Nationwide High Accuracy Positioning Infrastructure and Services, Including for Intelligent Transportation Systems: Background, Technology, Uses, Developments and Challenges

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To Skybridge Spectrum Foundation and the "Telesaurus" LLCs, Berkeley California ("SkyTel").[*]

See also the accompanying papers: (1) by C. Rizos and associates, *"Impact of Next Generation GNSS on Australasian Geodetic Infrastructure,"* and (2) by Dan Paull, CEO of PSMA Australia Ltd, *"The Provision of Access to a Nationally Coordinated CORS Network.*[1] Both of these, also provided by C. Rizos to SkyTel, are on the same topics as and augment this paper.

Executive Summary

This Report provides an introduction to the background, technology and uses of augmented GPS (Global Positioning System) and GNSS (Global Navigation Satellite System) positioning systems; how they are being deployed and planned in many nations for high accuracy positioning serving both traditional professional geodetic, surveying and mapping applications, and a host of other, mass market applications that may include ITSs (Intelligent Transportation Systems) of the future; and some of the challenges to a nationwide communications-based high accuracy location ("C-HALO") infrastructure and services.

In this regard, an assessment of the costs and benefits of C-HALO is being developed for publication later in year 2010 or early 2011 by a team at the University of California- Berkeley Institute of Transportation Studies[2] (the "Berkeley C-HALO Study"). This Study was initiated

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[*] Skybridge Spectrum Foundation, Telesaurus Holdings GB LLC, Intelligent Transportation & Monitoring Wireless LLC, V2G LLC, Verde Systems LLC, Environentel LLC, and ATLIS Wireless LLC.

[1] [These two copies have margin notes and highlights added by SkyTel. – W. Havens.]

[2] *A Cost-Benefit Study of Cooperative High-Accuracy-Location Based Services Infrastructure (Next Generation US Positioning Infrastructure),* Christian Manasseh, Raja Sengupta, Adib Kanafani, and Kannan Ramchandran, work in progress commenced 2010, outline posted by Sky-Tel at the following link: http://www.scribd.com/doc/24091737/Sky-Tel-Proposed-US-High-Accuracy-Location-Infrastructure-Cost-Benefit-Study-Outline-UC-Berkeley

and is funded by Skybridge Spectrum Foundation and its donor "Telesaurus" LLCs of Berkeley California ("Sky-Tel") which also provided support for this Report.

This Paper assumes that readers are familiar with the essential concepts regarding GPS/GNSS, the need for augmentation for higher accuracy and reliability, the ITS and its needs, and other matters relating to positioning applications in transportation and similar industry sectors. A primary purpose of this Paper is to contribute to the discusson of the matters addressed herein among persons, government agencies, and companies in the United States planning the means and ways for the rollout of a nationwide C-HALO.

POSITIONING & INTELLIGENT TRANSPORTATION SYSTEMS ("ITS") AND OTHER APPLICATIONS

Among the targeted readers (see above), the need for ITS for efficient roadway, maritime, train and aircraft transportation is generally well understood. What is not well understood or addressed is how to achieve truly "intelligent" transportation systems over wide areas. A fundamental need is for the ITS to know precisely the location and trajectories of the individual vehicles (and other objects such as roadside infrastructure) along a transportation system, in as many of the places and times as possible, with sufficient accuracy and reliability for the ITS to guide vehicles across and along lanes to minimize accidents and congestion, reduce fuel use and pollution, to aid the collection of tolls and road-use fees, etc. This requires C-HALO.

The latest U.S. Radionavigation Plan (RNP, 2008) summarizes the value of C-HALO for ITS and other wide-area domains and applications. Relevant excerpts of the Plan are included as Attachment 2 in this Paper. While that Plan describes the need for GPS *augmentation* along the lines of C-HALO with decimeter-level accuracy (horizontal), this Paper considers the issue of higher accuracy, since sub-decimeter accuracy can provide many additional benefits. Systems providing a substantial margin of error are warranted for many C-HALO applications, starting with those involving the safety-of-life in ITS systems. The Berkeley C-HALO study, cited above, describes other potential applications and services of C-HALO, many of which require this higher accuracy.

HIGH ACCURACY POSITIONING

As indicated above, this Paper assumes readers are familiar with the essential aspects of Global Positioning System (GPS) technology, and the principal uses and benefits. In addition, it is important to understand the disadvantages or even "dangers" of non-augmented GPS. In short, insufficient accuracy and reliability for many critical location and navigation applications. Discussion of these problems may be found in many publications, including in *The Dangers of GPS/GNSS*, by Professor Borje Forssell of the Norweigian University of Science and Technology, in *Coordinates*, Volume 2, Issue 2, February 2009.[3] In addition, the 2008 U.S. Radionavigation Plan (RNP, 2008) addresses the need for GPS augmentation to remedy these

[3] Sky-Tel has posted a copy at: http://www.scribd.com/doc/24275897/Sky-Tel-Dangers-Shortfalls-in-Unaided-GPS-GNSS-Wireless-N-RTK-Solutions-of-This-for-Intelligent-Transport

problems. Furthermore, the Berkeley C-HALO study is pursuing an analysis of the domains, costs, and benefits of a nationwide C-HALO to addresses these shortcomings of GPS.

Introduction to GPS

The only fully operational satellite-based Positioning, Navigation and Timing (PNT) system is the GPS. The first GPS satellite was launched on 22 February 1978, over 30 years ago, and GPS as a PNT system was declared fully operational with 24 orbiting satellites on 17 July 1995. Russia has deployed its own Global Navigation Satellite System (GNSS) called GLONASS which will be fully operational (with 24 satellites) by 2010-2011. Fuelling growth in precise positioning applications during the next decade will be next generation GNSSs that are currently being developed and deployed, these include the U.S.'s modernized GPS-IIF and GPS-III, the revitalized GLONASS, Europe's GALILEO system, and China's COMPASS system. However, the GPS PNT computation algorithms, and the GPS operational procedures will be in common with all GNSS, as they all make use of the basic concept of one-way ranging with the aid of satellite and receiver clocks. All planned GNSS will be multi-satellite constellations, transmitting L-band carrier signals, spread using special modulation codes. Therefore we can predict many of the performance parameters and extrapolate the likely impact of "next generation GNSS" based on current knowledge of the GPS. (This Paper refers almost exclusively to GPS, though many of the comments are equally applicable to next generation GNSS, except that accuracy, reliability, availability will be increased, and receiver cost and operational constraints will be reduced.)

Over the last three decades GPS has revolutionized first the disciplines of geodesy and surveying, and subsequently, as the availability of satellite signals and appropriate user receiver equipment improved, the navigation community as well. Nowadays GPS is often discussed in the context of consumer applications such as car and personal navigation, and location-based services in general. However, the truly impressive performance of GPS is best exemplified by the improved PNT accuracy that can be achieved with the current GPS generation of user equipment and ground infrastructure. This Paper will focus on current high accuracy users and their applications, as well as new high accuracy applications in advanced *Intelligent Transportation Systems* (ITS).

All GPS receivers are capable of making *pseudorange* (PR) measurements, but in addition the receivers used for high accuracy applications also make *carrier phase* (CPH) measurements. Both types of measurements are made on the tracked L-band (microwave) frequencies transmitted by the satellites (Hofmann-Wellenhof et al, 2008): L1 at 1575.42MHz and L2 at 1227.60MHz. The CPH measurements are a thousand times more precise than the PR measurements. The standard civilian GPS receivers cannot easily track the GPS L2 frequency due to the effect of "anti-spoofing", and hence only specialist user segments (such as geodesy, surveying and machine guidance) operate equipment that (sub-optimally) track the L2 signal to make the necessary measurements. (This issue of high cost dual-frequency instrumentation, L1 and L2, has been a significant constraint to more widespread adoption of high accuracy GPS positioning.)

GPS Modernization

The U.S. has embarked on a program of *GPS Modernization* to provide better accuracy and more powerful and secure signals from future GPS satellites. It is not possible to describe this program in detail here, and readers are referred to easily accessible information on websites such as NavCen (http://www.navcen.uscg.gov/gps/default.htm) and PNT (http://pnt.gov/), as well as reference texts such as Prasad & Rugieri (2005) and Hofmann-Wellenhof et al (2008). While there are a range of planned improvements, noteworthy are the extra signals to be broadcast by the *next generation* GPS satellites:

- An improved PRN code family (instead of the current L1 C/A-codes) on the L2 frequency of GPS (the so-called *L2C-code*) is being implemented to enable civilian receivers to better account for ionospheric error, as well as to be more immune to RF interference and multipath. The L2C-code is an 'open' signal, hence the PRN code algorithm can be implemented in civilian receivers. This permits the appropriately designed new generation dual-frequency receivers to more easily acquire and track the L2 frequency, and make PR and/or CPH measurements. The first GPS Block IIR-M satellite to broadcast L2C was launched 26 September 2005 - with a total of 8 GPS Block IIR-M satellites to be launched - the last on 17 August 2009 (but currently set 'unhealthy').
- The launch schedule to replace existing satellites is difficult to predict but full operational capability (FOC) for L2C will not be declared until all 24 satellites (a combination of 8 GPS Block IIR-M, 12 GPS Block IIF and 4 GPS-III satellites) in the constellation are broadcasting the new signal, which is not expected to occur until 2016.
- The older GPS Block IIA (the last one was launched on 6 November 1997) and GPS Block IIR (the last one was launched on 6 November 2004) satellites will continue to broadcast signals until they are decommissioned. It is possible that by 2013-2015 there may still be several functioning GPS Block IIR satellites broadcasting on the L1 and L2 frequencies, and some new generation dual-frequency receivers may not be able to make PR and CPH measurements on the L2 frequency because they are not broadcasting the open L2C-code signal (with only the encrypted Y-code being available).
- The U.S. government has announced that it proposes to discontinue the broadcast of the encrypted Y-code on L2 from the end of 2020 by the modernized GPS satellites. The current generation of dual-frequency GPS receivers will therefore be unable to use codeless/semi-codeless tracking techniques to make PR and CPH measurements on L2. (Upgraded GNSS receivers will be unaffected, as they will track the L2C-code signal instead.)
- The radio spectrum for the L2 signal is not fully protected by International Telecommunications Union (ITU) rules, as it does not lie in the ITU's Aeronautical Radio Navigation Services band (in contrast with the L1 frequency, which does). This means that the L2C signal cannot be relied upon for *safety of life* applications such as navigation to aid civil aviation. Therefore a third civil frequency at 1176.45MHz (the so-called *L5 frequency*) is to be broadcast by the GPS Block IIF satellites (L5signal, 2003). The first GPS Block IIF satellite launch is scheduled for 2010, with FOC of triple-frequency L1-L2-L5 GPS satellites (i.e. 24 satellites, a combination of 12 GPS Block IIF and 12 GPS-III satellites) unlikely until 2018.
- The next generation GPS-III family of satellites will incorporate the extra L2 and L5 signals of the GPS Block IIR-M and GPS Block IIF satellites, as well as a new PRN code on the L1 frequency (the so-called *L1C-code*), which will be interoperable with GALILEO's E1 signal. However, to preserve backward compatibility with legacy user equipment, all current and planned GPS Block II signals will also be broadcast. The 30 GPS-III satellites are planned for launch from the year 2014 onwards, with completion by 2021.

- What remains unchanged throughout the modernization process will be: (a) GPS will be controled and operated by the U.S. Department of Defense, and (b) there will be no user charges introduced.

Principles of GPS Positioning

PNT accuracy is dependent on critical factors such as measurement type (PR or CPH), algorithm design (and in particular the degree to which measurement errors and system biases are mitigated or otherwise accounted for within the measurement processing algorithm), geometry of satellites relative to the ground receiver, and operational mode (see discussion below). In the case of GPS, applications are typically classified as follows according to absolute or relative positioning accuracy:

(1) *Single Point Positioning (SPP)* is the operational mode for which GPS was originally designed, using onboard algorithms that currently deliver horizontal *absolute* accuracy performance of the order of 5m in real-time. Vertical accuracy is typically 1.5-2 times worse than horizontal accuracy. The civilian users achieve such an accuracy using what is referred to as the GPS *Standard Positioning Service* (SPS), whether the user is stationary or moving. PR measurements made on only the L1 frequency are the basis of the SPS, and, as the name of the service implies, the vast majority of GPS user equipment falls in this category. The SPS is the service used by all car SatNav, hiker handheld and cellphone-based GPS receivers – more than 99.9% of all GPS users.

(2) *Differential GPS (DGPS)* can overcome some of the limitations of GPS by applying corrections to the basic PR measurements at the user receiver to mitigate or eliminate some of the more serious satellite system and atmospheric biases, based on a second receiver making similar measurements at a known point (a so-called 'reference' station). Again, only PR measurements on L1 are used for the subsequent PNT computations. The *relative* accuracy achievable can range from the few meter-level down to sub-meter, depending on the quality of the receivers and the particular DGPS technique that is used (see Table 1). DGPS is designed to operate in real-time, with continuous connectivity to a DGPS corrections service provider. Although used for many navigation and mapping applications, this accuracy is inadequate for machine guidance or advanced ITS applications.

(3) *GPS Surveying* also is a differential technique, that can achieve centimeter-level accuracy using receivers that measure the CPH of the underlying carrier wave signal. Efficiencies and high accuracy are assured when all measurements (PR and CPH) are made on both L1 and L2. For baselines between points separated by more than, for example, 5-20km (depending on the degree of ionospheric activity, which in turn influences the magnitude of the ionospheric delay on the L-band signals), it is necessary that such *dual-frequency* receivers can correct for ionospheric delay. For shorter baselines, dual-frequency receivers are necessary for rapid initialization of cm-level positioning (hence contributing to robust, efficient cm-level positioning when enough signals/satellites are tracked). During the last decade and a half GPS surveying has benefited from a number of innovations so that now cm-level positioning can be carried out in real-time, while the user receiver is in motion ("kinematic positioning"), over baseline lengths up at many tens of kilometers, without the need to operate their own reference station. The former two developments collectively

have given rise to CPH-based positioning capability in the so-called *"real-time kinematic"* (RTK) mode. The latter two are a consequence of the widespread establishment of permanent, continuously operating reference stations (CORS). RTK is an increasingly popular GPS technique for mission-critical applications of high accuracy GPS-based positioning such as machine automation/guidance of construction, mining and agricultural vehicles, and, in the future, several advanced ITS applications as well.

(4) *GPS Geodesy.* RTK and GPS surveying applications are adequately addressed with reliable cm-level horizontal positioning methods operating under local conditions. Geodetic applications, on the other hand, have been using GPS extensively since the early 1980s to address regional and global reference frame applications that do not require real-time results, nor need to account for the user antenna being in motion. GPS geodesy has therefore mainly supported national and global datum definition and maintenance, as well as the Earth science users, but at ever higher levels of accuracy. Currently relative accuracies are typically at the few parts per billion (1ppb is equivalent to millimeter accuracy over 1000km user-base station separation).

Differential GPS Positioning Techniques

High accuracy CPH-based GPS positioning techniques (positioning modes (3) and (4) above) have evolved since the early 1980s, from the first static geodetic control surveys to today's high efficiency RTK techniques. They all share a common requirement – application of the differential or relative positioning principle that requires one or more reference receivers operating at locations with coordinates known in the user's reference frame or datum. The characteristics of the high accuracy GPS positioning techniques are summarised in Table 1 (adapted from Table 12.1, Bossler et al, 2010). The following comments can be made:

- The least accurate differential positioning techniques are those based largely on PR measurements (possibly with some CPH smoothing), in either single-base DGPS mode or so-called "wide-area" DGPS mode.
- The dual-frequency CPH-based techniques are far superior in performance over single-frequency techniques, as they permit either (though not both at the same time) ionospheric measurement bias mitigation or very rapid ambiguity resolution.
- For all CPH-based positioning applications with relatively short static observation sessions (e.g. < 30 minutes), resolving the CPH ambiguities is crucial for cm-level accuracy. For static observation sessions of many hours in length, resolving ambiguities is not necessarily a prerequisite for cm-level accuracy – this is the typical geodetic mode of GPS operations.
- High productivity, high accuracy (rapid GPS positioning) requires comparatively short baselines, and reliable CPH ambiguity resolution.
- All high accuracy kinematic mode CPH-based GPS positioning requires that the ambiguities be resolved, either before commencing the survey task or "on the fly" if ambiguities are 'lost' due to loss-of-lock on the tracked signals.
- The RTK mode is increasingly popular for high productivity surveying, and mission-critical applications such as machine guidance/navigation.
- The "single-base RTK" mode was enhanced, from the late 1990s, by the so-called "network-RTK" (N-RTK) approach, where the spatially correlated atmospheric and satellite orbit errors could be better mitigated using *several* continuously operating GPS reference stations surrounding the user receiver. Furthermore, the length of the baselines could be relaxed by

perhaps up to 5 times, making N-RTK a viable cm-level accuracy GPS positioning technique across wide regions, states or an entire country.

- Increasingly the surveying/geodetic-grade receivers are also capable of tracking the next generation GNSS satellite signals, providing advantages primarily with respect to signal availability, but also improved reliability of cm-level accuracy in real-time or post-processed modes of differential positioning. They remain relatively expensive user equipment - costing many thousands of dollars.
- The GPS datum is *WGS84* (WGS84, 2000), which for all but the most precise geodetic applications may be considered coincident with the *International Terrestrial Reference Frame 2005* (soon to be superseded by ITRF2008).
- *Precise Point Positioning* (PPP) is not discussed here as it is not widely used beyond the geodetic community.

GPS POSITIONING INFRASTRUCTURE

Introduction to CORS

We can distinguish in GPS two types of ground receiver *infrastructure*. First, there is standard "system infrastructure", such as the *Control Segment* of GPS consisting of 16 monitor stations, and then there is *civilian augmentation infrastructure* consisting of "continuously operating reference stations" (CORS) to support differential positioning activities (see above). The former are necessary for system operations, amongst other tasks to track the satellites (from which the satellite ephemerides and satellite clock errors are estimated), and monitor the health of the signals so as to ensure GPS can be used in the SPP mode. The latter is a considerable civilian investment (by national and state government agencies, and the private sector or individual users) to facilitate high accuracy differential positioning (as well as system and signal integrity monitoring for critical navigation applications), in which the resulting user receiver coordinates are expressed in the datum implied by the *reference stations* – and not by the Control Segment datum (i.e. WGS84) as is the case with SPP.

GPS, the IGS and Geodesy

GPS in the 1980s was almost exclusively used for geodetic control surveys, and the inter-receiver distances were at first several tens of kilometers, being the average distance between first order geodetic groundmarks. However, at about this time GPS was also proving itself to be an effective tool of *Space Geodesy* for measuring crustal motion and establishing the global reference frame. Following, the distances between receivers increased progressively to hundreds and then thousands of kilometers, while the relative accuracies simultaneously increased. These developments ensured cm-level accuracy within GPS receiver networks even as inter-receiver distances grew significantly. These GPS geodetic stations inevitably became permanent reference stations for: (a) the monitoring of the station motion itself (due to horizontal and vertical crustal motion), (b) defining geocentric geodetic datums at the national level, and (c) the extension and increasing density of the geodetic control (groundmark) networks using GPS techniques. Since the late 1980s, and commencing in earnest in the 1990s, there has been a steady growth in permanent CORS to support high accuracy positioning. It is important to recognise the significant contribution of the "super-network" of reference stations of the *International GNSS Service* (IGS – http://igs.org) to geodesy, and to the GNSS community in general. Several

hundred globally distributed GPS receivers (Figure 1) operate on a continuous basis, contributing data to the IGS analysis centers and other users. The GPS measurements they have collected have been used in progressive *realisations* of the *International Terrestrial Reference Frame*. Many countries have redefined their national datums to be 'compatible' with an ITRF reference frame, by typically linking primary stations and/or first order geodetic control groundmarks to the ITRF via differential CPH-based GPS surveys, using the nearest IGS reference stations as the fixed known datum points. These national datums are geocentric, and as far as most users are concerned they are equivalent to the GPS datum WGS84. Many countries have also established *active* primary networks of GPS CORS to monitor the *stability* and *integrity* of their datums. This is particularly the case for countries located on or near tectonic plate boundaries that cause their datum (or to be more correct, the realisation of their datum in the form of 3D coordinates of groundmarks and reference stations) to undergo deformation (or coordinate *change*) with time.

National CORS Infrastructure

Even countries that do not experience a level of widespread crustal deformation that challenges a national datum's internal integrity regard permanent GPS CORS networks to be important infrastructure that supports national (and international) geodetic and geoscientific studies. However, the inter-receiver spacing was rarely less than a hundred kilometers, and often it was much more. Furthermore, all such infrastructure until relatively recently did not have a *real-time* data transfer or processing capability. In the 1990s, when the establishment of such CORS networks was justified on geodetic grounds, national networks were similar to IGS stations. That is, although operated on a '24/7' basis, the data were only periodically downloaded from each receiver as (typically) ASCII files in the Receiver Independent Exchange (RINEX) format, and sent to an archive or data center. From there the data were available to users for post-processing. Note that no distinction is made between data sourced from an IGS station, or from any other GPS receiver network. Nevertheless it is sometimes useful to refer to a hierarchy of permanent GPS reference stations, for example: (1) *Tier 1* being the IGS stations, (2) *Tier 2* the primary national geodetic network, and (3) *Tier 3* the state (or secondary) and private GPS networks. For some applications the source of the GPS data is irrelevant. However, other applications seeking the highest accuracy and/or integrity may only use data from Tier 1, and perhaps Tier 2, stations or networks. The monumentation and facilities of the different tiers of CORS would vary considerably. Tier 1 and 2 stations would be extremely robust, established on highly stable ground, with deep pillars. Tier 3 stations typically would cost a tenth or less to establish, exemplified by building-mounted antennas.

Over time, the fact that national GNSS CORS networks could also satisfy surveying applications came to be viewed as an important justification for the provision of *geodetic infrastructure* in its own right. Note that this can be considered an *extra* benefit of a Tier 2 permanent network operated by a national geodetic agency (the primary justification always being that the network allows the national geodetic framework to be monitored, as in the case of Geoscience Australia, National Resources Canada, the U.S. National Geodetic Survey, and similar organizations in many other countries, see e.g. Figures 2, 3, 4). However, for other states or agencies in many countries Tier 3 networks are rarely justifiable solely on 'geodetic grounds', and hence supporting professional users (surveyors, engineers, etc.) and critical industries (agriculture, mining, etc.) so that they can carry out high accuracy GPS surveys with greater efficiency may be the *sole* justification. CORS networks will be able to support real-time high accuracy positioning

in the form of either RTK or N-RTK implementations. Such a rollout of CORS infrastructure will benefit advanced ITS applications as identified by the proponents of C-HALO.

GPS AUGMENTATIONS

'Augmentation' implies techniques for improving the basic level of GPS performance. The performance may be measured in terms of accuracy, availability, reliability or integrity. In general, safety-of-life applications place greater importance on reliability and integrity than accuracy or availability. There are a variety of augmentation techniques, including improved GPS user equipment (e.g. GPS receivers making CPH measurements in addition to PR measurements to improve accuracy, or 'receiver autonomous integrity monitoring' algorithms within aviation receivers), or space-based techniques (e.g. the program of GPS Modernization can be considered a form of augmentation, providing extra and improved signals), but the best known augmentation techniques used single or networks of ground 'reference' stations that also track the GPS satellites and therefore contribute to improving accuracy and/or integrity.

This Paper highlights two forms of augmentation that are relevant to advanced ITS applications. Both imply the establishment of 'Positioning Infrastructure', a critical civilian co-investment in improved GPS-based PNT. The first is the use of CORS that address the challenge of improving accuracy, especially for real-time positioning (see previous section). The second is the use of extra, terrestrial pseudolite transmitters to improve availability. Both are discussed briefly in the following sections.

Real-Time CORS Infrastructure

Increasingly data is streamed in real-time from IGS and other CORSs in order to address high accuracy real-time positioning via techniques such as RTK and N-RTK. With the advent of RTK techniques in the early 1990s, CPH-based GPS technology finally could be seriously considered a *surveying tool*. Productivity increased to such a degree that private survey companies could invest in the receiver equipment. *Productivity* can be measured in many ways, but essentially refers to the number of points that could be coordinated in a day, with minimum constraints on field operations. CORS nowadays provide the fundamental infrastructure required to meet the needs not only of *geodesy* and the geosciences, but also of many professional GPS *surveying*, *mapping* and *navigation* users. Furthermore, the widespread use of the RTK techniques means that such reference station receivers increasingly have to support ever expanding non-geodetic, *real-time* applications of high accuracy positioning for *engineering*, *machine guidance, precision agriculture,* and in future *advanced ITS*. This requires additional investment in communication links - between reference receivers for monitoring performance and computing network parameters, as well as with real-time users via wireless telecommunications. Such *real-time* CORS infrastructure (sometimes also referred to as Real-Time Networks, or RTN) is increasingly seen as being another *utility* for modern society, much like water, power, transportation and telecommunications. GPS high accuracy techniques which rely on RTN-CORS may on their own, or in combination with other technologies such as pseudolites, inertial sensors, RFID and various DSRC-based systems, address ITS applications in difficult environments such as in urban downtown areas, or rural canyons.

Constraints to GPS-based RTK

However, to ensure high productivity RTK (rapid and reliable cm-level accuracy) there were a number of constraints, including: (a) that all GPS receivers (reference and rover) must have dual-frequency tracking capability, and (b) the inter-receiver distance should be less than ten or so kilometers. These are significant constraints, hence the greatest impact on GPS receiver infrastructure was the development of *network-based techniques* that enabled cm-accuracy positioning with less dense reference receiver spacing - of the order of 50-100kms - even in real-time. Such CORS spacing could now be considered feasible as *surveying infrastructure*, and by the late 1990s and early 2000s many government and private network operators became interested in the *economics* of so-called "network-RTK" (N-RTK). With ever increasing demands for RTK for machine guidance, and even for ITS, the concept of a National Positioning Infrastructure (NPI) to provide widespread, reliable, continuous cm-level positioning for *all* applications is worthy of study.

RTK and N-RTK

The concept of N-RTK GPS originated in the mid-1990s and has been progressively developed into the commercially viable systems available today. Conventional single-base RTK has long been limited to distances of 10-20 km from the reference station under ideal geometric and atmospheric conditions. With N-RTK, highly accurate positioning is achievable over distances of several tens of kilometers (reference station spacing should generally not exceed 70-100km). N-RTK provides GNSS positioning results with homogeneous and high accuracy, reliability (i.e. repeatability and precision) and availability (of corrections) through the measurement of GPS signals, modeling of the distance-dependent systematic error sources (i.e. primarily the ionospheric and tropospheric delays and orbit errors) and representation of these errors as real-time corrections for roving GPS user receivers. These corrections are typically transmitted in the standard Radio Technical Commission for Maritime Services (RTCM – http://www.rtcm.com) format via radio, cellphone or wireless internet. Several competing N-RTK implementations exist including the Virtual Reference Station (VRS) technique, the use of area correction parameters (in German *Flächenkorrekturparameter*, FKP), as well as the Master-Auxiliary Concept (MAC) and its Master-Auxiliary Corrections (MAX) and individualized Master-Auxiliary Corrections (i-MAX). All have a requirement for a CORS network of appropriate density, coverage and sophistication to support real-time services.

N-RTK Implementations

The *Virtual Reference Station* (VRS) concept is a technique of creating GPS reference station data for an invisible, unoccupied station in order to improve the positioning results achievable with conventional single-base RTK by providing RTK corrections that are based on the entire network. The CORS network is continuously linked to a control center which creates a database of regional area corrections across the network. These are then used to create a VRS, situated only a few meters from where the user is initially located, together with GPS data which would have come from this VRS. The user interprets and uses the data just as if it had come from a real reference station. The implementation of the VRS technique requires at least three reference stations which are connected to the network server, and the rover must be capable of two-way communications. The GPS rover sends its approximate (i.e. SPP) position to the control center in National Marine Electronics Association (NMEA – http://www.nmea.org) format, generally

using a cellphone or mobile internet link. The control center accepts this position as the location of a new VRS and calculates RTCM corrections so that they appear to be coming from this VRS in close vicinity to the rover, effectively reducing the RTK baseline length. On the rover side, standard RTK algorithms are employed to obtain a position fix. The VRS concept is illustrated in Figure 5. In order to apply this technique, the network provider has to perform the following steps:

1. Fixing the ambiguities of the baselines within the reference network allows determination of the ionospheric, tropospheric and orbit errors on the observables with cm-accuracy.
2. The data of a selected reference station, generally the closest to the rover, is geometrically displaced to simulate the new position of the VRS.
3. The errors measured in the network are interpolated to the VRS location using linear or more sophisticated models.

From the user's perspective, the following procedure is performed:

1. After starting the rover receiver in real-time positioning mode, the user dials into the VRS network service via a cellphone capable of data transmission or mobile internet.
2. When the caller is successfully authenticated, the rover receiver sends a navigation solution of its current position as a rough position estimate to the computing center.
3. After receiving the rough position estimate, the computing center creates a VRS at this location.
4. A continuous data stream of reference data generated for the VRS position is sent to the field user receiver. This can be done in RTCM or other real-time formats.

The Master-Auxiliary Concept (MAC) concept is to transmit all relevant correction data from a CORS network to the rover in a highly compact form by representing "ambiguity-leveled" observation data as correction differences of dispersive and nondispersive data for each satellite-receiver pair. Two reference stations are said to be on a common ambiguity level if the integer ambiguities for each phase range (satellite-receiver pair) have been removed (or adjusted) so that when double-differences (involving two receivers and two satellites) are formed the integer ambiguities cancel. In order to reduce the volume of data to be transmitted for a network, full correction and coordinate information is sent only for a single reference station, i.e. the master station. For all other stations in the network or sub-network, i.e. the auxiliary stations, correction *differences* and coordinate *differences* are transmitted. Splitting the corrections into dispersive and non-dispersive further reduces the bandwidth required since tropospheric and orbit errors are known to only change slowly over time, so the data rate does not need to be as high as for the dispersive error. The master station does not need to be the nearest reference station to the rover, although it may be preferable, since it is used simply for data transmission purposes and plays no special role in the computation of corrections. N-RTK messages can be used in both static broadcast (one-way communications) mode and in automatic mode (two-way communications). In static broadcast mode, the master station is predetermined, and in automatic mode it will be the station closest to the rover.

MAX contains the network corrections as specified by the MAC concept. The interpolation of the network corrections is performed by the rover using the full information of the network but is only available for rovers that support RTCM 3.1 network messages. MAX corrections are available in both one-way and two-way communications mode. The generation of MAX corrections is explained in Figure 6. It is important to note that if network corrections are not

available (e.g. because not enough stations/satellites are ambiguity-fixed) then no corrections will be sent. In such a circumstance, the user receiver must switch to a single-baseline solution. If a rover interpret RTCM 3.1 messages 1004, 1005 (but not the network messages 1015, 1016), it can still use the MAX corrections to compute a single baseline from the master station.

In order to support legacy model user receivers not able to interpret the RTCM 3.1 network RTK messages, individualized master-auxiliary corrections (i-MAX) are produced. These i-MAX corrections require two-way communications in order for the network operator to choose the appropriate cell and interpolate the network corrections for the rover's position. The corrections are based on the same interpolation algorithm used in the rover with MAX corrections and can be transmitted in the RTCM 2.3 and RTCM 3.1 single base station formats. In contrast to the VRS concept, i-MAX uses a physical reference station as the source for the network corrections, enabling consistency and traceability for the corrections received by the rover. The basic steps in the use of i-MAX are illustrated in Figure 7. It should be evident that i-MAX is very similar to VRS and therefore has many of the same problems, e.g. in both cases the network server calculates corrections using proprietary algorithms. Two important differences are: (1) i-MAX always uses a real reference station and not a virtual one and is therefore legally traceable. (2) If the reference stations are approximately 70km apart then there will be baselines of 40km or more in length which may prevent some rovers from getting an ambiguity-fixed solution with i-MAX.

RTK/N-RTK as described above implies that RTCM messages are transmitted to users, where they are applied within their own receivers to generate the high accuracy positioning results. The two levels of communications are: (a) linking the individual CORS to stream raw CPH and PR measurements to a server at a control center, and (b) broadcasting the RTCM messages to all users. It is possible to reverse the latter flow and stream GPS data from the user back to the control center, and to execute "server-side" RTK/N-RTK. This may be useful for certain applications such as monitoring the positions and motions of many receivers. An even more radical implementation would mirror the situation within ad hoc (or "peer-to-peer") wireless networks, where the computational load is shared amongst a large number of *cooperating* user receivers so that all receivers then have information on the relative positions of all other receivers within a cluster. This form of cooperative positioning could be useful for advanced ITS applications such as collision avoidance.

Locata Technology

Locata's positioning technology solution has been proposed as an alternative to GPS in 'difficult' GNSS environments. A network of ground-based transceivers (known as *LocataLites*) transmit positioning signals. These transceivers form a positioning network (known as *LocataNet*) that can operate in combination with GPS, or entirely independent of GPS. One special property of the *LocataNet* is that it is time-synchronous, allowing *single point positioning* with cm-level accuracy using CPH measurements. In its early days, the Locata system as a prototype used the L1 frequency band, and therefore was a "pseudolite" technology which assumed that the user receiver could be just a modified GPS receiver. The *LocataLites* now transmit their own proprietary signal structure in the 2.4GHz ISM (licence-free) band. This allows for considerable flexibility in system design due to there being complete control over both the signal transmitters and the user receiver.

A large number of tests have been conducted using Locata on its own, or in combination with GPS and INS (in a so-called "triple-integration" mode). These tests include static applications such as high accuracy deformation monitoring, as well as moving (kinematic) applications both indoors and outdoors. The results are reported in many papers[4]. Continuous Locata tests have been conducted over many years at Locata Corporations' Numerella Test Facility, located outside Canberra, Australia. The signals can be received over distances of many kilometers. The density and distribution of the LocataLite ground infrastructure has important implications on the utility of this technology, used either on its own or in combination with GPS/GNSS technology. Locata would appear to be best suited for limited coverage of "hot spots", such as urban cores or critical zones where PNT availability, accuracy and reliability are of paramount concern. Recently Locata Corporation was contracted by the USAF Holloman Airforce Base to provide Locata signal coverage over an area of over 1000 square miles. The success (or failure) of this deployment will confirm (or not) the viability of the Locata technology as a GPS augmentation in difficult GNSS signal environments.

NATIONAL POSITIONING INFRASTRUCTURE (NPI)

NPI & Heirarchies of CORS

Users of CPH-based GNSS techniques (Table 1) may be moving or static, use single-frequency or dual-frequency measurements, require coordinate results in real-time or post-mission (post-processing), track GPS signals only or both GPS and GLONASS, and have varying requirements with regard to integrity. These users are drawn from different disciplines: geodesy, surveying, engineering, machine automation, and precise navigation. In an earlier section the CORS infrastructure to support such users was catergorized according to "tiers": (1) *Tier 1* being the IGS-class stations, (2) *Tier 2* the primary national geodetic CORS network, and (3) *Tier 3* the state (or secondary) and private CORS networks. The Tier 3 networks are densified to the level that they can cover a large region, state or even an entire company. These CORS networks would provide the bulk of the high accuracy services to most users via real-time CPH-based positioning techniques such as RTK and N-RTK.

Within such a heirarchical structure we can envisage even additional "tiers". For example, *Tier 4* could be the high accuracy infrastructure of terrestrial transmitters or transceivers for "pseudolite" (using GPS/GNSS frequencies) and other terrestrial multilateration technologies (non-GPS/GNSS frequencies). An example of the latter is Locata. *Tier 5* may be the relatively low accuracy, but ubiquitous short-range communications based technologies such as WiFi, RFID, Zigbee, DSRC, and so on. In fact communications is fundamental to making the NPI work in an integrated fashion, but also to ensure timely delivery of PNT services to users, wherever they may be.

Next Generation CORS Infrastructure

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[4] Download papers from the School of Surveying & Spatial Information Systems, University of New South Wales website, http://www.gmat.unsw.edu.au/snap/about/publications_year.htm.

All high accuracy GNSS techniques rely on the differential mode of operation. In 2013-15, when all (or at least the majority) of GNSS constellations are transmitting L-band signals, appropriately equipped users would benefit from:

- enhanced *accuracy* (more observations, greater measurement redundancy, faster filter convergence, lower PDOP, etc.),
- improved *availability* (about three times more visible satellites, dual- and triple-frequency signal availability, more rapid time-to-first-fix, lower constraints regarding user-reference receiver separations, etc.), and
- higher *integrity* (high measurement redundancy, minimised interference vulnerability, enhanced QC algorithms, etc.).

The CORS infrastructure must address the needs of such users by operating receivers with at least the same level of signal tracking capability as those users. The IGS is currently in the process of defining the specifications (principally in terms of which signals will be tracked) of the "next generation geodetic GNSS receiver". It is likely that top-of-the-line GNSS geodetic receivers will be designed to track all signals, from as many GNSS as is practicable. Hence Tier 1 and 2 CORS will be equipped with what may be considered to be the 'Rolls Royce' of GNSS receivers. But what about Tier 3 CORS intended to address the requirements of non-geodetic users? That is not an easy question to answer. Consider the following characteristics of high productivity, cm-level accuracy techniques based on resolving ambiguities in double-differenced CPH observables (to convert them to precise carrier range observables):

(1) Dual-frequency techniques are likely to require CORS separations of the order of 50-100kms; an extrapolated claim based on the assumption that the N-RTK operational mode will be used, with extra satellites providing quicker and more reliable CPH ambiguity resolution due to improved residual atmospheric bias mitigation.

(2) Studies of triple-frequency techniques (employing so-called "triple carrier ambiguity resolution" – TCAR – algorithms, and even multiple carrier ambiguity resolution – MCAR – techniques), suggest that far sparser CORS networks may be adequate; perhaps CORS separations of a few hundred kilometers or more.

The choice would appear stark. Establish sparse networks of triple-frequency CORS receivers to support long-range TCAR for suitably equipped users, or maintain dense networks of dual-frequency CORS receivers to support a far larger range of users. One possible scenario is that there will be a combination of *both* types of CORS networks; sparse ones equipped with geodetic-type multi-frequency, multi-GNSS receivers, and far denser networks equipped with low-cost, dual-frequency (L1-L5) multi-GNSS receivers. Whatever the 'mix' of CORS receiver types, in the author's opinion the CORS ground infrastructure investment is likely to continue to grow significantly in the future. This investment will manifest itself as an enormous number of continuously operating GNSS receivers, numbering many tens of thousands across the world, collectively representing the largest financial contribution to GNSS capability by national governments and private companies – apart from the satellites themselves. The economic arguments for nationwide NPI are very compelling, suggesting that it is very likely that in the coming 3-5 years substantial investments in wide-area coverage CORS, and associated N-RTK services, will be made. For example, there is currently a proposal before the federal government for Australia to rollout a nationwide network of approximately 3000 CORS, at about 70-100km spacing, at an estimated cost of AUD$300 million. The primary beneficiaries will be the rural sectors of precision agriculture, automated mining and construction. Nevertheless the the

majority of users – potential consumers of advanced ITS services – will be located in urban and suburban areas. In the U.S., this would lead to the morphing of CORS/N-RTK into C-HALO.

It is likely that future dual-frequency receivers will be substantially cheaper than current systems. Some, including this author, future receivers will be one tenth of cost of today's. There is no reason to believe that sub-US$1000 Tier 3 receivers may not be available by the middle of this decade. This is partly due to the rapidly declining cost of electronic hardware, so that dual-frequency receivers need not be very much more expensive than today's single-frequency (L1-only) receivers, especially if units are manufactured in the millions of units volume. For example, L1-GPS receivers inside today's cellphones cost less than US$10 each! RTK/N-RTK software costs should also drop dramatically due to the availability of open source CPH data processing software[5]. Low-cost dual-frequency receivers that can be deployed in millions of vehicles, capable of sub-decimeter accuracy (using N-RTK techniques), supported by dense Tier 3 CORS networks, would enable advanced ITS applications.

CORS Infrastructure: Organizational Issues

However, questions arise as to the nature of the CORS infrastructure, who would operate it, what would be the density of CORS receivers, what tracking specifications (and therefore receiver cost) would they have, and others. The following is mostly taken from Rizos et al (2010). A useful framework for considering organizational issues as we move to a multi-GNSS future is to set out some clear principles for the positioning infrastructure. Higgins (2008) developed the following list of principles to inform the development of a policy for a National Positioning Infrastructure (NPI) for Australia:

- **Public Good**: Meet public good needs such as strengthening rather than fragmenting a nation's geospatial reference frame, and supporting improved management of natural disasters and climate change;
- **Open Standards**: Conform to well defined and open standards in relation to issues such as interoperability for equipment and data transmissions and for connection to the geospatial reference frame;
- **Multi-purpose**: Enable multiple applications where possible;
- **Beneficial**: Allow full realisation (by users and operators) of the economic, environmental and societal benefits for a nation;
- **Optimal**: Avoid unnecessary duplication of stations and associated infrastructure to minimise the costs of establishment and maintenance to the economy as a whole;
- **Collaborative**: As well as a need for collaboration between different state government departments, the approach should encourage participation by non-state government parties in the public, private and research sectors;
- **Sustainable**: Allow for revenue streams for station owners to recover operating and replacement costs either directly or through partnerships with commercial service providers;
- **Extensible**: Recognize that availability of resources to build the positioning infrastructure may vary in time, location and across sectors.

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[5] See http://www.scribd.com/doc/24333925/Sky-Tel-RTKLIB-Open-Source-Low-Cost-RTK-Receiver-Toyko-Uni-Maritime

Although developed with the Australian NPI in mind, these principles, and the organizational roles identified above, have universal applicability. Higgins (2008) also proposed a model for understanding and facilitating discussion of the roles that a given organization may play in the delivery of precise positioning services, which would involve all three tiers of CORS coming together in a unified network. The model breaks up the process into five discrete roles that an organization might play (Figure 8):

- ***Specify the network and services***; through issues such as the required stations density, coverage and quality, the service accuracy, reliability and availability and technical issues such as the geodetic reference frame.
- ***Own the reference stations*** and deal with site selection, site construction, equipment purchasing, data communications from stations, site maintenance and equipment replacement cycles.
- ***Network the data*** by running the network control center and associated information technology and communications, and carrying out the quality control and archiving of raw data.
- ***Process the network***, which involves processing the raw data from the stations and producing the correction data streams and distributing them to users.
- ***Deliver the Services*** is the final role that an organization may play and involves activities such as retail sales and marketing of data products, support to end users and their rover equipment, and liaison with communications providers for end users.

Higgins (2008) also points out that if different organizations play these different roles there will be a need for strong *governance processes* to underpin the service and enable clarity and transparency in terms of business and legal issues. Good governance mechanisms also ensure that end users have confidence in the service. Typical governance mechanisms required would be agreements on responsibilities of each organization and setting agreed levels of service within and between each of the roles outlined above. The organization roles outlined above can be helpful for an individual organisation to understand how its role may evolve as we move into a multi-GNSS future. Some specific issues (an incomplete list) to consider include:

- It is likely that in a multi-GNSS future, government agencies responsible for geodesy and national mapping will want to continue to play the first three roles of *specifying* and *owning stations* and in *networking those stations and their data*.
- That is especially true for Tier 1 and Tier 2 stations, where the primary purpose is to establish and maintain the geospatial reference frame, and to support the IGS activities such as generating high quality products such as the ultra-rapid orbits, which are widely relied upon by precise positioning service providers.
- However, when one considers the possible role of geodesy and national mapping agencies in Tier 3 stations the situation is less clear. This is because the primary purpose of Tier 3 CORS is to create the network density necessary for generation of real-time corrections with centimeter-level accuracy via RTK or N-RTK services.
- As outlined earlier, the characteristics of a multi-tier CORS network, in a multi-GNSS future, will vary according to the needs of the users of the service, and those future needs are not yet clear.

ADVANCED ITS & HIGH ACCURACY POSITIONING

Vehicle-based Position Determination

There is increasing interest in vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications in order to support advanced ITS applications. One of these applications is collision avoidance. Collision avoidance will require high accuracy (and high reliability) relative positioning. Such positioning will necessarily be a modification of standard RTK/N-RTK (see, for example, Efatmaneshnik et al, 2010; Alam et al, 2010), to incorporate the principles of "cooperative positioning". Nevertheless, a discussion of the future of V2V and V2I positioning can be conducted within the framework of standard *vehicle-based* RTK/N-RTK techniques:

(1) The N-RTK network or control center delivers the RTCM corrections to vehicles using narrowband wireless broadcast (narrowband, since this is sufficient, and since that results in far better coverage and reliability than broadband wireless).

(2) Vehicles use those N-RTK corrections to calculate their accurate positions, where there is little signal blockage and multipath.

(3) Broadcast of corrected coordinates could be provided in defined areas in which corrections of certain accuracy are needed (this would typically be of the order of 50-100km). For example, if we have 100 CORS to cover most of California, each one may broadcast a unique set of corrections, and those would change as often as needed.

(4) Vehicles, at least those that have the need or otherwise bear the cost, supplement those N-RTK corrections with inertial navigation systems (INS) and other techniques, such as terrestrial multilateration (if available), etc., as well as using less-accurate (few decimeter-level) wide-area differential GPS services such as Nacom's Starfire or Fugro's Omnistar as the backup option. [6]

(5) For many situations and applications needing ITS directions, the vehicles would send their position information (and trajectories) to the ITS network (each using of course a unique narrowband wireless communication channel),[7] and where needed (for some, but not all situations) receive back location-based instructions (to keep most safe and efficient lateral and longitudinal spacing, to authorize priority-lane use, warn of impending crashes, drifting off lanes or roadway edges, etc.).

System-based Position Determination

Server-side or system-based positioning is a mode of positioning where all the computations are acrried out at the control center or system server. This could be implemented for a small number of users, or a cluster of user receivers, as in the case of deformation monitoring of a structure such as a bridge, or dam, or tall building. The user receivers are relatively "unintelligent", simply making CPH and PR measurements, and sending them to a centralized 'computation engine'. Such receivers may be even lower cost, and lower powered, than the dual-frequency (L1-L5) receivers referred to earlier.

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[6] '(3)' and '(4)' would be sufficient for simple navigation and other purposes, but perhaps not always for the more critical ITS applications.

[7] Over a dedicated wireless system just for these purposes. But there would also be use of commercial wireless (cellular, PSC, broadband, other) as backup and in times and places where the dedicated systems are not in operation.

Issues to be Addressed

The rollout of Positioning Infrastructure in the form of CORS and associated information and communications technologies is proceeding at a fast rate in many countries around the world. The development "drivers" vary from place to place, a variety of business and organizational models are being trialled, standards and quality procedures are being established, and technical issues are being addressed. In most cases the CORS are being developed in order to give expression to a nation's geospatial/geodetic reference frame, to provide easy access to this datum, to monitor the stability of the datum (and the earth's surface in general in zones of tectonic activity), to contribute to geoscientific research, and to support vital economic sectors such as agriculture and (open-cut) mining. Hence the agencies responsible tend to be government geodetic or mapping departments. Increasingly the private sector is also establishing CORS networks to support fee-paying users with RTK/N-RTK services. However, advanced ITS is a new class of high accuracy PNT user applications that has its own challenges:

- The CORS infrastructure and services (as indicated above) are currently being rolled out to support "traditional" surveying, mapping and precise navigation users. Advanced ITS is not seen as an "early user" application.
- Advanced ITS applications would require true nationwide RTK/N-RTK coverage, and not just in areas of agricultural activity. Several spatial deployment strategies are possible, including densification of Tier 3 CORS at intervals of 50-100km, within a sparser Tier 1 or 2 CORS backbone network. The former would be much less costly to establish and operate than the latter – perhaps by an order of magnitude.
- Coverage would also be expected in urban areas, however GPS/GNSS on its own may provide insufficient availability, accuracy or reliability. Multi-sensor systems may therefore be required.
- It is crucial that the stability of the CORS antennas be monitored on a continuous basis. The organizational model used to operate and monitor the CORS would define the responsibilities of different stakeholders, as well as the quality of service to be provided. There may be different levels or users, with the most demanding paying a premium for their RTK/N-RTK service over users with less stringent requirements.
- How the raw data from CORS are transformed into value-added services such as RTK/N-RTK needs some attention. Will there be different "service providers" for different user segments? What will be the role of governments? What will be the role of the private sector. (See Figure 8.)
- The cost of user equipment must be substantially less than current RTK-capable dual-frequency instrumentation – perhaps by one or two orders of magnitude cheaper than current systems.
- Industry standards are crucial for "mass market" advanced ITS applications, hence the vital role played by the RTCM.
- Blanket coverage of reliable wireless communications is essential so as to ensure no/few breaks of RTK/N-RTK service.
- In addition to highway users, such a nationwide RTK/N-RTK service could support other transport users (such as the railways), as well as non-positioning applications (such as estimation of precipitable water vapor, to support near-term weather forecasting).

Finally, all infrastructure is vulnerable. Strategies need to be developed to protect vital positioning infrastructure, or to mitigate the impact of denial of service in the event of a national emergency.

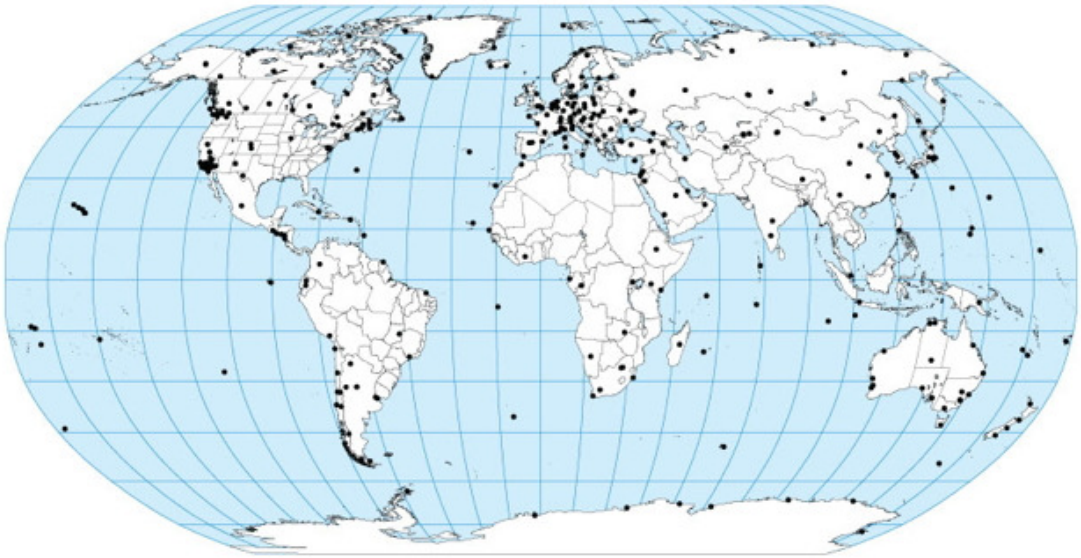


Figure 1 Global distribution of IGS stations (http://igs.org/network/netindex.html)

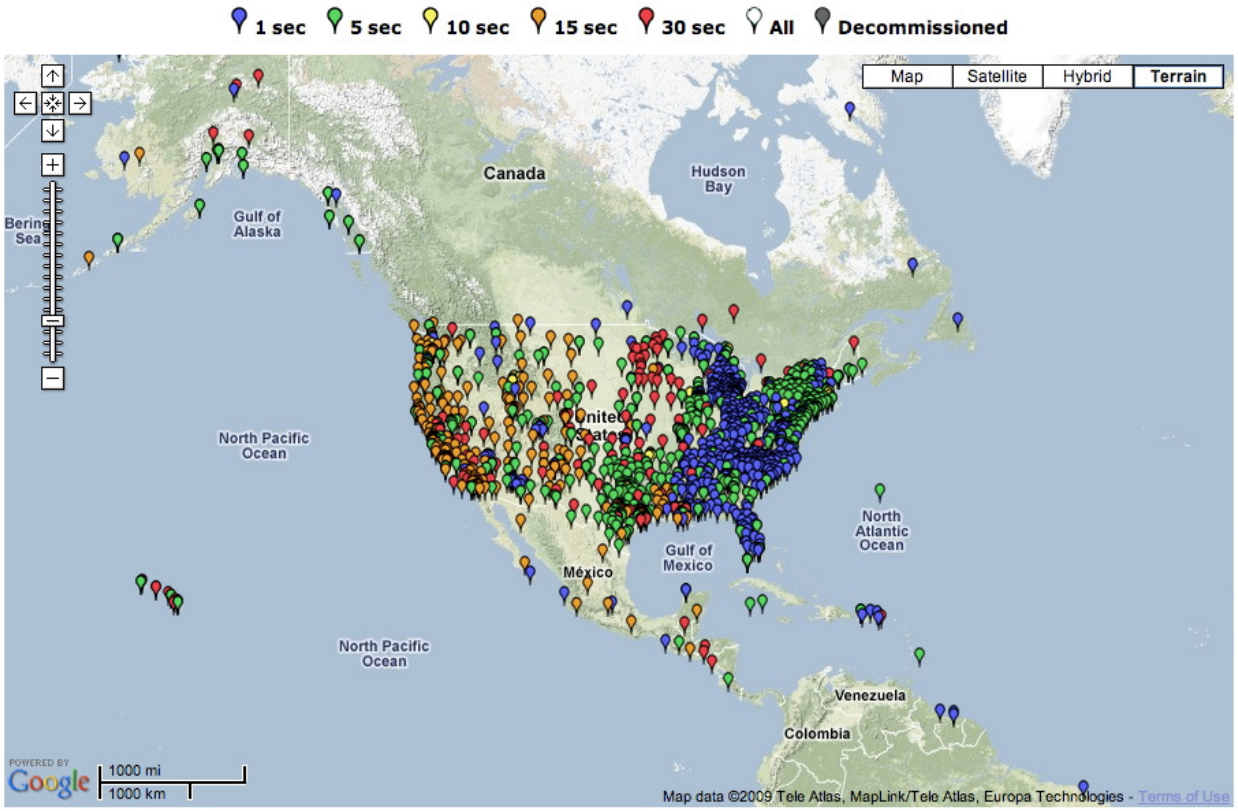


Figure 2 The U.S. NGS reference station network (http://www.ngs.noaa.gov/CORS/)

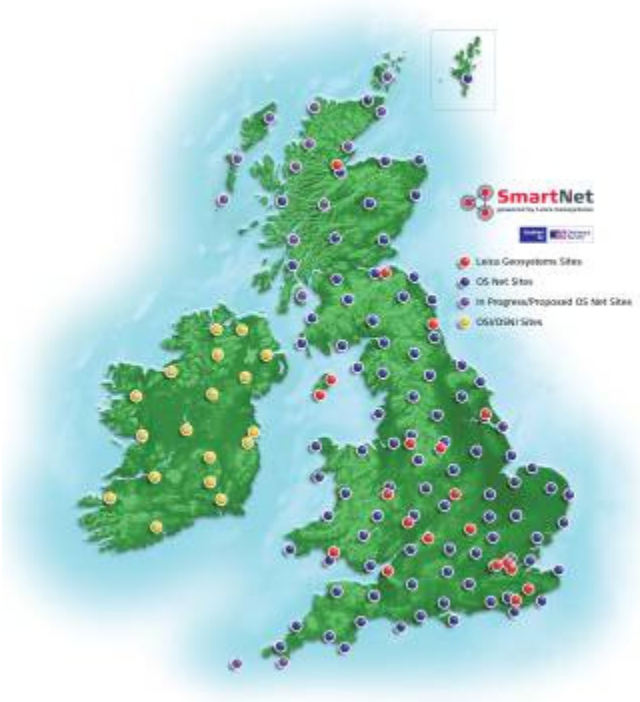


Figure 3 Regional RTK network in Great Britain (http://smartnet.leica-geosystems.co.uk/spiderweb/weblink/information2.htm)

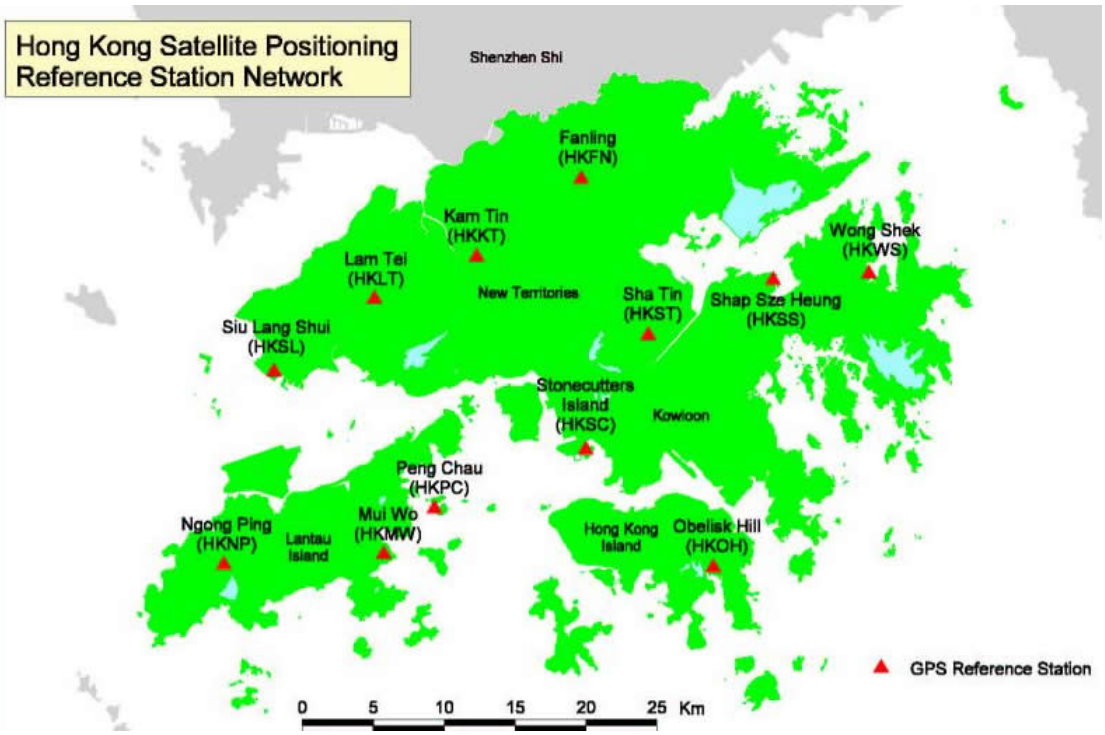


Figure 4 The Hong Kong GNSS permanent station network (http://www.geodetic.gov.hk/smo/gsi/programs/en/satref.htm)

Table 1 Primary GPS Survey Options

Range (km) [1]	**Accuracy (meters)** [2]	**Survey type** [3]	**Occupation time per point**	**Operational mode** [4]	**Vulnerability** [5]	**Infrastructure** [6]
> 100	0.5 – 2	WADGPS (RTCM)	Instantaneous	RT, PR	***	SP
> 100	0.1 – 0.5	STATIC (DF)	< 30 mins	PP, CPH+	**	CORS
> 100	< 0.02	STATIC (DF) (geodesy)	Several hours	PP, CPH	*	CORS
< 100	0.5 – 5	DGPS (RTCM)	Instantaneous	RT, PR	***	SP
< 100	< 1	DGPS (DD)	Instantaneous	PP, PR	****	CORS
< 100	< 0.2	STATIC (DF)	> 30 mins	PP, CPH	**	User
< 50-70	< 0.02 – 0.2	NETWORK-RTK	Instantaneous[7]	RT, CPH	*****	SP
< 50	< 0.1	STATIC (DF)	< 30 mins	PP, CPH	**	User
< 50	0.2 – 0.5	STATIC (SF)	> 30 mins	PP, CPH	***	User
< 20	< 0.02 – 0.2	RTK	Instantaneous[7]	RT, CPH	*****	SP or User
< 20	< 0.02	RAPID-STATIC	< 30 mins	PP/RT, CPH+	****	CORS or User
< 10	< 0.02	RTK	Instantaneous[7]	RT, CPH+	****	User

Notes:
[1] Indicates distance from nearest GPS reference station (limits are approximate only)
[2] 95% confidence interval, relative precision or accuracy within the geodetic or reference station network
[3] DF – dual-frequency instrumentation; SF – single-frequency instrumentation; RTCM – differential PR corrections; DD – double-differenced data; RTK – real-time kinematic; geodesy – scientific SW, precise orbits, network processing
[4] RT – real-time with data link; PP – post-processed; PR – pseudorange; CPH – carrier phase; CPH+ – CPH plus PR
[5] Susceptibility of technique to degradation due to poor sky visibility (* little or no problem - ***** very vulnerable)
[6] Includes ambiguity initialization (and re-initialization) time using OTF ambiguity resolution algorithm (at best a few seconds)
[7] SP – service provider; CORS – continuously operating reference station; User – assumes user operates own reference station

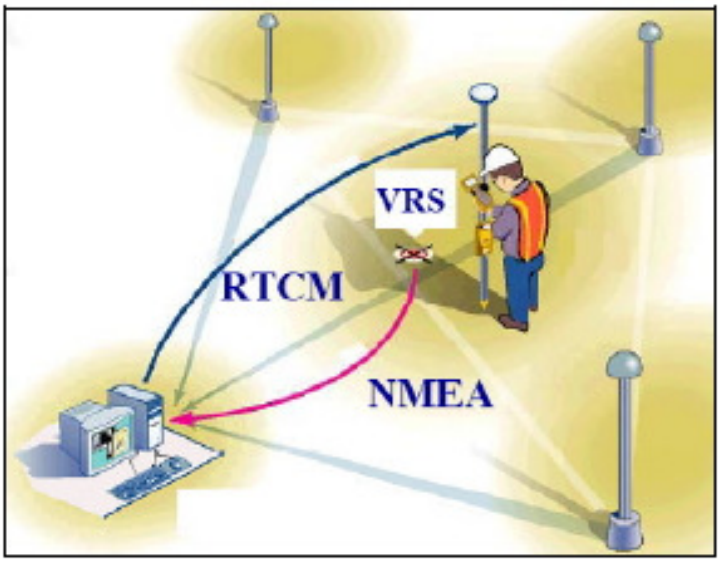


Figure 5 The rover transmits a NMEA message for the VRS position to the network server, which then transmits a RTCM correction stream for this VRS position to the rover

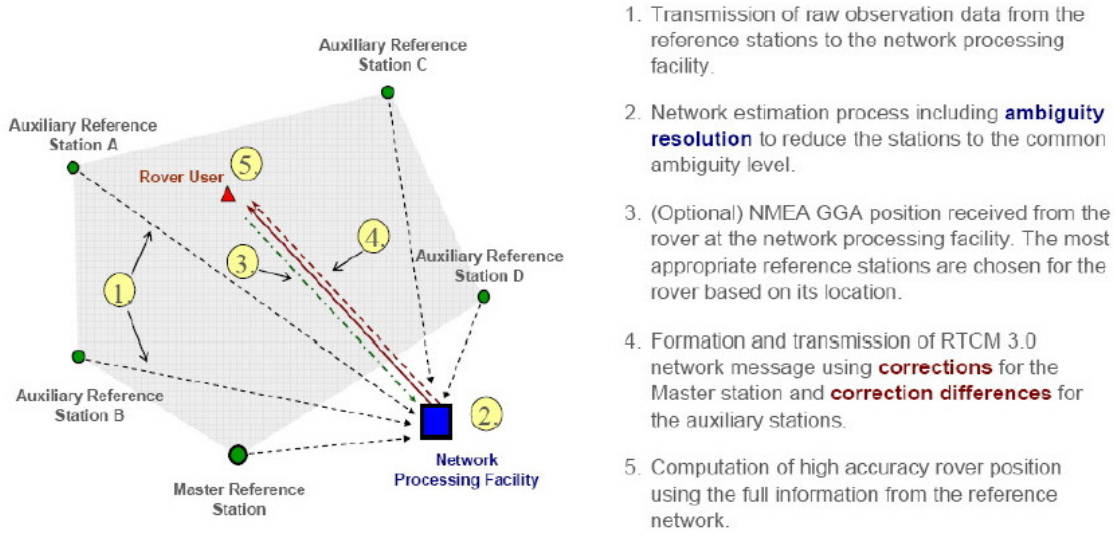
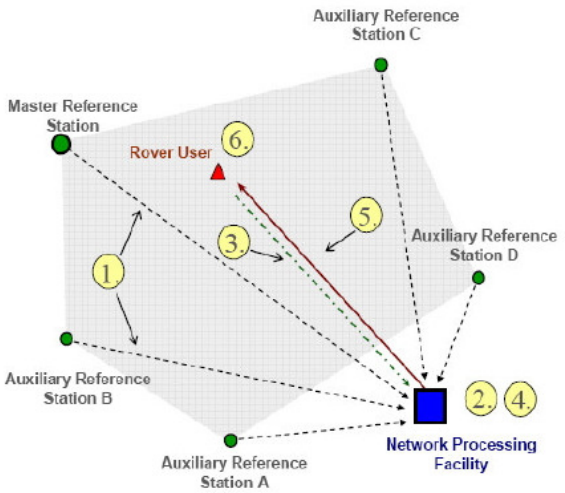


Figure 6 Generation of master-auxiliary corrections (MAX) for a rover



1. Transmission of raw observation data from the reference stations to the network processing facility.
2. Network estimation process including **ambiguity resolution** to reduce the stations to the common ambiguity level.
3. NMEA GGA position received from the rover at the network processing facility. The most appropriate reference stations are chosen for the rover based on its location. The master station is chosen as the reference station closest to the rover.
4. Leica GPS Spider calculates the **network corrections** for the rover and applies them to the observations from the master station.
5. Formation and transmission of RTCM 2.3 or Leica format corrections from the master station.
6. Computation of high accuracy rover position using the reference network.

Figure 7 Generation of individualized master-auxiliary corrections (i-MAX) for a rover

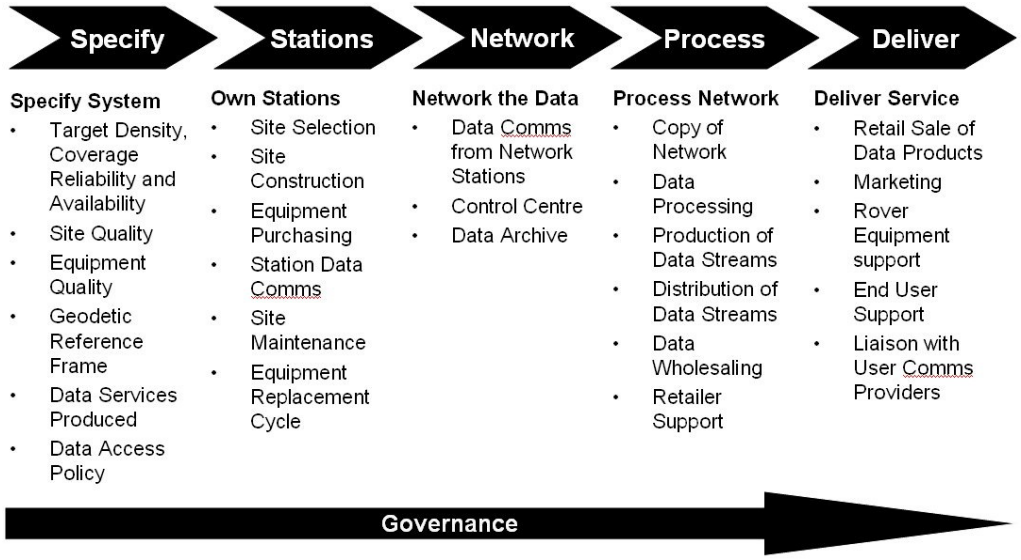


Figure 8 A model for organisational roles within a National Positioning Infrastructure (Higgins, 2008)