Garmin GPS 12XL) through several areas of the city of Leicester, by car and walking. Figure 11.2 shows a photograph of the simple equipment used for this test. The different location estimates were compared between the different operators and also with the 'true' position determined by the GPS. The chosen service provider for this test was

*FollowUs*, because it offered a facility to access historical location queries (Childlocate only offers a location in 'real time'), so that all locations could be batch-processed later. Moreover, the information about the locations could be accessed as a pair of British National Grid coordinates at 1 metre accuracy, substantially facilitating the transfer of the data to the GIS. The test consisted of 87 location requests placed from different points scattered around the study area, retrieving 83 valid TLS (95.4% availability rate). The temporal resolution of the mobile phone location requests in this test was considered irrelevant, because the importance of the test was to cover a dense number of different locations within the study area despite their time intervals. GPS data was collected at 30-second intervals, and later matched to TLS data by their closer time stamp through a temporal query, and then the spatial difference between GPS and TLS measurements was calculated. Figure 11.3 shows the scatter plot of those spatial differences by operator, while Figure 11.5 shows a map with the visualisations of the itinerary taken and the TLS locations by operator. Further analysis of these results is presented in Section 11.5.

- **Test 3** - Measured inter-urban movements, by tracking a single mobile phone during several car trips around the UK. The aim of this test was to assess the advantages of mobile phone location in measuring *inter-urban* mobility patterns as opposed to the *intra-urban* ones measured in Test 1. Test 3 was envisaged as an additional experiment to find the best scale of application for mobile phone location technology, in order to point out directions for further research. The test consisted in measuring both mobility patterns through the location of a mobile phone (a single operator in this case; O2) while moving by car between cities in the UK at distances between 100 km and 300 km. In order to perform this test, the service provider chosen was again *FollowUs* due to their ability to program automatic location requests, that for this test were set at every hour from 6:00 to 21:00h (the maximum temporal resolution allowed). The TLS data was retrieved in a different way for this test, since the automatic location requests to *FollowUs* send back an email with the mobile phone's position. The relevant information (mobile phone number, location coordinates, date-time stamp, postcode, etc.) was retrieved from the email and imported into the research database.

These three tests provided a total number of 309 different TLS with their corresponding estimated accuracy. These data were processed in a spatiotemporal database and analysed using ArcGIS and its *Tracking Analyst* extension. An overview of the general characteristics of the three tests is summarised in Table 11.1.

**Table 11.1.** Summary of location tests performed.

Test No.	Test to measure	No. phones located	No. time location stamps (TLS)	Service provider	Study area	Length of test	Temporal res. (daytime)
1	Intra-urban mobility tracking	9	152	ChildLocate	Leicester	3 days	2.3 hours
2	Location accuracy of operators	3	83	FollowUs	Leicester	2 days	N/A
3	Inter-urban mobility tracking	1	74	FollowUs	England	1 week	1 hour
<b>TOTAL</b>			<b>309</b>				

## 11.5 The results: real accuracy of the ‘new cellular geography’

The results of the methodology described in the previous section throw new light on the understanding of the ‘new cellular geography’, that would not have been possible to assess with the scarce secondary data available from the industry. These findings can be summarised around the topics of 1) location accuracy and configuration of the cellular geography, 2) temporal accuracy and 3) aggregation and visualisation.

### 11.5.1 Location accuracy and the structure of the cellular geography

The tests described in Section 11.4 confirmed that the spatial disposition of mobile phones’ geography is determined by the location method used by all the GSM operators in the UK in 2004, the basic *Cell-ID* method, without even a slight enhancement such as *Cell-ID++* (Faggion and Trocheris, 2004). The results of Tests 1 and 2 revealed that the mobile phone location estimates provided by the operators as a pair of coordinates always coincide with a few common points in space that will be called here ‘milestones’ for simplicity. For example, the 152 TLS obtained in Test 1 were all located at 24 fixed ‘milestones’, and the location accuracy estimate at each ‘milestone’ was always the same. This means that the location reported is that of the base station or transmitter, and thus the reported location accuracy is determined by the cell size of each base station.

The consequence of the predominance of this location method is a very coarse spatial resolution, which determines the geographical scale of studies that could use mobile phone location as a proxy for mobility. The tests have demonstrated that the actual location accuracy provided by operators is substantially worse than commercially advertised, and worse than previously reported research in Japan (e.g. Hato and Asakura, 2001). The average estimated accuracy of actual locations in the tests performed is 3615 metres, with a minimum of 500 metres and a maximum of 5000 metres, while the values commercially advertised vary between 150-400

metres (Childlocate, 2004). At the time of writing this chapter, a year after the tests were performed, those commercial claims have changed their estimated accuracy to 150–900 metres (Childlocate, 2005).

Operators provide accuracy estimates for all locations given, but the tests showed that they always provide the worst possible accuracy estimate (cell radius), when in most cases the real accuracy is much better (somewhere between the cell radius and the centre of the cell). In fact the true accuracy, that is, the actual difference between the true position of the mobile phone (measured with a GPS) and the estimated position provided by the operator is generally significantly smaller (average 800 metres) than that reported by the operator (average 3615 metres). Figure 11.3 shows the scatter plot of those two measurements of accuracy for each position in Test 2, where the reported accuracy is plotted in the Y-axis and the true accuracy (GPS) in the X-axis. As it can be seen, except for five TLS out of 83, the reported accuracy is worse than the real one. In addition, all of those five TLS where the operators report a better accuracy than the real one are under the 2000 metres threshold, with differences of 100-500 metres above measured accuracy. This could also mean that at these shorter distances GPS error induced by buildings was also altering the measurement of the 'true' position.

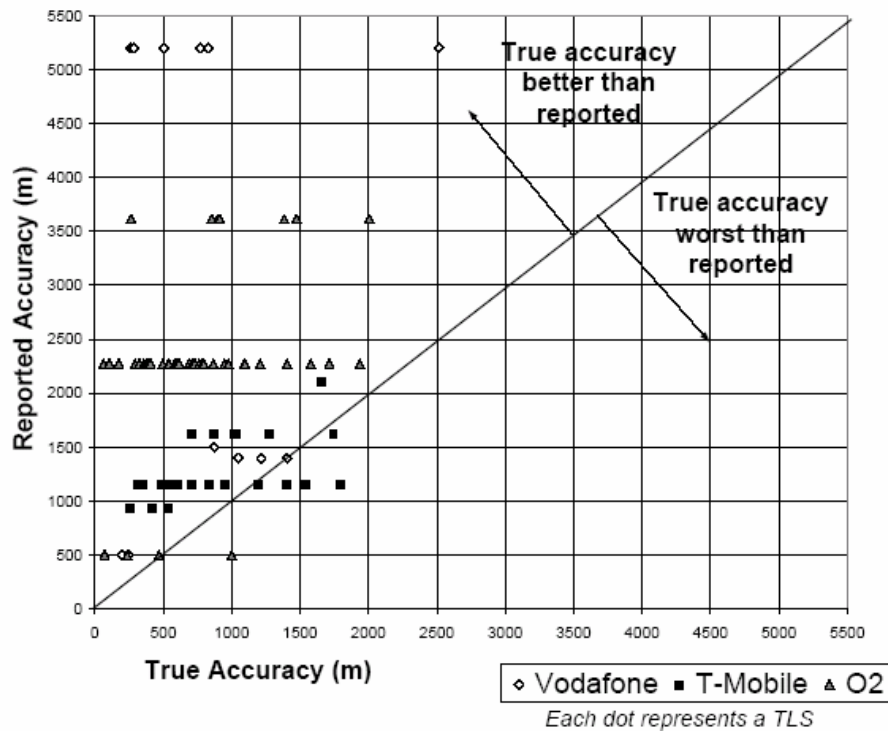


Figure 11.3. True vs. reported accuracy scatterplot (Test 2).

Another limitation of the ‘cellular geography’ resulting from this technology is the differences between the operators’ location estimates provided for the same actual position (differences averaging 1800 metres between operators). This is due to different network layout (location of cell centroids), types of transmitter technology (sizes of cell radius), and height and topography, which influence reception coverage (as explained in Section 11.3.4). There is an additional complication of overlapping cells for the same operator: the mobile phone tends to ‘stay’ connected to the same transmitter even when there is a closer one, following an apparent rule of ‘cell loyalty’.

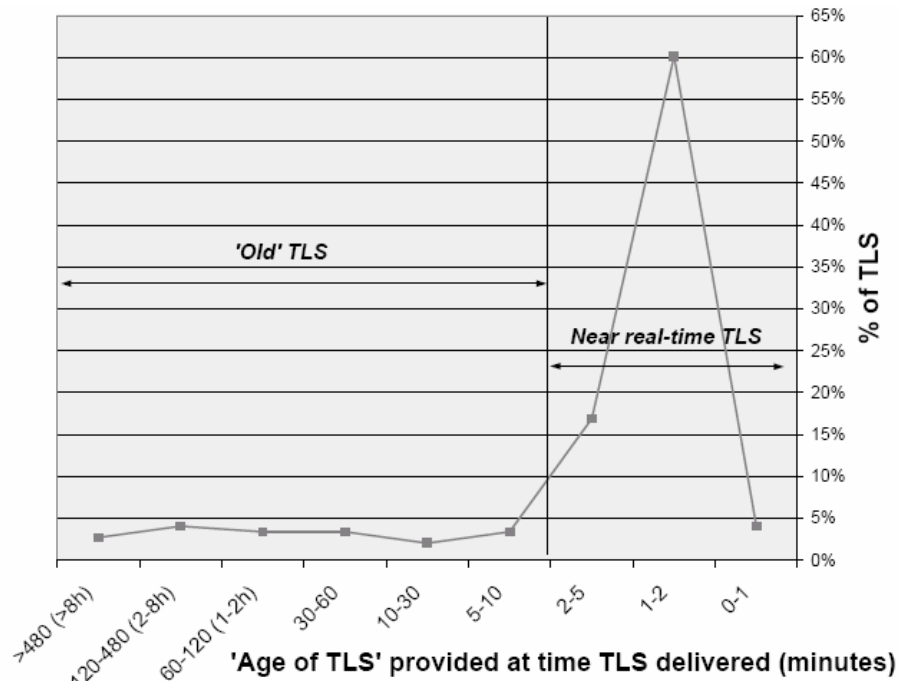
Therefore, this technology is only appropriate for mobility studies that require locations that are less specific than the cell, i.e. they require a geographical resolution greater than about 3000 metres radius. Since a spatial resolution of that size would not be very meaningful to study intra-urban mobility for most cities, the most-indicated example of application would be in inter-urban mobility analysis. Test 3 proved the usefulness of such analysis and a visualisation of the type of inter-urban flows measured can be seen in Figure 11.6.

### 11.5.2 Temporal resolution

The time dimension is as important as the spatial one in dynamic and mobile GIS, especially in phone location, and many of the implications of Hägerstrand’s ‘Time Geography’ (Hägerstrand, 1970) can be re-applied to this technology. The datasets will have a specific temporal resolution that will drive the type of applications in which it will be used. The minimum temporal resolution will be determined by the ‘amount of mobility’ that is to be monitored (i.e. high speed will require high temporal resolution).

The research identified the issue of assessing temporal accuracy, since not all the TLS were provided in real time. That is, there is a difference between the time when the location request was placed into the network and the time at which the mobile phone actually was at the reported location. This time difference will be called here ‘temporal lag’. Figure 11.4 shows the frequency distribution of the temporal lag for the three tests’ TLS (X-axis) for different time intervals (Y-axis). The figure shows that a significant proportion of TLS happened to be ‘old locations’, in other words, the location provided was showing where the phone was ‘in the past’, not at the time of the location request.





**Figure 11.4** Frequency distribution of time-location stamps (TLS) temporal lag (all tests).

Out of the total TLS collected in the three different tests only 80% of them have a temporal accuracy of less than five minutes (which could be regarded as 'near real time' for most purposes), while 10% of them are between five and 60 minutes 'old', and the remainder 10% over one hour 'old' (with outliers more than eight hours later). Since all necessary devices were switched on at the time of testing and at the time of requesting TLS, the observed temporal lags can only be a consequence of the operators not always processing a new location request to the network but actually relying on stored information about where the mobile phone was the last time it was spotted in the network. Therefore, they assume the phone has not moved. This assumption is a major issue, which seems to have been overlooked by Location Based Services literature, and can have serious consequences for certain services such as emergency response applications.

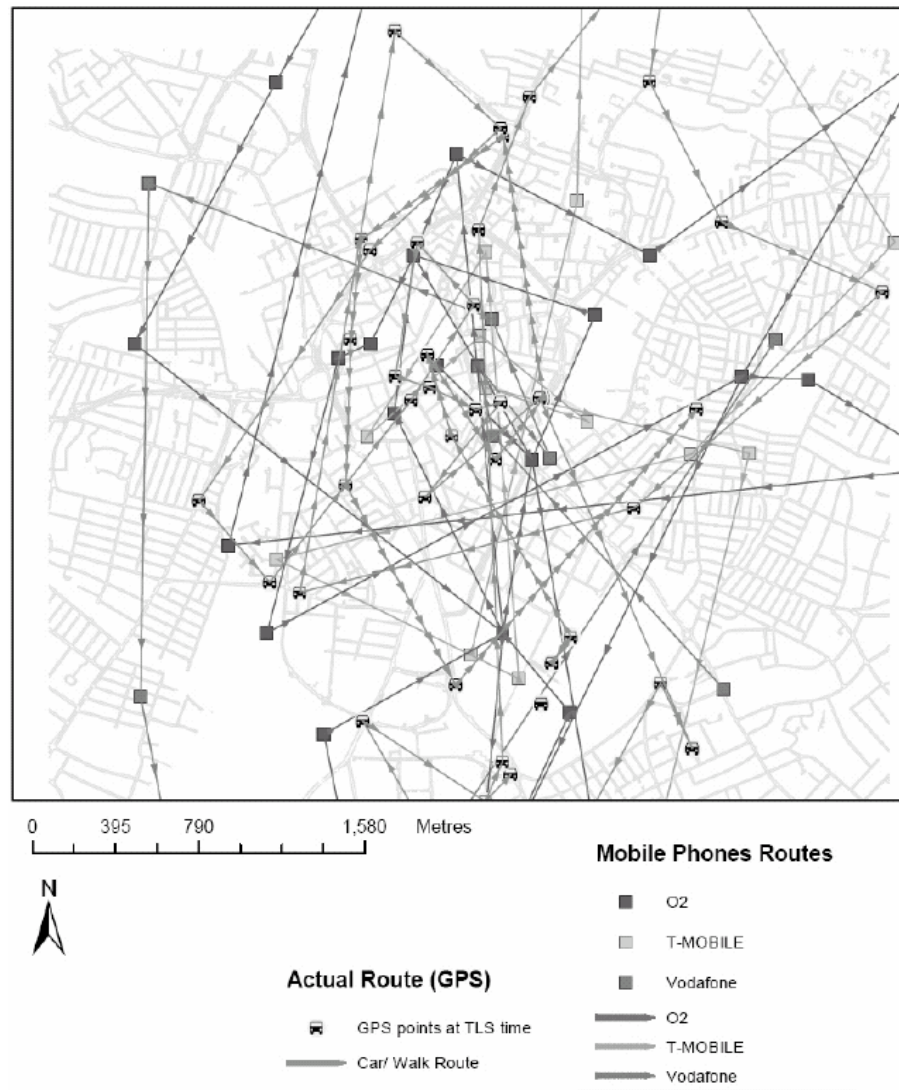
### 11.5.3 Aggregating and visualising mobility

The visualisation of mobility flows places an enormous pressure on the creativity of aggregation and visualisation techniques to make sense of such data. Through the tests performed in this research it has been clear that the characteristics and amount of these data require new data models, aggregation methods and visualisation techniques. Figure 11.5 tries to offer a visualisation of Test 3 results, which only represented one person travelling for two days with three mobile phones and a GPS,

a few data flows that obviously challenges traditional cartographic representations of movement.

The problem of aggregating the individual itineraries into meaningful common flows in order to search for general patterns is directly linked to the problem of previously selecting the right data model behind the representation of the phenomena being measured. One type of a spatiotemporal GIS data model to represent mobile phone location is a 'cell time-space' (Forer, 1998). For example, the datasets can be visualised showing cell-to-cell movements, amount of change of cell, differential cell intensity, etc. Another approach is to build density surfaces based on the number of occasions that a location is visited by the moving individual, and the time length of the 'stay' (Dykes and Mountain, 2002).

Further research is required into the different optimum data models and visualisations to understand the complexity of the 'mobile society', which increases with the number of subjects tracked, their spatiotemporal extensibility (Miller, 2004), and the temporal coverage and resolution of the datasets.



**Figure 11.5.** Visualisation of Test 2, GPS vs. TLS tracks through Leicester, UK. (See colour version following page XXX.)

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## 11.6 Conclusion and further developments

This chapter has presented the benefits of mobile phone location as a very efficient methodology to capture the mobility of large groups of the population, as well as

some of its restrictions and challenges to become the spatial referencing system of the 'new cellular geography'.

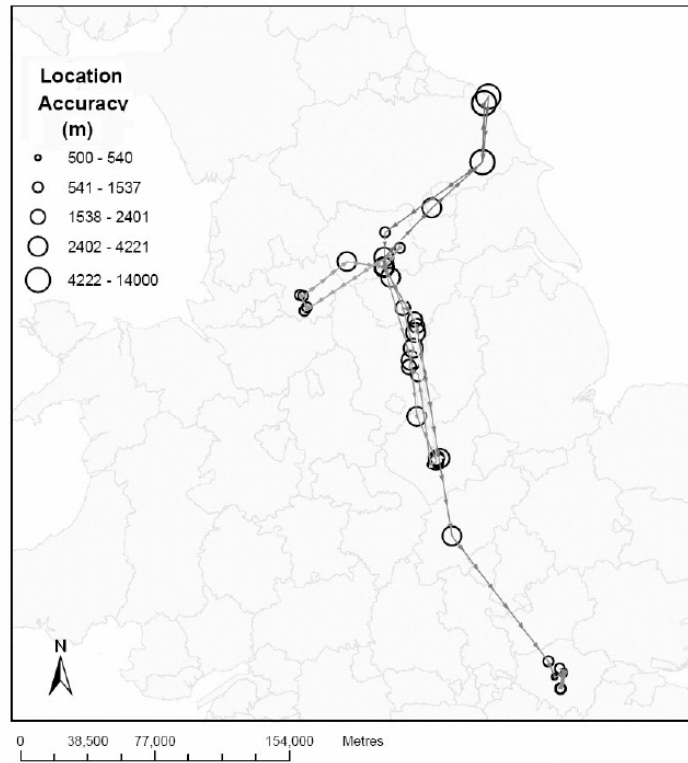
Amongst its benefits, this technology presents significant advantages over GPS to track mobility, such as its low setup costs as the existing technology already covers nearly 80% of the adult population, its accepted ubiquitous presence in all aspects of everyday life, and its better urban coverage inside and between buildings. Amongst its restrictions, its current limited spatiotemporal accuracy makes it only suitable to measure inter-urban mobility, as the research presented here has indicated, and the reasonable need for user consent to disclose their location (Fisher and Dobson, 2003) limits the size of population sample than can be surveyed.

The results of the evaluation of spatiotemporal accuracy of mobile phone location carried out in the research presented here can be summarised as follows:

- ❑ Current spatial accuracy range: 1500–3000 metres
- ❑ Operators-reported spatial accuracy is substantially worse than the real one (measured by GPS)
- ❑ Temporal accuracy: five minutes to one hour
- ❑ Differences in accuracy are due to operator technology or base station placement, but not to third party service provider
- ❑ Recommended scales of application:
  - ❑ Measurement of inter-urban or international mobility (as shown in Figure 11.6)
  - ❑ Spatial resolution > 3000 metres
  - ❑ Temporal resolution > 5 minutes

As technological developments in the area of personal mobile computing devices rapidly replace one another, the geographical accuracy and coverage of what has been traditionally known as 'mobile phones' is continuously improving. Assisted-GPS technology introduced in mobile phones, in mobile computers, and in other mobile objects, will allow more accurate spatiotemporal measurement no later than by the year 2010. This will yield urban researchers an innovative tool to measure intra-urban mobility at much finer geographical scale (below 20 metres) and with nearly total population coverage.

It is believed that once this point is reached (spatiotemporal resolution of less than 20 metres and ten seconds), mobile phone location will indeed be a new spatial reference system, drawing a parallelism with the evolution of the postcode to become the 'New Geography' a decade ago (Raper et al., 1992). This parallelism is based on the fact that if postcodes enabled the linking of many different datasets about the population to a unique spatial reference from which to undertake cross-sectional geographical analysis, mobile phones (or their technological successors) will soon allow the linking of many different datasets about individuals to their spatiotemporal flows, linking datasets through their different *timespaces*, facilitating the longitudinal analysis of the network society linking a space of 'cellular geographies'.



**Figure 11.6.** An example of inter-urban mobility application – Visualisation of Test 3 TLS on different car trips through England.

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Once mobile devices become the new spatial reference system to analyse population, as the postcode did in the 1990s, it is believed that from a social science perspective, legislation should be introduced to develop a new central government statistical survey effort that samples the personal location of the population (through mobile-phone-like devices) on certain survey days without the need for prior individual consent. This initiative should be based on similar guidelines as the national census of population to safeguard anonymity and require coverage of a large part of the population. This information should then be published and visualised in aggregated ways to preserve individual privacy, but that would allow access to much more accurate and frequent population mobility data for urban researchers and many other parties interested in the mapping of the ‘new cellular geography’.

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