TRENDS IN GEOPOSITIONING FOR LBS, NAVIGATION AND MAPPING

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Abstract

The Global Positioning System (GPS) is a satellite-based technology that has truly revolutionised many positioning and navigation activities, and today stands unchallenged as the 'first choice' position determination technology for all outdoor applications. GPS is global, works in all weather conditions, is available 24hrs a day and is free of user charges. Thanks to the revolution in microelectronics, over the last 20 years GPS has evolved into a compact, low-cost, low-power chipset that is easily integrated into mobile devices. However, GPS suffers from one important weakness, the attenuation of the GPS satellite signals indoors or under foliage is such that they cannot be tracked by conventional GPS receiver designs. During the last 10 years advances in signal processing, receiver design and the development of various "assistance" techniques has resulted in GPS now being able to be used inside buildings with varying degrees of success. Although the accuracy is not as high as in the 'open air', GPS signal availability does mean that this technology can be considered a candidate for integration within mobilephones, to address emergency response requirements or consumer applications such as location-based services (LBS). Modernized GPS and the new Galileo Global Navigation Satellite System (GNSS) will enhance satellite-based positioning even further. GNSS is not the only wave-based positioning technology being proposed for indoor applications. Recent research in the use of terrestrial RF signals (including "pseudolites") shows promise that they could be used on their own, or as an augmentation to GNSS, in "hot spot" deployments. In addition, positioning via mobilephone signals themselves, or other wireless communications technologies such as WLAN and Bluetooth, is also possible. These may use range-like measurements or received signal strength, or positioning may be based on the proximity or "cell" mode. The latter mode is also used in RFID systems. Finally, a very promising non-RF solution is based on inertial technology. This paper reviews the various available technologies and comments on their suitability for LBS, navigation and traditional mapping/surveying applications.

1.0 INTRODUCTION

1.1 Background

Since the launch of the first Global Positioning System (GPS) satellite 27 years ago the technology and applications of satellite-based positioning has inextricably progressed. With every technological innovation, a new class of positioning applications was addressed. There is no sign that this trend is waning, and in fact we may be on the verge of a massive explosion of new markets for GPS and associated position determination technology. GPS is the first (and currently only) operational *Global Navigation Satellite System* (GNSS). The term "GNSS" was coined in the 1990s to acknowledge that GPS is merely the 1st generation of satellite-based positioning technology, and that by the end of the current decade there would be one (or more) independent GNSS that would complement and/or compete with GPS. Nevertheless, many of the positioning and technological concepts, as well as the current and future markets and applications of GNSS, can be analysed using GPS as the exemplar.

Although GPS was designed from the start to be a dual-use technology (although the military use was considered more important), it was not until the mid-1990s, when GPS was declared operational, that the number of civilian applications and volume of civilian GPS receivers grew rapidly. It is worth recalling the past history of GPS development in order to compare it with the predicted future for GNSS in general. Although a significant generalisation, we can characterise the 1980s as the years when GPS was primarily of interest to the military and to specialist research applications such as *geodesy*. During these years the satellite constellation was not yet complete (there was no real-time, '24/7/365' operation), and hence civilian users were those who were content with collecting GPS measurements and then processing these measurements in offline (post-mission) mode. It was at this time that the first significant civilian innovation was made, the development of high accuracy relative positioning techniques based on the analysis of carrier phase data. An excellent review of the utility of GPS for geodetic applications is Evans et al. (2002). Many of these geodetic applications are still important today, and as the accuracy of modelling improves new applications continue to emerge.

During the 1990s, and particularly after GPS was declared fully operational, the benefits of GPS for marine and air *navigation* became obvious. It was during the 1990s that international organisations such as the International Civil Aviation Authority (ICAO) and the International Maritime Organisation (IMO) adopted new navigation concepts based upon the global and ubiquitous positioning capabilities of GPS. The market for land navigation systems was also launched. This was also the decade of *Selective Availability* (SA), the intentional degradation of the GPS positioning capability by the system operators. This had two main effects, to encourage the development of differential GPS techniques (to 'claw back' the accuracy 'lost' due to SA), and to strengthen the arguments made by many countries that the control of GPS by the U.S. military authorities was ultimately not in the best interests of the global community. The 1990s also saw first the full deployment of the Russian Federation's *GLONASS* satellite constellation, and its subsequent slow demise by the end of the 1990s. Nevertheless, GLONASS was the first non-U.S. GNSS to challenge the monopoly of GPS.

At this time, early in the first decade of the 21st Century, GNSS is poised to experience an explosive growth, as it is increasingly embedded within consumer electronics devices, and used to address the needs of a new mass market in 'Telematics'-type products and services (Karimi & Hammad, 2004). Within the next few years it is predicted that as much as 90% of the market for GNSS products and services will be for personal and vehicle applications. (It is often difficult to distinguish between so-called *Location Based Services* and *Transport Telematics*.) The review presented in this paper does not claim to be exhaustive. The author has taken a very personal approach and highlighted developments that, in his opinion, are significant in understanding how the future of GNSS will play out. The focus is on what we know about the GNSS technology, and its expected development, at the dawn of this century, and the possible roles that non-GNSS positioning technologies may play.

1.2 Introduction to GPS

The NAVSTAR Global Positioning System (GPS) is a satellite-based, all-weather, continuous, global radiolocation and time-transfer system, designed, financed, deployed and operated by the U.S. Department of Defense. The concept of GPS was initiated in 1973, and the first GPS satellite was launched in 1978. In 1993 the system was declared fully operational. GPS technology was designed with the following primary objectives:

- Suitability for all platforms: aircraft, ship, vehicle and spacecraft, and a wide variety of dynamics.
- Real-time positioning, velocity and time determination capability.
- Availability of the positioning results on a single global geodetic datum.
- Restricting the highest accuracy to a certain class of users (military).
- Redundancy provisions to ensure the survivability of the system.
- Providing the service to an unlimited number of users worldwide.
- Low-cost, and low power users' unit.

GPS consists of three fundamental segments: *Satellite Segment*, i.e., the satellite constellation itself, the *User Segment*, including all GPS receivers and operational procedures used in a variety of civilian and military applications, and the *Control Segment*, responsible for maintaining the proper operability of the system. The Control Segment consists of five monitor stations (to be increased), each checking the exact altitude, position, speed, and overall health of the orbiting satellites 24 hours a day. Based on these observations, the satellite orbital position and clock bias, drift and drift-rate can be predicted for each satellite, and then transmitted to the satellite for re-transmission back to the users via the navigation message modulated on the downlink L-band signals.

The nominal GPS constellation consists of 24 satellites (although there are currently 29 deployed) that orbit the Earth at an altitude of ~20,000 km, in just less than 12 hours. The satellites approximately repeat the same track and configuration once a day, advancing by about 4 minutes each day. They are placed in six nearly circular orbital planes, inclined at about 55 degrees with respect to the equatorial plane, with nominally four satellites in each plane. This configuration assures the simultaneous visibility of five to eight satellites (sometimes more) at any point on Earth. Since February 22, 1978 – the launch date of the first GPS Block I satellite – the system has evolved through several spacecraft designs, focussed primarily on increased design life, extended operation time without contact from the Control System (i.e. autonomous operation), and better satellite clocks. Block II satellites are the first operational satellites (first launched in February 1989), Block IIA satellites are the second series of operational satellites (first launched in November 1990), and Block IIR satellites, the operational replenishment satellites have carried the GPS into the 21st Century (first launch in January 1997). The Block IIF, the follow-on satellites, are expected to have their first launch in 2006-2007. Information about the current status of the constellation can be found at http://www.navcen.uscg.gov/gps/.

Each satellite transmits PRN codes modulated on the L-band carrier frequencies: a unique C/A-code (which is in fact the satellite's designated ID) and a one-week long segment of P-code. The PRN is a binary code, or a complicated sequence of 'on' and 'off' pulses that looks almost like random electrical noise. This carrier modulation enables the measurement of the signal travel time between the satellite and the receiver (user), which is a fundamental GPS observable. Access to the C/A-code is provided to all users, supporting the so-called *Standard Positioning Service* (SPS). Under the *Anti-Spoofing* (AS) policy imposed by the U.S., the P-code is encrypted to form the Y-code, available only to military/authorised users, for a service known as the *Precise Positioning Service* (PPS). Current GPS satellites transmit two L-band carrier frequencies that can be used for positioning: the L1 frequency of 1575.42MHz, and the L2 frequency of 1227.60MHz. Both are modulated by the P-code, but only the L1 is modulated by the C/A-code.

1.3 Positioning with GPS

There are two fundamental GPS measurements: *pseudorange* and *carrier phase,* both subject to measurement errors of either a systematic and random nature. For example, systematic errors due to the ionosphere or troposphere delay the GPS signal, and cause the measured range (or distance) to be different from the true range by some systematic amount. Other errors, such as the receiver noise, are considered random. *Pseudorange* is the geometric range between the transmitter and the receiver, distorted by the lack of synchronisation between the satellite and the receiver clocks, and the propagation media (atmosphere). It is recovered from the measured *time difference* between the epoch of the signal transmission and the epoch of its reception by the receiver. The actual time measurement is performed with the use of the PRN code. The receiver and the satellite generate the same PRN sequence. The arriving signal is delayed with respect to the replica generated by the receiver, as it travels ~20,000km. In order to find how much the satellite's signal is delayed, the receiver-replicated signal is delayed until it falls into synchronisation with the incoming signal. The amount by which the receiver's version of the signal is delayed is equal to the travel time of the satellite's version. The travel time, Δt (~0.07s), is converted to a range measurement by multiplying it by the speed of light. There are two types of pseudoranges: (1) C/A-code pseudorange, and (2) P(Y)-code pseudorange. The precision of the pseudorange measurement is partly determined by the wavelength of the chip in the PRN code. Thus, the shorter the wavelength, the more precise the range measurement would be. Consequently, the P(Y)-code range measurement precision (noise) of 10-30cm is, in theory, 10 times higher than that of the C/A-code. The pseudorange is the principal observable used for conventional single receiver positioning (under the SPS or PPS).

Carrier phase is defined as a difference between the phase of the incoming carrier signal and the phase of the reference signal generated by the receiver. Since at the initial epoch of the signal acquisition the receiver can measure only a fractional phase, the carrier phase observable contains the initial unknown *integer ambiguity*. Integer ambiguity is a number of full phase cycles between the receiver and the satellite at the starting epoch, which remains constant as long as the signal tracking is continuous. After the initial epoch the receiver can count the number of integer cycles that are being tracked. Thus, the carrier phase observable can be expressed as a sum of the fractional part (measured with mm-level precision), and the integer number of cycles counted since the starting epoch. The initial ambiguity can be determined using special *ambiguity resolution (AR) techniques* (Seeber, 2003) Dual-frequency AR (using both the L1 and L2 carrier phase data) is much faster and more reliable than using L1 carrier phase data alone. Once the ambiguity is resolved, the carrier phase observable can be used to determine the user's location for high accuracy geodetic and surveying applications.

There are two primary GPS positioning modes: *point positioning* (or *absolute positioning*), and *relative positioning*. However, there are several different strategies for GPS data collection and processing, relevant to both positioning modes. In general, GPS can be used in static and kinematic modes, using either pseudorange or carrier phase data (or both). GPS data can be collected and then post-processed at a later time, or processed in real time, depending on the application and the accuracy requirements (see, e.g. http://www.navcen.uscg.gov/pubs/frp2001/default.htm).

In point positioning a single receiver observes pseudoranges to multiple satellites to determine the user's location. For the positioning of the moving receiver the number of unknowns per epoch equal to three receiver coordinates plus a receiver clock error (or correction – *to give precise time*) term.

The relative positioning technique (also referred to as *differential GPS*, or *DGPS*) employs at least two receivers, a reference (or base) receiver at a site whose coordinates are known, and the user's receiver, whose coordinates can be determined relative to the reference receiver(s). Thus, the major objective of relative positioning is to estimate the 3D baseline vector between the reference receiver and the unknown location. Using the known coordinates of the reference receiver and the estimated ΔX, ΔY and ΔZ baseline components, the user's receiver coordinates can be readily computed. The advantage of relative positioning is removal of systematic error sources from the observable, leading to increased positioning accuracy (especially using carrier phase data). Since for short to medium baselines (a few tens to hundreds of km) the systematic errors in GPS observables due to atmospheric, satellite clock and satellite orbit errors are of similar magnitude DGPS allows for the removal (or at least significant mitigation) of these error sources.

DGPS services have evolved during the 1990s, when SA was turned on, and are now commonly provided by the government, industry and professional organisations, and enable the user to use only one GPS receiver collecting pseudorange data, while still achieving superior accuracy as compared to the point-positioning mode. Naturally, in order to use a DGPS service, the user must be equipped with additional hardware capable of receiving and processing the *differential corrections*. DGPS services involve some type of wireless transmission system. They may employ VHF or UHF systems for short ranges, low-frequency transmitters for medium ranges (e.g. marine beacons) and L-band or C-band geostationary satellites for coverage of entire continents. Wide Area DGPS (WADGPS) schemes involves *multiple* GPS base stations that track all the GPS satellites in view and, based on their precisely known locations and satellite broadcast orbital information, estimate the errors in the GPS pseudoranges. This information is used to generate pseudorange *corrections* that are subsequently sent to the master control station, which uploads corrections to the communication geostationary satellite, which transmit them to the users. The positioning accuracy of WADGPS is typically at the sub-metre level, and is trending towards a few decimetres. Other types of free-to-air DGPS services in North America include the FAA-supported (Federal Aviation Administration) satellite-based Wide Area Augmentation System (WAAS), ground-based DGPS services, referred to as Local Area DGPS (LADGPS), such as the U.S. Coast Guard and Canadian Coast Guard services, or the FAA-supported Local Area Augmentation System (LAAS). LADGPS supports real-time positioning typically over distances of up to a few hundred kilometres, using corrections generated by a single reference station.

WAAS is currently operational, and LAAS is still under development, with a major objective of both *augmentation systems* being support for civil air navigation.

Another strategy gaining popularity in many countries is to establish local permanent networks of reference stations that can support a range of applications, especially those requiring the highest accuracy, in post-processing or in real-time. Scientific organisations such as the International GNSS Service (IGS) deploy and operate global networks, allowing the users free access to the archived data (http://igscb.jpl.nasa.gov/). Alternatively, network-based positioning using carrier-phase observations with a single user receiver in real-time can be accomplished with local networks (Rizos, 2002).

Depending on the design of the GPS receiver and the measurement type/technique employed, the positioning accuracy with pseudoranges varies from about sub-10m (SA off) to better than 1 centimetre, in the case of carrier phase-based relative positioning. The geometric factor *Geometric Dilution of Precision* (GDOP) reflects the instantaneous geometry related to a single point. In general, more satellites yield a smaller GDOP value, and a GDOP of six or less typically indicates good geometry. Other DOP quantities, such as Position DOP, or Vertical DOP or Relative DOP (related to the satellite geometry with respect to a baseline), can be also used as *quality indicators*. Other factors affecting the GPS positioning accuracy are: (1) whether the user is stationary or moving (static vs. kinematic mode), (2) whether the positioning is performed in real-time or offline, (3) the data reduction algorithm used, (4) the redundancy in the solution, and (5) the measurement noise level.

1.4 GPS Instrumentation

Over the past two decades the civilian as well as military GPS instrumentation has evolved through several stages of design and implementation, focussed primarily on achieving an enhanced reliability of positioning and timing, modularisation and miniaturisation, and reduction in cost and power requirements. One of the most important aspects, especially for the civilian market, has been the decreasing cost of the receivers, as the explosion of GPS applications calls for a variety of low-cost and application-oriented equipment. By far the majority of the receivers manufactured today are of the C/A-code single-frequency (L1) variety. However, for high precision geodetic and surveying applications the dual-frequency receiver configuration is the standard.

1.5 Shortcomings of GPS

GPS has over the last two decades enjoyed tremendous success, and it is now a ‘first choice’ position, velocity and time (PVT) technology for new civilian and military applications. While civilian use far outweighs military usage (it is estimated that there are 100 times the number of civilian GPS receivers vis-à-vis military receivers), GPS remains a curious ‘child of the Cold War’. The effectiveness of GPS-guided munitions in the recent Afghanistan and Iraq conflicts was a dramatic demonstration of the tactical and strategic power of precise positioning technology. This will ensure that GPS remains firmly under the control of the U.S. Department of Defense.

Because the GPS signals are offered free to all users, across the world, and the receiver technology is comparatively mature, reliable and inexpensive (at least the instrumentation for single-frequency SPS-type positioning), GPS’s popularity is rapidly rising. However, GPS has many shortcomings, but none greater than that arising from the weak strength of the signal at the receiver antenna. The received L1 signal strength is of the order of –160dB (10^{-16} Watt), and the signal can be easily blocked by buildings and other objects, including foliage. Standard GPS therefore cannot be used indoors or in urban (and forested) environments where there are many signal obstructions. Although this has permitted other positioning technologies to gain some popularity (sections 3.3 & 3.4), it has also spurred GPS R&D into weak signal acquisition and tracking (section 3.2). Furthermore, the GPS signals can also be easily jammed or degraded by unintentional RF interference. This vulnerability in terms of signal *availability* has been identified in a report by Volpe (2001), and is increasingly viewed as a serious GNSS shortcoming. In addition, there is no efficient means by which users are warned when the satellite system is not operating within specifications, i.e. GPS’s *integrity* cannot be assured.

Hence, for critical user applications such as air and marine navigation, GPS-only positioning is not recommended, and must be *augmented* in some way. GPS shortcomings (some of which are also relevant for all GNSSs) can be summarised as follows:

- Weak signal strengths make the signals vulnerable to interference (intentional or unintentional), exposing critical user applications to possible episodes of denial-of-service.
- GPS in its standard mode cannot be used indoors, under trees, or in urban environments.
- There is currently no built-in integrity warning/assurance signal or service for GPS users.
- In order to improve the accuracy of GPS to the metre-level or below, DGPS techniques must be used, leading to more complex user technology.
- Only single-frequency GPS positioning is possible using standard GPS receivers, with expensive dual-frequency GPS receivers justified only for geodetic, survey and scientific applications.
- Civilian and military applications both use the same GPS signals.
- GPS control is firmly in the hands of the U.S. military.
- The budget and maintenance of GPS is often subject to an annual tussle in the U.S. Congress (though it is embedded within the military budget).
- GPS signals do not have a communication capability, hence requiring the integration of separate wireless communications technology for many Telematics-type applications.

2.0 THE FUTURE OF GNSS

By the end of the first decade of the 21^{st} Century there will be several GNSSs, each with unique features, each operated by different agencies, and each essentially addressing the same user markets. We may speak of generations '1G' (GPS and GLONASS), '1.5G' (modernized GPS) and '2G' (Galileo and GPS-III), operating side-by-side over the next few decades. The best outcome would be that although the various GNSSs would be independent of each other (so that one catastrophic failure would not deny global GNSS operations), they would also be *compatible* and *interoperable* in order that user equipment may be developed that can utilise some or all of the broadcast signals.

2.1 GPS Modernization and GPS-III

GPS modernization refers to the collection of system improvements (satellite, signal, and control segment) that will change GPS to what might be referred to as a *1.5G GNSS*, principally by transmitting additional user signals. GPS modernization is focussed on improving the accuracy, and addressing signal vulnerability, for civilian uses, primarily through the implementation of a new publically-available PRN ranging code on the L2 signal (known as L2C), and a new civilian signal at the L5 frequency of 1176.45MHz. The former permits civilian users to make pseudorange measurements on either L1 or L2 or both, hence providing system redundancy. An open (non-encrypted) L2 signal will lead to a reduction in the cost of dual-frequency receivers. The latter (L5) signal is in the protected aeronautical frequency band, and is intended to satisfy civil aviation and other safety-of-life applications, but will be used for other applications as well.

The combination of three frequencies will revolutionise carrier phase-based position techniques, as *ambiguity resolution* will become a comparatively simple and robust accuracy enhancement process. (Note that these new signals will still be provided free to all users.) The new dual-frequency civilian tracking capability will be available on the Block IIR-M GPS satellites scheduled for launch from late 2005, while the other improvements (including transmission of the L5 signal) are intended for Block IIF satellites that are scheduled for launch starting in 2006-2007. However, it may be as long as 10 years before a full 'modernized' constellation is available. In the meantime *hybrid* GPS positioning will be the norm, with receivers having to track both the 'old' GPS satellites, as well as the 'modernized' satellites progressively brought online. In addition, a new (encrypted) M-code will be implemented exclusively for military use, on offset L1 and L2 frequencies, ensuring that military and civilian users will have entirely separate signals and codes. Consequently, both the SA and AS policies will have finally been abandoned (SA has already been turned off in 2000). However, it is unlikely that control of GPS will be wrested from the U.S. military. Studies for the 2^{nd} generation GPS, or

GPS-III, have commenced. However, GPS-III satellites are unlikely to be launched before 2012 at the earliest, several years after Galileo is scheduled to be fully operational.

2.2 GLONASS

GLONASS is a GNSS developed by the former U.S.S.R. during the Cold War, and like GPS was initially intended primarily for military applications. Although the signal and code structure is different from that of GPS (see, e.g. Seeber, 2003) there are also many similarities. For example, GLONASS is a dual-frequency satellite-based radiolocation system that permits pseudorange and carrier phase measurements to be made. In addition, both point positioning and relative positioning is possible, with similar levels of accuracy to GPS. GLONASS became operational with a full 24-satellite constellation in 1996. However, as of July 2005 the number of operational satellites has dropped to 14 (although several years ago it was much lower than this!); and the system's long-term stability has been considered questionable. Recently the President of the Russian Federation made a statement committing Russia to having again an operational GLONASS by the end of this decade. There exist GPS/GLONASS receivers that take advantage of the extended constellation of satellites. For more information on GLONASS the reader is referred to http://www.glonass-center.ru/.

2.3 Galileo

Since the late 1990s the European Union has been promoting the development of an independent GNSS under *civilian control*. The primary motivation has been to address the needs of the transportation sector (particularly civil aviation) for a GNSS with guaranteed *integrity*. *Galileo* is the GNSS that has been approved for development and deployment by 2008-2010. The signal and code structure is far more complex than for GPS, consisting of up to ten trackable signals and codes (Hein et al., 2003). There are common signals with GPS L1 and L5, permitting a significant degree of interoperability (i.e. combined GPS/Galileo receivers able to track signals from both constellations). Unfortunately there are no plans for a Galileo signal that overlays the GPS L2/L2C signal. Nevertheless increasing the number of signals-in-space (from nearly 60 orbiting satellites!) is to be applauded, as this leads to greater *availability*, particularly in urban environments. The combination of GPS and Galileo would certainly benefit many users. GPS has two free-to-air services: the SPS (civilian) and the PPS (military). However, Galileo proposes to offer *four positioning services*, two free-to-air (equivalent to the GPS-SPS, as well as a safety-of-life service), one commercial (high accuracy, high integrity service based on several frequencies), and an encrypted service for 'public authorities' (non-military) such as police, etc. Galileo may therefore be described as a 2nd generation GNSS. Furthermore, it is likely to be deployed several years before the first GPS-III satellites will be launched. For more information on Galileo the reader is referred to http://www.galileoju.com/.

2.4 Summary Remarks

There is a bright future for GNSS. The monopoly that GPS currently enjoys will be challenged by the end of the decade by the EU's Galileo system. A revitalised GLONASS may also be broadcasting signals. There is still some concern in the U.S. about the manner in which Galileo has been promoted, its partnership program with China, and how it will compete with GPS. Be that as it may, the rest of the world welcomes more signals-in-space, and more user equipment options. Furthermore, it could be argued that without the EU's plan for Galileo the U.S. government may not have accelerated the upgrade of the ageing GPS. Some of the new signals will provide better tracking performance in weak signal environments. Regional augmentations involving *extra* satellites, broadcasting GPS, GLONASS and/or Galileo-like signals, increase availability even further, as well as offer more user services. One example is Japan's proposed *QZSS* (Quasi-Zenith Satellite System - Petrovski et al., 2003), and India's *GAGAN* (GPS Aided Geo Augmented Navigation). However, all GNSSs suffer from essentially the same shortcoming, the relatively weak received signal strength. Various satellite and ground-based augmentation systems, as well as other positioning technologies, will still be necessary in order to address user concerns about *accuracy*, *availability* and *integrity*.

3.0 POSITIONING TECHNOLOGY TRENDS

There are many user requirements for positioning, and one would therefore expect a plethora of technological solutions. It is perhaps surprising that GPS has been so successful across a wide spectrum of applications. However, it is still instructive to consider the positioning technology options from a 'taxonometric' perspective, as indicated in Figure 1.

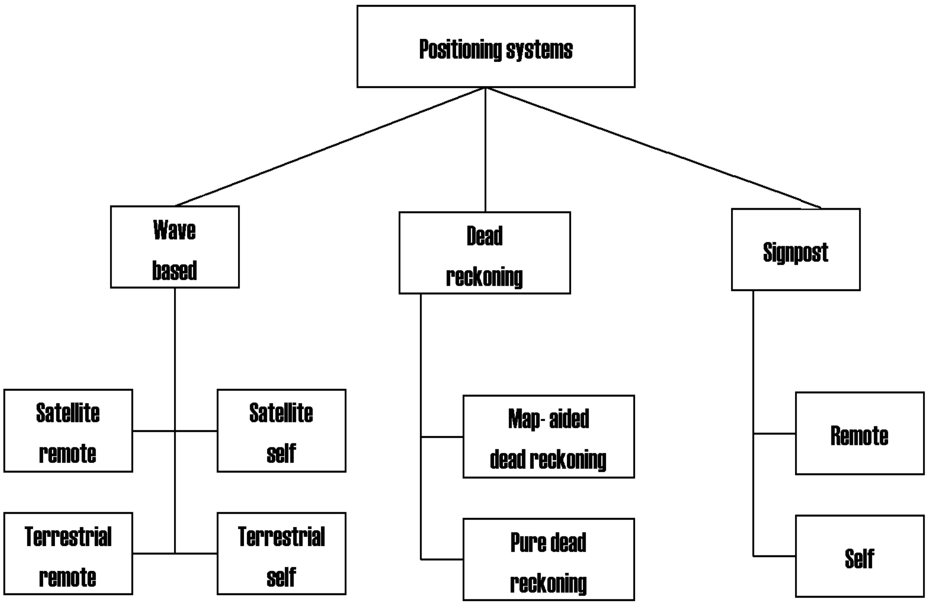

Figure 1. Taxonomy of positioning systems (Drane & Rizos, 1998).

The most common positioning technologies are 'wave-based', relying on RF, ultrasonic or infrared wave propagation. The other main categories are 'dead-reckoning' (inertial and orientation systems) and 'signpost' (proximity, RFID or cell-ID type systems). 'Remote' positioning refers to the circumstance where a network or centre computes position (as in a tracking-type application), as opposed to a 'self' positioning system where the position calculation is performed on the user's device. The former may also be referred to as "network-centric" positioning, while the latter is "user-centric" positioning. GNSS is therefore a *wave-based, satellite-self positioning system*.

The utility of GPS (and other GNSSs) varies from application to application. In some cases GPS has made such an impact that there is no competitive technology. *Geodesy* is an example of such an application area. In the case of high accuracy positioning in support of surveying and mapping operations, GPS is a very valuable technology that is but one part of the 'toolkit'. In some scenarios GPS is clearly the best option, but sometimes an alternative terrestrial-based system is used. For many navigation applications *GPS-only* positioning is not recommended. There has been a long history of integrating GPS with other navigation sensor technologies. For example, GPS integrated with an Inertial Navigation System (INS) has been the architecture of choice for marine and air navigation, machine guidance and control, field robotics, as well as for precise mobile mapping/imaging applications (Grejner-Brzezinska, 2001a, b). INS developments are themselves moving very rapidly, with lower-cost, higher-performance, smaller-sized MEMS (Micro-Electro-Mechanical Systems) sensors becoming increasingly an indispensable component of multi-sensor systems for a wide variety of civilian and military applications (Grewal et al., 2001).

The applications described above are all what might be referred to as *professional* applications. However, by far the majority of positioning applications will be associated with products and services marketed to *consumers*. We can identify two significant consumer application areas: 'personal location' (PERLOC) and 'transport telematics' (TRANTEL). PERLOC primarily is concerned with positioning a small portable device, and therefore GPS has to overcome its greatest shortcoming (section 1.5). GPS (and GNSS in general) is not reliable (or accurate) when satellite signals are blocked and/or reflected, as is the case inside buildings or in 'urban canyons'. Although significant progress has been made in improving weak signal tracking, it is still not clear whether GPS will be the only, or even the preferred, solution for mobilephone/personal-device position determination. TRANTEL applications, on the other hand, do have GNSS as its core positioning technology, though the incorporation of 'dead-reckoning' sensors does significantly improve availability and accuracy.

3.1 GNSS Receiver Trends

When considering the trends in GNSS receiver development we may parody the Olympian Ideal: *faster*, *smaller*, *cheaper*, and *better*. What do we mean by 'better'? The answer is: lower power consumption, increased accuracy, less susceptibility to RF interference, multi-featured, improved APIs, and higher sensitivity to weak received signals. Modern digital receiver designs have achieved a high degree of miniturisation as a result of the microelectronics revolution. Current receiver designs are 'postage-stamp' size, consisting of two (and even one) hardware chips, making them well suited for embedding within more complex systems. Already over ten million GPS receiver chipsets have been embedded within mobilephones. In fact, we are already seeing the GPS receiver functions being subsumed, as an IP-core, into a multi-purpose chip. In the near future full software-based receivers (using standard DSP and FPGA chips) may reach similar levels of performance as current hardware-correlator designs. Such receivers will be easily reconfigurable, and hence will be upgradeable to track any GNSS (and/or RF augmentation system) signals.

The modernization of GPS and the deployment of Galileo over the next decade or so will have a profound impact on future GNSS receiver designs. Instead of single-frequency receivers being the norm (and expensive dual-frequency receivers used for mainly niche applications), multi-frequency receivers will be used for all but the most price-sensitive applications. Such receivers will permit higher positioning accuracy, will be less susceptible to RF interference, and will be able to acquire and track lower strength signals than current GPS receivers. The cost of integrated GNSS receivers (e.g. GPS+Galileo, or GPS+GLONASS, or GPS+GLONASS+Galileo) may be only of the order of 10-20% more than single-system receivers. In fact, the majority of the value of a receiver will be in its software (particularly application-specific software), not hardware. In such a short review paper it is not possible to provide a comprehensive overview of GPS receiver developments. What is presented below is therefore a brief (subjective) summary of trends:

- Small-sized, low-cost OEM receivers that are well suited for developing new applications.
- Tracking of SBAS signals such as WAAS, QZSS, etc., will be a standard receiver capability.
- More sophisticated signal tracking, including multi-frequency, multi-GNSS capability.
- Improved signal processing to mitigate multipath interference, and to track low strength signals.
- Increasing use of carrier phase-based receivers (especially with multi-frequency tracking capability) to support sub-metre positioning accuracy.
- Greater integration with other sensor technologies, and wireless communications.
- Enhancement of positioning capability through the ability to augment signals from terrestrial pseudolites (transmitting GNSS 'look-alike' signals).
- More powerful onboard microprocessors, permitting the porting of more sophisticated application-specific software into the receiver's firmware.
- Power management, e.g. better sleep modes, better TXCOs, lower voltage, etc.
- The embedding of GPS receiver functions into multi-purpose chips.

3.2 Weak Signal Tracking & A-GPS

The U.S. Federal Communication Commission's (FCC) mandate to telecommunications carriers to deploy an 'enhanced' 911 emergency response system for mobilephones (known as 'E911' – http://www.fcc.gov/911/enhanced/) has been an important driver for the development of positioning technologies capable of being embedded within mobilephones. The *E911 mandate* does not specify which technology is to be used. It only defines the general specifications, including that the positioning accuracy of a device making a '911' call be of the order of 50m (67% of the time) and 150m (95% of the time) for 'user-centric solutions', or 100m (67%) and 300m (95%) if a 'network-centric solution' is used. Initially it appeared that GPS would not satisfy such requirements, as GPS signals could not be tracked indoors. Hence much of the attention during the late 1990s has been on mobile telephony-based systems (section 3.3). In fact the number of GPS receivers currently embedded within mobilephones far outnumbers 'standard' GPS receivers. It must be acknowledged, however, that although safety/security has been the main driver for mobilephone positioning in the U.S., in other countries it has been Location Based Services (LBS).

GPS has enjoyed significant success as a position determination technology for almost all *outdoor* applications. However, its most significant shortcoming is the weak received signal strength. Several of the new GPS and Galileo signals will be optimised for acquisition/tracking in weak signal environments (see, e.g. the discussion on L2C at http://www.navcen.uscg.gov/gps/modernization/default.htm). In addition, the last decade has seen a renewed interest in improving the GPS receiver technology in order to track very low signal strengths - as would be encountered inside buildings - of the order of 20-30dB below the 'open sky' signal strength. As a result, Wireless Assisted-GPS (A-GPS) and *high sensitivity* GPS receiver designs have been developed (Djuknic & Richton, 2000), and such systems will increasingly be deployed within mobilephones, competing with (or complementing) other mobile telephony-based techniques.

How can A-GPS help? For example, the timing and navigation data for GPS satellites may be provided by a ground network, which means that the receiver does not need to wait until the broadcast navigation message is decoded (in fact it may not be possible to decode this message in the case of very low signal strength). In essence, the assistance data makes it possible for the receiver to make the time measurements (equivalent to ranges) to GPS satellites without having to decode the actual GPS message, significantly speeding up the positioning process. A-GPS assistance messages (delivered to the GPS over the wireless telephony link) can also aid the receiver by providing information on visible satellites and their predicted Doppler-shifted signal frequency. A-GPS can also be implemented as a network solution; the raw measured pseudoranges being transmitted to a server where the computations take place. Sophisticated new tracking signal processing algorithms have led to the development of high sensitivity receivers. Such a receiver, with assistance data, would be able to acquire signals, make measurements and compute position almost instantly. High sensitivity GPS receiver manufacturers include *Snaptrack* (http://www.snaptrack.com), *Global Locate* (http://www.globallocate.com), *SiRF* (http://www.sirf.com), *uNAV* (http://www.unav-micro.com), and *SigNav* (http://www.signav.com.au).

3.3 Complementary & Competitive Mobilephone Positioning Technologies

In this section we will focus on competitive and/or complementary location technologies to GNSS for PERLOC applications such as E911 and LBS. These Telematics-type applications distinguish themselves from many other navigation/positioning applications in that what is required is a suitable relationship between Telematics Service Providers, mobile telephony networks and mobile users' devices, in order to locate the user with a required accuracy and to deliver to him/her the appropriate location-filtered information. While high sensitivity GPS is now a serious contender as a positioning technology for indoor and/or urban environments it is not the only option. Consider the options for positioning a *mobilephone*, as this represents by far the largest potential market for PERLOC devices.

The signal parameters most commonly used in mobilephone radiolocation are: angle-of-arrival, time-of-arrival, and signal strength (which can be converted into a range measurement), and signal multipath signature matching (sometimes also referred to as received signal strength 'fingerprinting'). The most popular techniques for finding the user's location is 'triangulation', based on angular measurements, and 'trilateration' when distance measurements are used, or some combination of both, connecting the mobile user and the base stations. The base stations are either mobilephone service towers (cellular network) or GNSS satellites. Thus, in general, the technologies for finding the user's location can be divided into *network-based* or *satellite-based* (currently GPS-based) systems. Another classification is based on the actual device that performs the positioning solution, i.e., mobile user or at some network control centre (NCC), leading to *mobile terminal (user)-centric* or *network-centric*, as well as *hybrid solutions*. In the network-centric systems, the user's position is determined by the NCC, while in the terminal-centric solution the position computation is performed by the user's handset. In this section we present an overview of these PERLOC techniques. Much of this information has been taken from Hjelm (2002), Grejner-Brzezinska (2004), and web sites such as http://www.wirelessdevnet.com/channels/lbs/features/mobilepositioning.html. A summary of the characteristics of these techniques is presented in Table 1, and discussed below.

The *terminal-centric solutions* rely on the positioning software installed within the mobilephone. They are further divided into:

- GPS
- Wireless-Assisted GPS (A-GPS, section 3.2)
- Enhanced Observed Time-Difference (E-OTD)

The *GPS method* provides instantaneous point-positioning information with an accuracy of 5-50m, depending on the availability of GPS signals. *A-GPS* uses an assisting network of ground-based GPS receivers that can provide information over the mobile telephony network, enabling a significant reduction of the time-to-first-fix to a few seconds at most. However, due to multipath problems the accuracy is degraded relative to standard 'open-sky' GPS. Another terminal-centric solution is the *E-OTD*, which measures the time of the signal arrival from multiple base stations (within the wireless network) at the mobilephone. The time differences between the signal arrivals from different base stations are used to determine the user's location with respect to the base stations. For the positioning and timing purposes, the base stations might be equipped with stationary GPS receivers. Thus, the base stations in E-OTD serve as reference points, similar to GPS satellites. However, this method is not subject to limitations in signal availability affecting GPS, but still suffers from multipath (as all radiolocation systems do). The horizontal positioning accuracy of E-OTD has been quoted at 100-125m (95% of the time).

The main *network-centric solutions* are:

- Cell Global Identity with Timing Advance (CGI-TA)
- Time-of-Arrival (TOA)
- Uplink Time-Difference-of-Arrival (TDOA)
- Angle-of-Arrival (AOA)
- Multipath (Location) Pattern Matching (or 'fingerprinting')
- Received Signal Strength (RSS)

CGI uses the *Cell-ID* to locate the user, where the cell is defined as a coverage area of a base station (the mobilephone tower nearest to the user). This is a form of proximity or signpost technology (Figure 1). It is an inexpensive method, compatible with the existing devices, with the accuracy limited to the size of the cell, which may range from 10m to 500m (indoor micro-cell), to an outdoor macro-cell reaching many kilometres in size. CGI is often supplemented by the TA (Timing Advance) information that provides the time between the start of a radio frame and the data burst. This enables the adjustment of a mobilephone's transmit time to correctly align the time, at which its signal arrives at the base. These measurements can be used to determine the distance from the user to the base, further reducing the position error. *TOA* is based on the travel time (equivalent to distance) information between the base station and the mobilephone. In essence, the user's location can be found by trilateration, at the intersection of three (or more) arcs centred at the tower locations, with radii equal to the measured distances, similar to single receiver GPS positioning. The concept of *TDOA* is similar to E-OTD, however, in TDOA the time of user's signal arrival is measured by the network of base stations that observe the apparent arrival time differences (equivalent to distance-differences) between pairs of sites. Since each base station is usually at a different distance from the caller, the signal arrives at the stations at slightly different times. To calculate the distance-difference between the two base stations, a hyperbola is defined, with each base station located at one of its foci. The intersection of the hyperbolas defined by different pairs of base stations determines the 2D location of the mobilephone. A minimum of three stations must receive the signal to enable the user's location estimation as an intersection of two hyperbolas.

Table 1. Review of technologies for mobilephone positioning (Grejner-Brzezinska, 2004).

Technique	Primary Observable	Upgrade of the User Terminal or Network	Location Calculation & Control
GPS A-GPS	• Range to multiple satellites • 3D location • Minimum of 3 ranges required for 2D positioning	• User Terminal (GPS Rx, memory, software) • Non-synchronised networks may require an enhancement	Mobile Terminal A-GPS may also be computed by Network
Location/ Multipath Pattern Matching	• Multipath signature at the user's location • 2D location	• None	Network
RSS	• Received signal strength • 2D location	• None	Network
TOA	• Signal travel time between the user and the base stations • 2D location	• Supports legacy terminals • Monitoring equipment at every base station	Network
E-OTD	• Signal travel time difference between user and base stations • 2D location	• User Terminal (memory, software) • Base station time synchronisation	Mobile Terminal
TDOA	• Signal travel time difference between user and base stations • 2D location	• Network interconnection	Network
AOA	• Signal from multiple towers (minimum of 3 measurements is required) • 2D location	• Network interconnection • Antenna arrays to measure angles	Network
CGI	• Cell ID • Low accuracy, but ubiquitous • 2D location	• None	Network
Hybrid System (A-GPS + CGI)	• GPS range • Cell ID • 3D or 2D location	• Same as for GPS method	Mobile Terminal plus Network

The *AOA* method is based on the observation of the angle-of-signal arrival by at least two mobilephone towers. The towers that receive the signals measure the direction of the signal (azimuth) and send this information to the AOA equipment, which determines the user's location using basic trigonometry. The accuracy of AOA can be high, but may be limited by signal interference and multipath, especially in urban areas. Much better and more reliable results are obtained by combining AOA with TOA. The *Location (Multipath) Pattern Matching* method uses multipath signature in the vicinity of the mobile user to find its location. The user's terminal sends a signal that gets scattered by bouncing off the objects on its way to the tower. Thus, the tower receives a multipath signal and compares its signature with the multipath location database, which defines locations by their unique multipath characteristics (or 'fingerprint'). This method is comparatively unreliable and is unlikely to be favoured over other network-centric methods, although it may be used for WLAN-based positioning (section 3.4). Another method is based on the signal strength model observed for the area. By using a signal-propagation model the *Received Signal Strength (RSS)* can be converted to the receiver-transmitter distance. As in other ranging techniques, the user is located on a circle around the base with a radius equal to the distance derived from the signal strength. Accuracies of the order of tens to hundreds of metres have been reported. An important feature of this technology is that it can determine the location of *any* wireless device with no modification or add-ons or enhancements to the mobile telephony network. There is no 'best' technology, as each has advantages and disadvantages

(Table 1). Perhaps a hybrid solution, for example, based on GPS with a network-based CGI-TA, would offer a more reliable solution, or AOA plus TDOA, E-OTD plus A-GPS, or AOA plus RSS.

3.4 Other Positioning Technology Options

Although PERLOC applications like E911 have driven the development of alternatives to GPS, there is also an increasing interest in positioning for applications where the demands of *accuracy*, *availability* and *integrity* cannot be satisfied by the mobile telephony-based positioning technologies (section 3.3). Location-based gaming and computing, augmented reality, and positioning in 'difficult environments' (indoors and urban areas, in the presence if RF interference, etc.) for emergency service operations, robotics, logistics and warehousing, machine guidance/control, tourism, and so on, demands a new set of positioning technology options (summarised in Table 2):

- **Pseudolites** (or 'pseudo-satellites', PL) are ground-based GPS signal transmitters which can improve the 'open air' signal availability, or even replace the GPS satellites constellation for indoor applications. PLs typically transmit signals at the GPS L1 frequency, and both pseudorange and carrier phase measurements can be made, making possible the full range of GPS-like accuracy capability (Wang et al., 2001). More sophisticated systems based on non-GPS signal frequencies, such as *Locata*, have also been recently trialled (Barnes et al., 2004).
- **Terrestrial RF-based** systems have also been under intense study. There are a few operational systems (such as *Paric*, http://paric.co.nz/) and *Ranger*, http://www.ensco.com/), and a large number of systems developed in labs based on many different principles of measuring the TOA of a RF signal.
- **Wireless Local Area Network** (WLAN)-based systems (currently) use the 802.11b WiFi signals received from the mobile user or the Access Point (AP), and hence can used for 'self' or 'remote' positioning. There are essentially two methods of using WLAN: (1) convert RSS to distance and then trilaterate position (Wang et al., 2003), or (2) use the characteristics of the RSS (the 'fingerprint' method) to look up a database of RSS and postulate location on this basis (Li et al, 2005). Accuracies as high as a few metres have been reported. Obviously can only operate where there is a network of WLAN APs. **Bluetooth** is a short-range wireless communications technology that can also be used as a positioning system, applying the proximity method. That is, the location of the Bluetooth AP is known, and when a mobile device comes within range of the AP (typically less than 10m from it) it is 'discovered', and hence its location can be assumed to be somewhere within the Bluetooth cell (hence it is similar to CGI – Table 1). **RFID** is another proximity-based positioning technology, that is used to 'track' where objects and even people are by detecting when they come within range of a RFID 'reader' (equivalent to an AP).
- Other *wave-based positioning systems* have been developed, and may find applicability for specific scenarios. These include **acoustic** systems (which are primarily used in underwater positioning systems, but have been considered also for battlefield applications such as the detection of snipers), especially in **ultrasonic** indoor systems, (electro-)**magnetic** systems, **infrared**, and **UWB** (Ultra Wide Band) technology. However, in most implementations, their range of operations is likely to be of the order of tens of metres or less.
- A significant class of *tracking* techniques are **optical** in nature. These include the various **photogrammetric** techniques (short and long range), **EDM/total station** based systems (up to several kms), and even **CCTV** systems operating as a proximity sensors. Non-visible light systems are also possible.
- Increasingly important for many *robotic/autonomous navigation systems* are those that use **laser scanning** (LiDAR), **vision** or **radar** to detect obstacles. These are used to 'map' the immediate environment, though they are not usually used to determine *absolute* position.
- Finally, in a class of their own are the **inertial-based sensors**, consisting of a combination of *accelerometer*, *turnrate gyro*, *odometer/pedometer*, and *magnetometer* (or *compass*) sensors. None require external infrastructure such as base stations or signal transmitters, and hence they are truly autonomous in operation. The most sophisticated are integrated into Inertial Navigation Systems (INS) (see, e.g. Grejner-Brzezinska, 2001a, b). Rapid developments in sensor technology promise significantly less bulky, lower cost and high accuracy future INS suitable for a wide range of applications (including PERLOC). Simpler combinations of odometer and gyro are used in 'dead

reckoning' systems intended for TRANTEL applications. All such systems are typically integrated with GPS/GNSS to control the growth of position errors with time. Readers are referred to such texts as Grewal et al. (2001) for details of the sensors and how they may be integrated together.

Table 2. Review of technologies for general positioning (adapted from Grejner-Brzezinska, 2004).

Technique	Positioning Method	Environment/ Availability	Accuracy
Radiolocation			
• GPS	Range/time-based, 3D	Outdoor/global	4-10m
• DGPS	Range/time-based, 3D	Outdoor/global	Sub-metre to sub-cm
• Pseudolite	Range/time-based, 2D & 3D	Outdoor/indoor/local	Sub-metre to sub-cm
• RF-terrestrial	Range/time-based, 2D	Outdoor/indoor/local	High-to-moderate
• WLAN(1)	Range/RSS-based, 2D	Outdoor/indoor/local	3-20m (geometry)
• WLAN(2)	Fingerprint RSS, 2D	Outdoor/indoor/local	3-20m
• UWB	Range/time-based, 2D	Local (few metres – >10m)	High-to-moderate
• Bluetooth & RFID	Proximity or signpost	Local (<10m)	Size of 'cell' or range of signal
Inertial Navigation System (INS)	Integration of accelerations, 3D; turn sensing by gyros; needs position/orientation initialisation	Outdoor/indoor/local	High-to-Low (errors grow with time)
Dead Reckoning (DR)	Distance travelled by odometer, orientation by magnetometer, turn sensing by gyro; needs position initialisation, 2D	Outdoor/indoor/local Vehicle & marine apps	Moderate-to-Low (errors grow with time)
Acoustic (ultrasonic)	Range/RSS-based, 2D & 3D Phase coherence, 2D & 3D	Indoor/outdoor/local	High-to-low; affected by noise & multipath
Optical Tracking	Triangulation (photogrammetric), range/angle, 3D; CCTV proximity sensor	Indoor/outdoor/local	High (mm to cm)-to-low; affected by obstructions
Object Detection • Laser • Radar • Vision	Relative positioning, object detection, collision avoidance	Indoor/outdoor/local	High relative accuracy; affected by obstructions
Magnetic	Triangulation, 2D & 3D	Indoor/local	High-to-low; affected by magnetic field distortions

A common characteristic of these positioning technology options (apart from INS/DR) is that they are likely to find application in "hot spot" deployments, rather than being promoted as *ubiquitous* positioning technologies (such as in the case of GPS and mobile telephony-based systems). That is, most require an installed infrastructure, which makes them more suited to localised applications. It is unlikely that one technology will be globally favoured over the others. Furthermore, hybrid systems based on the *integration* of several sensor technologies (usually with GNSS, and INS/DR) will become increasingly common. Note also that the range of accuracies varies enormously.

4.0 CONCLUDING REMARKS

Although there are many different user requirements for positioning, over the last decade or so GPS has been very successful as a 'first choice' technology for all new civilian and military applications. In 2003 estimates of GPS receiver sales were of the order of US$15B, with the rate of increase over the last five years being 25% or so. Furthermore this rate of receiver sales increase is predicted to be maintained at the level of 20% pa through to the end of the decade and beyond. This is clearly good news for new GNSSs such as Galileo.

However, GNSS is unlikely to be the sole positioning technology used for the majority of applications. Many precise navigation, machine control and mapping applications will use GNSS integrated with other navigation sensors, such as terrestrial RF-based and INS, to ensure high accuracy, availability and integrity. However, the largest potential market for GNSS receivers is for personal and vehicle location applications. Although hybrid solutions will be offered, for the most price-sensitive applications there may only be one adopted positioning technology. In the case of vehicles GNSS is most likely to be the only (or at least the core) technology. For embedding within personal mobile devices it remains to be seen whether GNSS will be the technology of choice.

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