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Contribution of GNSS CORS Infrastructure to the Mission of Modern Geodesy and Status of GNSS CORS in Thailand

Chris Rizos[1] and Chalermchon Satirapod[2*]

[1] School of Surveying and Spatial Information Systems,
The University of New South Wales Sydney NSW 2052, Australia
[2] Department of Survey Engineering, Faculty of Engineering,
Chulalongkorn University, Bangkok 10330, Thailand
Email: c.rizos@unsw.edu.au[1] and chalermchon.s@chula.ac.th[2]*

ABSTRACT

Geodesy is the science of measuring and mapping the geometry, orientation and gravity field of the Earth including the associated variations with time. Geodesy has also provided the foundation for high accuracy surveying and mapping. Modern Geodesy involves a range of space and terrestrial technologies that contribute to our knowledge of the solid earth, atmosphere and oceans. These technologies include: Global Positioning System/Global Navigation Satellite Systems (GPS/GNSS), Satellite Laser Ranging (SLR), Very Long Baseline Interferometry (VLBI), Satellite Altimetry, Gravity Mapping Missions such as GRACE, CHAMP and GOCE, satelliteborne Differential Interferometric Synthetic Aperture Radar (DInSAR), Absolute and Relative Gravimetry, and Precise Terrestrial Surveying (Levelling and Traversing). A variety of services have been established in recent years to ensure high accuracy and reliable geodetic products to support geoscientific research. The reference frame defined by Modern Geodesy is now the basis for most national and regional datums. Furthermore, the GPS/GNSS technology is a crucial geopositioning tool for both Geodesy and Surveying. There is therefore a blurring of the distinction between geodetic and surveying GPS/GNSS techniques, and increasingly the ground infrastructure of *continuously operating reference stations* (CORS) receivers attempts to address the needs of both geodesists and other positioning professionals. Yet Geodesy is also striving to increase the level of accuracy by a factor of ten over the next decade in order to address the demands of “global change” studies. The Global Geodetic Observing System (GGOS) is an important component of the International Association of Geodesy. GGOS aims to integrate all geodetic observations in order to generate a consistent high quality set of geodetic parameters for monitoring the phenomena and processes within the “System Earth”. Integration implies the inclusion of all relevant information for parameter estimation, implying the combination of geometric and gravimetric data, and the common estimation of all the necessary parameters representing the solid Earth, the hydrosphere (including oceans, ice-caps, continental water), and the atmosphere. This paper will describe the background to the establishment of GGOS, discuss the important role to be played by GPS/GNSS infrastructure in realising the GGOS mission and provide an update status of GNSS CORS in Thailand.

KEYWORDS

GNSS, CORS, geodesy

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I. The Mission of Geodesy

According to Helmert's classical definition, geodesy is the "*science of the measurement and mapping of the Earth's surface*" by direct measurements, such as terrestrial triangulation, levelling, and gravimetric observations, and, in the past 50 years, also with space techniques, based primarily on the tracking of a wide range of artificial Earth satellites. Following [1], the primary *mission* of Geodesy can be defined as:

- Establishment of geodetic reference frame and determination of precise global, regional and local 3D positions,
- Determination of the Earth's gravity field and its related models, such as geoid,
- Measurement and modelling of geodynamical phenomena, such as crustal deformation, polar motion, Earth rotation, tides, etc.

Since the launch of the first artificial satellite, SPUTNIK, in 1957, geodesy has evolved into a combination of a number of geosciences and engineering sciences. Several important research discoveries gave rise to the development of satellite geodesy. For example, by analysing SPUTNIK's radio-signals it was discovered that the observed Doppler shift could be converted to useful navigation information if the satellite's location in space were known. An increasingly important contribution of satellite geodesy is satellite-based navigation, facilitated through radio-navigation signals transmitted by Earth orbiting satellites as in the *Global Positioning System* (GPS). GPS is now not only an indispensable tool for space geodesy, but it has also revolutionised surveying and navigation, and is increasingly used for personal positioning. Nowadays the phrase "*Global Navigation Satellite Systems*" (GNSS) is used as an umbrella term for all current and future global radio-navigation systems. Although GPS is currently the only fully operational GNSS, the Russian Federation's GLONASS is being replenished and will be fully operational by the end of 2010, the European Union's GALILEO is planned to be deployed and operational by 2013 (though it may take up to 5 more years according to recent reports), and China's COMPASS is likely to also join the "GNSS Club" by 2020 (after first deploying a regional navigation satellite system by 2012).

The *International Association of Geodesy* (IAG – http://www.iag-aig.org) has established *services* for all the major satellite geodesy techniques: *International GNSS Service* (IGS – http://igs.org), *International Laser Ranging Service* (ILRS – http://ilrs.gsfc.nasa.gov), and the *International DORIS Service* (IDS – http://ids.cls.fr), as well as for the *International Very Long Baseline Interferometry Service* (IVS – http://ivscc.gsfc.nasa.gov/). These services generate products for users, including precise orbits, ground station coordinates, Earth rotation values, and atmospheric parameters. All have networks of ground tracking stations that also are part of the physical realisation of the *International Terrestrial Reference System*.

For satellites to serve as space-based reference points, their trajectories (or orbits) must be known. The precise computation of orbits is accomplished by geodetic techniques combined with orbital mechanics. Precision Orbit Determination (POD) also requires the use of accurate geodetic models for gravity, tides and geodetic reference frames. At the same time, POD's sensitivity to various types of geodetic information makes it a powerful tool in the *refinement* of geodetic models. Consequently, a satellite can be considered as a probe or sensor, moving in the Earth's gravity field, along an orbit disturbed by the gravitational attraction. Thus, measurements of directions, ranges, and range-rates between terrestrial tracking stations (and sometimes also from other orbiting satellites) and the satellite "targets" provide, in addition to navigation parameters, a wealth of information about the size and the shape of the Earth and its gravity field. The first example of gravitational mapping by the use of satellites was the 1958 determination of Earth flattening from measurements to the EXPLORER-1 and SPUTNIK-2 satellites, followed by the discovery of the "pear-shape" of the Earth in 1959. The latest generation of gravity mapping missions, CHAMP, GRACE and GOCE, now are determining the features of the gravity field down to 100km or so in size, on a monthly basis, monitoring changes in the gravity field with time due to mass transports such as due to the Water Cycle. This is an exciting time for gravimetric geodesy with the recent establishment of the International Gravity Field Service (IGFS – http://www.igfs.net) and the release of the most detailed and precise model, EGM2008, of the Earth's gravity field ever.

Aside from their navigation and precise positioning function, geodetic satellites serve as *remote sensing* tools. An example is satellite radar altimetry, a remote sensing technology that can measure the ocean surface topography (TOPEX/Poseidon, Jason-1, etc) or ice topography (e.g., ICESat, CRYOSAT). Variations in ocean surface topography indicate gravitational variations due to undersea features, such as seamounts or trenches, as well as ocean circulation features from small eddies to basin-wide gyres. The altimeters can also be used to measure parameters such as wave height, wave direction, and wave spectra. Other geodetic remote sensing tools include differential interferometric synthetic aperture radar (DInSAR) satellites such as TerraSAR-X, ALOS, Radarsat-2, and others. These can detect changes in the shape of the topography as small as a centimetre with spatial scales of just a few metres.

Modern Geodesy is now equipped with an array of space technologies for mapping (and monitoring changes) the geometry of the surface of the solid Earth and the oceans, as well as its gravity field. However the fundamental role of geodesy continues to include the definition of the terrestrial and celestial reference systems. These reference systems are the bedrock for all operational geodetic applications for national mapping, navigation, spatial data acquisition and management, as well as the scientific activities associated with geodynamics and solid Earth physics, mass transport in the atmosphere and oceans, and global change studies.

The *International Celestial Reference System* (ICRS) forms the basis for describing celestial coordinates, and the *International Terrestrial Reference System* (ITRS) is the foundation for the definition of terrestrial coordinates. The definitions of these systems include the orientation and origin of their axes, the scale, physical constants and models used in their realisation, such as, for example, the size, shape and orientation of the reference ellipsoid that approximates the Earth's surface and the Earth's gravitational model. The coordinate transformation between these two systems is described by a sequence of rotations that account for precession, nutation, Greenwich Apparent Sidereal Time (GAST), and polar motion, which collectively account for variations in the orientation of the Earth's rotation axis and its rotational speed. GAST and polar motion are monitored by geodetic techniques, while precession and nutation are described by respective models [2].

While a reference system is a mathematical abstraction, its practical realisation through geodetic observations is known as a *reference frame* (or *datum*). The conventional realisation of the ITRS is the *International Terrestrial Reference Frame* (ITRF), which is a set of coordinates and linear velocities (due mainly to crustal deformation and tectonic plate motion) of well-defined fundamental stations (e.g. networks of stations of the IGS, ILRS, IDS, IVS), derived from space-geodetic observations collected at these points. The ICRS is realised through the *International Celestial Reference Frame* (ICRF), which is a set of estimated position coordinates of extragalactic reference radio sources. At present, the ICRF is determined by Very Long Baseline Interferometry (VLBI), while the ITRF is accomplished by a combination of several independent space-based geodetic techniques, including VLBI, Satellite Laser Ranging (SLR), GNSS, and Doppler Orbitography by Radiopositioning Integrated on Satellites (DORIS). The ITRF and ICRF are defined by the International Earth rotation and Reference Systems Service (IERS – http://www.iers.org/).

Geodesy is facing an increasing demand from science, engineering, the Earth observation community, and society at large for improved accuracy, reliability and access to geodetic services, observations and products. Thus, a challenge that geodesy is now facing is to maintain the ITRF at the level that allows, for example, the determination of global sea level change at the sub-millimetre per year level, determination of the glacio-isostatic adjustments due to deglaciation since the Last Glacial Maximum and to modern mass change of the ice sheets, at the mm-level accuracy, pre- co- and post-seismic displacement fields associated with large earthquakes at the sub-centimetre accuracy level, early warnings for tsunamis, landslides, earthquakes, and volcanic eruptions, mm- to cm-level deformation and structural monitoring, etc. In response, the IAG established in 2007 the *Global Geodetic Observing System* (GGOS), which will unify all the geometric and gravity services of the IAG, in order to address the demands for improved geodetic products by society and the scientific community [3] - [5]. *GNSS will play a vital role in GGOS*.

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II. GNSS Today

The only fully operational satellite-based Positioning, Navigation and Timing (PNT) system is the Global Positioning System. 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. Over the last two decades GPS has revolutionised 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 astonishing PNT accuracy that can be achieved with the current GPS generation of user equipment and ground infrastructure. However, the highest performing GNSS systems are the *combined GPS+GLONASS receivers* and corresponding ground infrastructure. These are top-of-the-line GNSS receivers for Geodesy and Surveying.

2.1 The Current GPS

The current (as of October 2010) GPS constellation consists of 31 active satellites. For a detailed description of the current GPS refer to the U.S. Coast Guard's Navigation Center (http://www.navcen.uscg.gov). While it is beyond the scope of this paper to provide detailed review material on GPS, the following is presented as summary information:

- GPS satellites broadcast two signals in the L1 and L2 frequency bands: L1 at 1575.42MHz and L2 at 1227.60MHz.
- As GPS signals are of the type known as CDMA (Code Division Multiple Access), each satellite is distinguished from the other by the PRN ranging "code" that is modulated on the L1 and L2 "carrier waves".
- There are several families of GPS ranging codes. The simplest set of codes (known as the *Coarse Acquisition* or C/A codes) are modulated on the L1 frequency only, with a different PRN Code for each satellite. There are only 32 PRN codes that can be used for the current GPS constellation.
- Simultaneous measurements of pseudo-range (PR) or carrier phase (CPH) made on two frequencies permit the ionospheric measurement bias or delay to be determined (and subsequently removed), hence improving positioning accuracy. Another benefit of dual-frequency measurements is that they permit rapid and reliable determination of the unknown integer carrier phase ambiguity in the CPH measurements, effectively converting ambiguous CPH to unambiguous range-like *carrier* or *phase range* – not unlike PR observations but with a thousand times less measurement noise.
- *Single Point Positioning* (SPP) is the operational mode for which GPS was originally designed, using onboard algorithms that currently deliver horizontal *absolute* accuracy performance better than 5m RMS 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).
- Civilians using low-cost receivers currently only have direct access to the L1 signal, using the C/A codes of the SPS.
- The top-of-the-line surveying and geodesy receivers make PR and CPH measurements on both the L1 and L2 frequencies.
- Military receivers can access the ranging code (the Precise or *P code*, since 31 January 1994 encrypted as the Y-code under the policy of *Anti-Spoofing*) on both the L1 and L2 frequencies, which enable them to correct for ionospheric errors and achieve higher accuracy and reliability of PNT results.
- Apart from the restrictions imposed by anti-spoofing, on the tracking of the L2 signal (the Y-code), civilians can freely use GPS without having to pay user charges.
- GPS nominally comprises only a 24 satellite constellation, hence the extra satellites are "doubling-up" on old satellites which may fail with little or no warning.
- The GPS Block IIR-M satellite PRN17 was launched on 26 September 2005, and is the first of the new generations of GPS satellites that broadcast new civilian signals under the programme of *GPS modernization*.

High accuracy CPH-based GPS positioning techniques have evolved since the early 1980s, from the first static geodetic control surveys to today's high efficiency "real-time kinematic" (RTK) GPS Surveying techniques. All high accuracy *GNSS* techniques share a common requirement – application of the *differential* or *relative* positioning principle that requires one or more base station or reference receivers operating at locations with coordinates known in the user's reference frame or datum.

2.2 The Current GLONASS

The abbreviation GLONASS is derived from the Russian "Global'naya Navigatsion-naya Sputnikovaya Sistema". The first four operational GLONASS satellites were launched by the then Soviet Union in January 1984. The design of Russia's GLONASS is similar to GPS except that each satellite broadcasts its own particular frequency, all modulated with the same PRN code. This is known as an FDMA – Frequency Division Multiple Access – scheme. Conversely, GPS satellites broadcast the same frequencies and a receiver differentiates between satellites by recognising the unique code(s) broadcast by a given satellite. For a detailed description of GLONASS see [6]. Current status information is available from the Roscosmos Information Analytical Center web site (http://www.glonass-ianc.rsa.ru/). As in the case of GPS, the satellite constellation and Ground Segment will remain under the control of the country's military authorities, and there are no plans to introduce user charges.

Although the frequencies of GPS and GLONASS are different, a single antenna can track the transmitted signals. The data modelling challenges for integrated GPS+GLONASS processing have already been addressed, and top-of-the-line geodetic/surveying receivers capable of making GPS and GLONASS measurements have been available for many years. These combined receivers have demonstrated a marked improvement in reliability and availability in areas where satellite signals can be obstructed, such as in urban areas, steep terrain, or in open-cut mines. All major manufacturers of survey-grade GNSS receivers now supply integrated GPS+GLONASS receivers.

Following the dissolution of the Soviet Union, the Russian Federation had initially struggled to find sufficient funds to maintain GLONASS. At the time of writing (October 2010) there were 21 satellites functioning (as opposed to the 24 satellites necessary for full operational capability – FOC – the total reached in the mid-1990s shortly after GPS's FOC was achieved). However, the Russian Federation has commenced a programme to *revitalise* GLONASS, with a planned 24 satellite FOC by the end of 2010.

III. The Current Ground Infrastructure

It is generally recognised today that a reference network comprised of permanent, *continuously operating reference stations* (CORS) equipped with GNSS (i.e., GPS+GLONASS) receivers provides 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 GNSS-RTK technique means that such reference station receivers may also have to support ever expanding non-geodetic, *real-time* applications of high accuracy positioning for engineering, machine guidance, precision agriculture, etc. 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. The following has mostly been adapted from [7].

3.1 CORS Networks for Geodesy and Surveying

GPS in the 1980s was almost exclusively used for geodetic control surveys, and the inter-receiver distances were at first several tens of kilometres, being the average distance between first order geodetic control groundmarks. However, at about this time GPS was also proving itself to be an effective tool of *space geodesy* for the purpose of measuring crustal motion and for establishing the global reference frame. Hence progressively the distances between GPS receivers increased to hundreds and then thousands of kilometres, while simultaneously the relative accuracies increased, ensuring cm-level relative accuracy within GPS receiver networks even as inter-receiver distances grew significantly. GPS is now the premier tool for modern geodesy,

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and relative accuracies at the few parts per billion (*ppb*) level are routinely achieved. These GPS geodetic stations inevitably became permanent reference stations for: (a) the monitoring of the station motion itself (due to crustal motion), (b) realising or defining modern geocentric geodetic datums at the national level, and (c) the extension and increasing density of the geodetic control (groundmark) networks using GPS techniques.

It is important to recognise the significant contribution of the "super-network" of reference stations of the IGS to geodesy, and to the GNSS community in general. Several hundred globally distributed GPS receivers (many increasingly with GLONASS tracking capability) operate on a continuous basis, many for over ten years, contributing data to the IGS analysis centres and other users (Figure 1). The satellite (CPH and PR) tracking data they have collected have been used in progressive *realisations* of the *ITRF*– the most recent being ITRF2008 (http://itrf.ensg.ign.fr/ITRF_solutions/2008/ITRF2008.php).

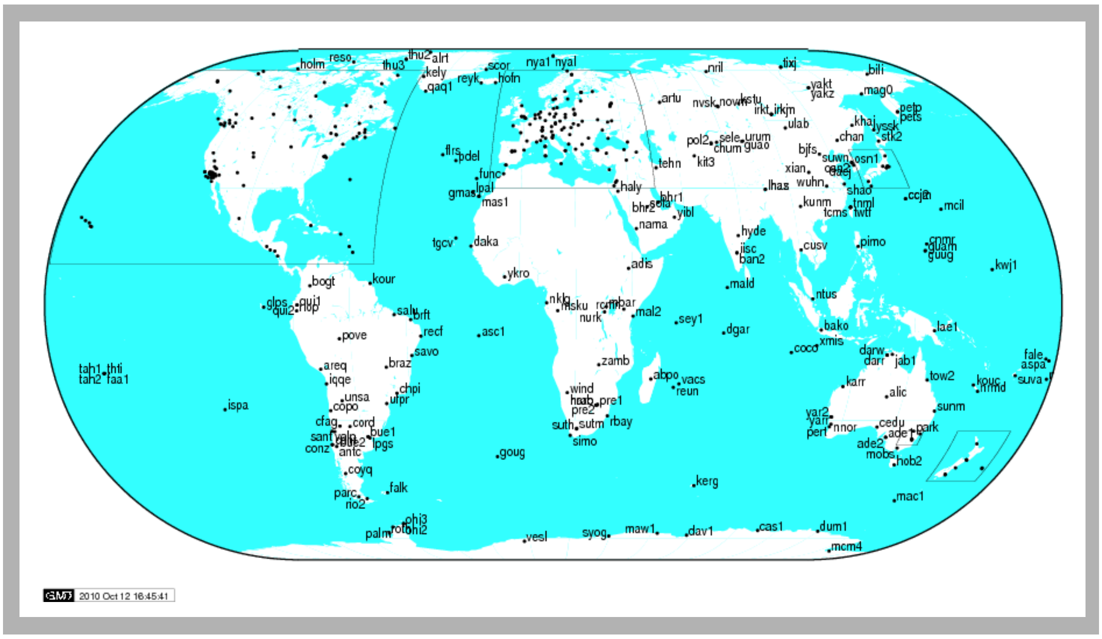

Figure 1
IGS Tracking Network (http://igs.org/network/netindex.html)

Many countries have redefined their national datums to be compatible with an ITRF datum, 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. 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.

Even countries that do not experience a level of 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 kilometres, 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 ASCII files in the Receiver Independent Exchange (RINEX) format, and sent to an archive or data centre. From there the data were available to users for post-processing.

Archived RINEX files from both IGS stations and national GNSS CORS networks are now accessed by users via the Internet. All IGS data have been, and continue to be, available free-of-charge. Although some GPS receiver network operators charge fees for their RINEX files, the trend is to increasingly make such data available for free. 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 or equivalent, (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.
Over time, the concept 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, Department of Survey & Mapping Malaysia, and similar organisations in many other countries). 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 GNSS surveys with greater efficiency may be the *sole* justification.

3.2 Commercialising GNSS-RTK Networks & Services

With the advent of GNSS-RTK techniques in the early 1990s, CPH-based GPS/GNSS 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 [8]. *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. This requires rapid ambiguity resolution, or at the very least the use of techniques such as “stop-and-go” that did not need frequent ambiguity resolution.

However, to ensure high productivity GNSS-RTK (reliable cm-level accuracy with rapid ambiguity resolution) there remain a number of constraints, including: (a) that all GNSS receivers (reference and rover) must have dual-frequency tracking capability, and (b) the inter-receiver distance should be less than ten or so kilometres. 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 [9]. 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”.

As a result of the “geodetic legacy” referred to earlier, the majority of CORS GNSS networks have been, and will continue to be for some time to come, initiatives primarily from (national and state) government agencies. A large number of IGS stations are expected to be upgraded in the coming years so as to provide real-time data streams (http://www.rtigs.net). This data (and IGS real-time products) will be available for free, broadcast over the Internet, to any user. On the other hand, at present more than 200 real-time CORS networks are estimated to exist [10], and perhaps increasing in number by about 10% per annum. Hence there will be an increasingly confusing “marketplace” for CORS data products. [7] identified the following models for the establishment of CORS networks, and services derived from them:

(1) Institutional CORS infrastructure, no commercial services.
(2) Government CORS infrastructure, operates commercial services.
(3) Government CORS infrastructure, licenses data to private sector.
(4) Cooperative privately-owned CORS infrastructure, operating commercial services.
(5) Privately-owned CORS infrastructure, operating commercial services

Which of these models – or combinations/variations of the above – will prevail will vary from country to country, and will be an increasingly important question in the context of *next generation CORS infrastructure*. Figure 2 shows the location of Ordnance Survey’s (http://www.ordnancesurvey.co.uk/) “OSNet” CORS network in the U.K., which licenses the raw GNSS data to two companies (model 3 above): Leica (which retails the RTK service to users via its “SmartNet” – http://smartnet.leica-geosystems.co.uk/SpiderWeb/frmIndex.aspx) and Trimble (which retails the RTK service to users via its “VRS Now” – http://www.trimble.com/vrsnow.shtml). In many countries, the official government survey, geodesy or mapping agency operates GNSS-RTK services on a commercial basis, as in model 2 above. One example is "MyRTKnet" (Malaysian Real-Time Kinematic Network – http://www.geodesi.jupem.gov.my/MyRTKnet/index.htm), comprising approximately 72 CORS across Peninsular and East Malaysia (Figure 3).

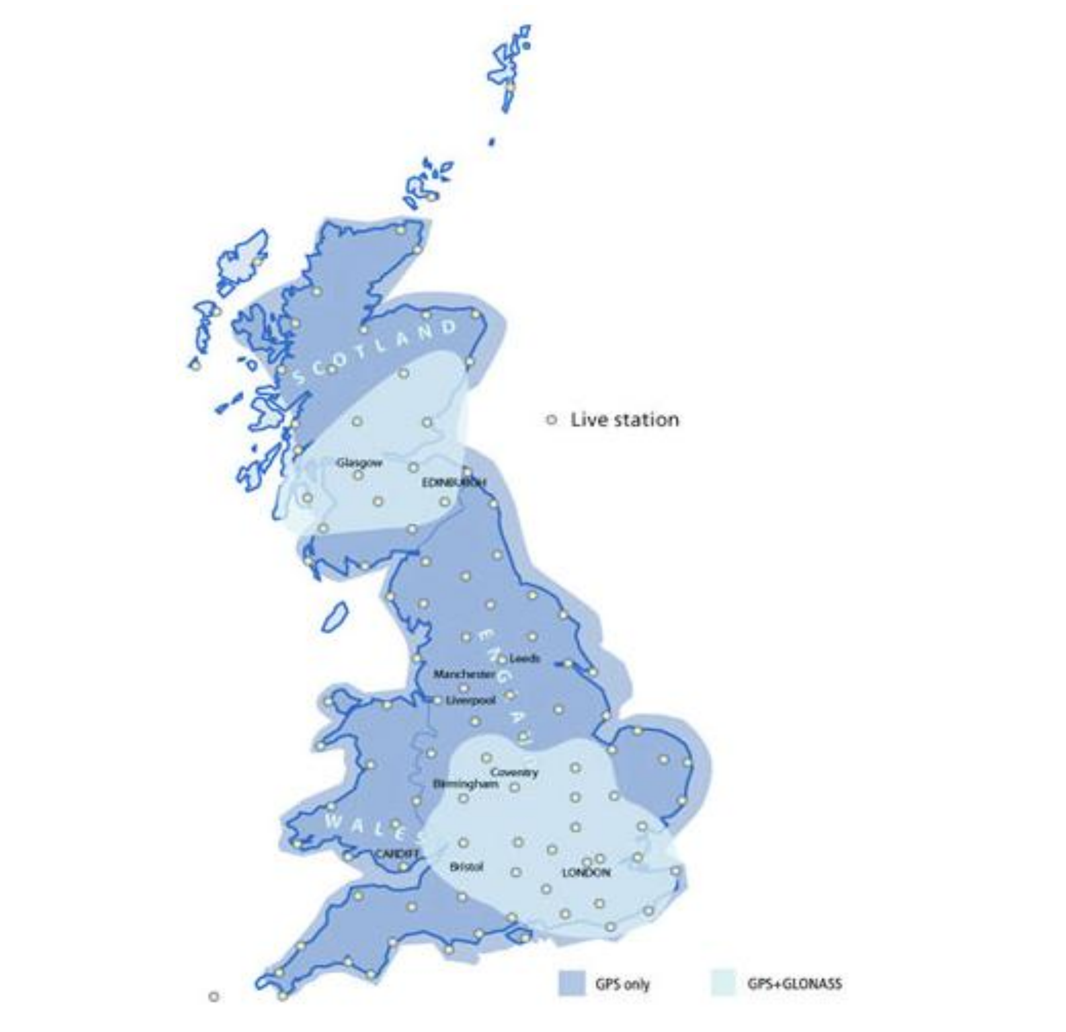

Figure 2
Ordnance Survey's OSNet CORS

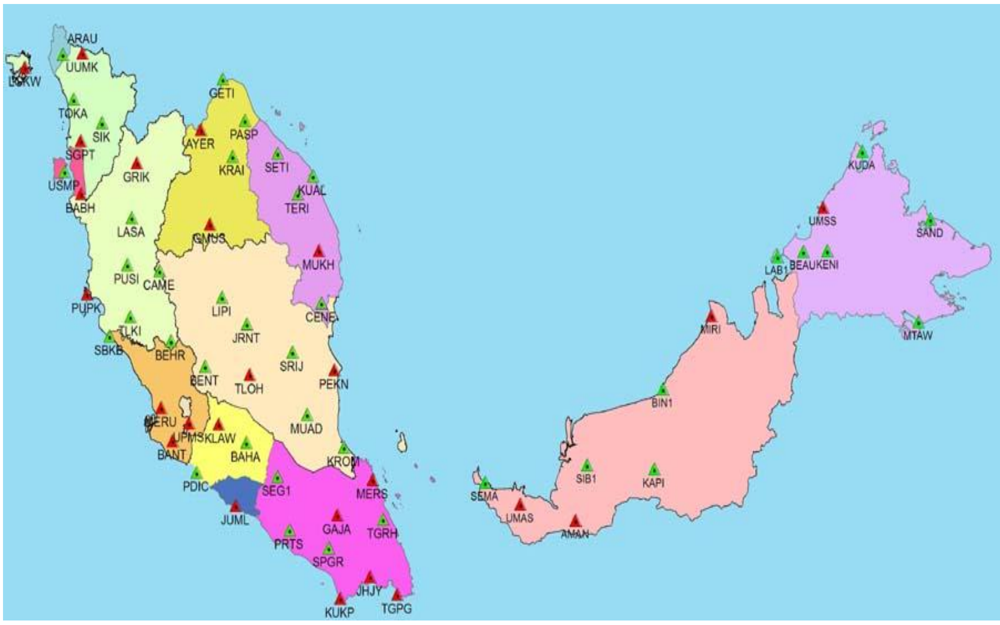

Figure 3
Department of Survey & Mapping Malaysia's MyRTKnet CORS

IV. Next generation GNSS Capability

Next generation GNSS will consist of the current and planned U.S., European, Russian and Chinese GNSSs, plus the several announced Regional Navigation Satellite Systems (RNSSs), and the Space Based Augmentation Systems (SBASs) primarily deployed for civil aviation. (RNSSs and SBASs are not discussed in this paper – the reader is referred to [11] for further details.) A "system of systems" receiver will be required to track all, or most, of the broadcast signals. While such an "all-in-view" tracking receiver will undoubtedly assure high accuracy users of good availability of signals and reliable coordinate results, with far less constraints than in the case of the current initial GNSS (GPS + partial GLONASS constellation), there will still be the requirement to invest in "system of systems" CORS networks.

4.1 GPS Modernization

The U.S. has embarked on a programme of *GPS Modernization* to provide better accuracy and more powerful and secure signals from future GPS satellites. It is not possible to describe this programme in detail here, and readers are referred to easily accessible information on websites such as NavCen (http://www.navcen.uscg.gov) and PNT (http://pnt.gov). 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 launch schedule to replace existing satellites is difficult to predict but full operational capability (FOC) for L2C will not be declared until 24 satellites 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 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 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. The first GPS Block IIF satellite was launched in 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 Block 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 in 2021.

The implication for future GPS user equipment is that low-cost receivers may not just be L1-only, as is currently the case, but they may be L2-only or L5-only, or even dual-frequency (likely to be the two interoperable frequencies L1+L5). However, top-of-the-line user equipment for centimetre-level accuracy will probably take advantage of triple-carrier ambiguity resolution (TCAR) based on L1-L2-L5 PR and CPH observations. Nevertheless powerful CPH-based techniques can still be used based on just dual-frequency observations (L1+L2, or more likely L1+L5). *The critical issue is what type of CORS infrastructure will be established to support triple-frequency or dual-frequency users tracking not just GPS signals, but other GNSS as well.*

4.2 Page Numbering / Header and Footer

In the last few years the Russian Federation has commenced a programme to *revitalise* GLONASS:

- Current activity centres on completing the launch of the GLONASS-M satellites with an improved 7-year design life, which broadcast in the L1 and L2 frequency *bands.* We may refer to the 1602-1609MHz GLONASS L1 band as being the “G1” frequency, and the 1246-1251MHz GLONASS L2 band as being the “G2” frequency. (Note, by way of comparison, that GPS frequencies are L1 at 1575.42MHz and L2 at 1227.60MHz.)
- From 2010 it is planned to launch GLONASS-K satellites with improved performance, and which will also transmit a third civil signal known as “G3” in the Aeronautical Radio Navigation Services band near (but not identical) to GPS’s L5 frequency. Current information suggests that the G3 frequency band will be 1198-1208MHz. However, a full constellation broadcasting three sets of civil signals is unlikely before the middle of the decade.
- Recently there has been an announcement that CDMA signals on the L1 and L5 frequencies will be transmitted by GLONASS-K satellites scheduled to be launched from 2010 in order to make these signals interoperable with GPS and GALILEO. In addition, the final GLONASS constellation may consist of more than 24 satellites.

Greater efforts are being made to increase the degree of *interoperability* of GPS and GLONASS (and subsequently GALILEO, as the system comes online), by having frequency overlaps at the L1/G1 and L5/G3 bands, at the very least. For example, the plan to launch future GLONASS satellites with CDMA signals on L1 and L5 goes a long way towards satisfying the goal of interoperability. Interoperability, for the benefit of users, is one of the goals of the U.N.’s Office of Outer Space Affairs *International Committee on GNSS* (http://www.unoosa.org/oosa/en/SAP/gnss/icg.html).

4.3 European Union’s GALILEO

For a detailed description of GALILEO see [6]. For the purposes of this paper the following points are relevant:

- The GALILEO design calls for a constellation of 30 satellites (including 3 in-orbit spares) in a similar medium earth orbit (MEO) configuration to GPS, but at an increased altitude (approximately 3,000km higher than GPS) which will enable better signal availability at high latitudes°.
- GALILEO satellites will broadcast signals compatible with the L1/G1 and L5/G3 GPS and GLONASS frequency bands. Those GALILEO frequencies are designated as “E1” and “E5a/E5b”. GALILEO will also broadcast in a third frequency band at “E6”, which is not at the same frequency as the GPS L2 or GLONASS G2.
- There will be up to ten trackable signals – though not all will be open [12].
- GALILEO proposes to offer *five* levels of service, using different combinations of open and restricted trackable signals (http://ec.europa.eu/comm/dgs/energy_transport/galileo/):
- The design of the GALILEO Open Service signal at the E1 frequency is intended to be (almost) identical to the GPS-III L1C signal, a significant concession to GNSS interoperability.
- With GPS, under the firm control of the U.S. Military and GLONASS under the control of the Russian Military, *augmentation systems* to improve accuracy or reliability are operated completely external to the GPS and GLONASS system architectures. Such services are available from third parties such as FUGRO’s Omnistar and NAVCOM’s Starfire, or maritime DGPS beacons operated by

national maritime safety authorities, or RTK-capable CORS networks. GALILEO, on the other hand, has a much more open architecture whereby sub-systems to improve service can be brought "inside" the system through a provision for *regional elements* and *local elements*. The GALILEO system architecture allows for regional *Up-Link Stations* to facilitate those improved services tailored to local applications in different regions of the world.

- It was originally planned that the majority of GALILEO's capital cost would be borne by a Public Private Partnership (PPP) – with the necessary funds jointly raised by the E.U. and a consortium of private companies (mainly from the aerospace and telecommunications sectors). However, negotiations progressed so slowly that by 2007 effectively the whole GALILEO project had stalled due to the reluctance of the private sector to invest in the satellite and ground infrastructure. Finally in late 2007 it was decided that 100% of the cost of designing, building and deploying the satellite constellation and ground control segment would be borne by the E.U. taxpayers. 3.4B Euros has therefore been budgeted to achieve GALILEO FOC. Recent reports suggest that the full cost will be significantly higher.
- The full constellation was originally planned to be launched in the period 2007-2008, with FOC by 2009. However these dates have slipped and it is now claimed that FOC will be in 2013. But there are indications that this date could slip by up to 5 years.
- GALILEO has moved out of its development phase and into the *In Orbit Validation* (IOV) phase. The two IOV satellites (GIOVE-A & B) are in orbit.

4.4 China's COMPASS

For a number of years China has had its own RNSS, known as BEIDOU. In 2006 China announced it would develop its own GNSS, commonly referred to as COMPASS (though sometimes BEIDOU/COMPASS – here we will distinguish between the original RNSS and the planned GNSS by referring to the latter simply as COMPASS). It appears that COMPASS is modelled on GPS and GLONASS in as far as it will be a dual-use system, fully funded by the government, with an open service (available to all users globally) as well as restricted, military/security signals [13].

The COMPASS constellation will consist of 30 satellites in MEO, plus 5 in geostationary earth orbit (GEO) [12]. The first MEO satellite was launched on 17 April 2007. It appears that the Ground Control Segment would be located only within the Chinese land territory. The U.S. and the E.U. have separately commenced bilateral discussions with China – the former due to possible incompatibility with the GPS M-code, and the latter because of the concern that some of the COMPASS signal frequencies filed with the ITU overlay those of GALILEO's Public Regulated Service. At the time of writing (October 2010) there are five COMPASS satellites in orbit.

4.5 "System of Systems" GNSS Receiver

Which signals will the combined multi-GNSS/RNSS receiver of the future track? At this stage it appears that the only common signals for all GNSS and RNSS will be in the L1 and L5 frequency bands. The increasing popularity of the phrase "GNSS system of systems" may be attributed to Professor Guenter Hein, who has written several excellent articles on this topic (e.g. [12]), and is an acknowledged expert on GALILEO, and GNSS in general. However, how feasible is the design of such a "system of systems" receiver? [14] have made some initial investigations and found that users in Australia, and South East Asia in general, will "see" all planned GNSS and RNSS signals and hence will stand to benefit from the extra satellite transmission more than users in Europe or North America. [14] conclude that: "Such a receiver would require significantly more resources than are required for a simple GPS L1 receiver – for the digital baseband processor, power (200x) and chip area (50x) much greater, and processing effort (50x) is also greater. In addition, antenna and RF front end design are far more sophisticated and likely to be more expensive. Such a receiver is unlikely to be useful for portable applications."

Despite these challenges it is technically possible to build multi-GNSS receivers that track ALL transmitted signals. However, triple-frequency data processing will only be possible on a system-by-system basis (e.g. TCAR GPS-only solutions, sub-optimally combined with TCAR GALILEO-only solutions, sub-optimally combined with TCAR GLONASS-only solutions, and so on), as is currently the case with combined

GPS+GLONASS receivers. It is debatable whether such receivers are true “system of systems” receivers, perhaps being more analogous to tri-band or quad-band mobile phones which can *separately* use the different cellular technologies deployed across the world. Although 100% interoperability across *all* GNSS/RNSS signals will not be possible, there will be enough interoperability on some signals, such as the L1/G1/E1 and L5/G3/E5, to warrant the label “system of systems” receivers for those receivers capable of *tracking* all signals and the *integrated processing* of some of the possible measurements.

Nevertheless, it must be emphasised that future CORS networks must have the appropriate density of “system of systems” reference receivers, otherwise the performance enhancements expected of multi-constellation GNSS will not materialise for high accuracy users. This is of particular importance for users in our hemisphere because they potentially have the most to gain from GNSS “system of systems” developments.

V. Next generation CORS Infrastructure

Next generation GNSS, with many more signals and frequencies, will have important implications for the development of CORS networks. For example, with the benefits of extra satellite visibility, and CPH tracking of three or more different transmitted L-band frequencies, the inter-receiver separations within GNSS CORS networks can be relaxed even further. Permanent CORS networks are increasingly facilitating real-time techniques such as GNSS-RTK, and this trend will become more evident with future CORS capable of multi-GNSS tracking. For instance, “single-base RTK” will be possible over baseline lengths that are over a hundred kilometres with cm-level accuracy, albeit with lowered reliability vis-à-vis “network-RTK” (N-RTK) techniques. Furthermore, if decimetre-level coordinate accuracy is adequate, the CORS separation can be relaxed to several hundreds of kilometres, significantly reducing the necessary ground infrastructure investment that needs to be made. The following conclusions concerning future CORS infrastructure can be drawn:

(1) True GNSS “system of system” CORS receivers will likely be established with relatively long inter-receiver separations, of the order of several hundred kilometres or more.

(2) Less sophisticated multi-GNSS CORS receivers, with dual-frequency tracking capability, will likely be established at a variety of closer spacings, from just several kilometres apart (e.g. to support structural deformation monitoring, and single-base RTK applications), to perhaps up to several tens of kilometres (e.g. to support most DGNSS and N-RTK users).

According to the nomenclature introduced earlier, the former may be referred to as “Tier 1” or “Tier 2” CORS, while the latter would be “Tier 3”. In the context of many countries, such as Australia:

- Tier 1 are the CORS to be used by IGS, or equivalent ultra-high accuracy networks to support geoscientific research and global reference frame definition.
- Tier 2 are the high accuracy CORS networks operated by national geodetic agencies for the purpose of maintaining national geodetic datums and providing the fundamental backbone of the national geospatial reference frame.
- Tier 3 are the CORS that densify the national CORS networks, operated by agencies such as state governments, or private companies providing commercial DGNSS services.

It must be emphasised that the signals from a GNSS “system of systems” will not be transmitted before 2013 at the earliest. Hence current investment in CORS infrastructure will be in GPS+GLONASS capable receivers. However, the upgrade to this infrastructure in the next 5 or so years time will have to incorporate multi-constellation GNSS tracking capability.

The IGS has launched a Real-Time Pilot Project (http://www.rtigs.net), with the following objectives [15]:

- Manage and maintain a global IGS real time (RT) GNSS tracking network.
- Enhance and improve selected IGS products.
- Generate new RT products.
- Investigate standards and formats for RT data collection, data dissemination and delivery of derived products.

- Monitor the integrity of IGS predicted orbits and GNSS status.
- Distribute observations and derived products to RT users
- Encourage cooperation among RT activities, particularly in IGS densification areas.

It is planned that new RT IGS products will be generated on a continuous basis, to augment the current set of post-processed products. This could happen in the next year or two.

In parallel with such an IGS internal development, the IGS is working with its parent organisation, the International Association of Geodesy (IAG), on the design of the *GGOS*. GGOS is the IAG 'flagship' initiative that will, in the coming decade (and beyond), integrate the activities and products of the IAG services and commissions, in order to provide the geodetic component of the Global Earth Observing System of Systems (GEOSS) now being established by the inter-governmental Group on Earth Observations (GEO) [3]. GGOS will provide the following geodetic capabilities: (a) reliable millimetre-level accuracy positioning in GNSS networks several thousands of kilometres across, (b) precise orbit determination of Earth orbiting satellites, (c) time transfer at the sub-nanosecond level of accuracy, (d) remote sensing of the Earth's troposphere and ionosphere, and (e) the estimation of ocean wave parameters from reflected GNSS signals. Such contributions will be vital to *Global Change* studies. The IGS, with its prime concern for high accuracy and high reliability processing of the signals of the GNSS constellations, and as provider of the consolidated inputs of the GNSS contribution to the ITRF, will necessarily play a key role in GGOS.

To satisfy these internal (trend to RT services) and external (establishment of GGOS) strategic objectives, elements of the IGS global tracking network (currently numbering several hundred CORS – Figure 1) will need to be upgraded in the coming years. New GNSS receivers, stable monumentation, and improved communications links will be required – as will improve modelling and data processing methodologies. *Such an upgrade strategy will no doubt also be followed by different countries with respect to their own CORS networks*.

In Australia, the federal government agency Geoscience Australia is coordinating the implementation of the geospatial component of the AuScope programme (http://www.auscope.org.au/home_frame.htm), which includes the establishment of over 100 new GNSS CORS across Australia by 2011-2012 (Figure 4). It has been decided that only GPS+GLONASS receivers will be purchased – though most receiver manufacturers claim their products can be upgraded easily to permit GALILEO tracking. This AuScope GNSS network will be used for a range of operational and geoscientific research tasks; hence it fits the Tier 1 or 2 CORS category – some monumentation will be to Tier 1 standard, some will not (and hence can be considered Tier 2 stations). The AuScope CORS network will satisfy most requirements for access to the fundamental national geodetic reference frame, and in some areas of Australia may be able to support standard high accuracy GNSS positioning applications. State government survey or land agencies are responsible for the surveying infrastructure (groundmarks and CORS). Some Australian states already have state-wide Tier 3 CORS, such as Victoria and NSW. Other states only have patchy CORS network coverage. *However, in future a far greater density of Tier 3 CORS will be required to support high accuracy survey, construction and engineering applications, using dual-frequency (L1+L5) multi-GNSS receivers*.

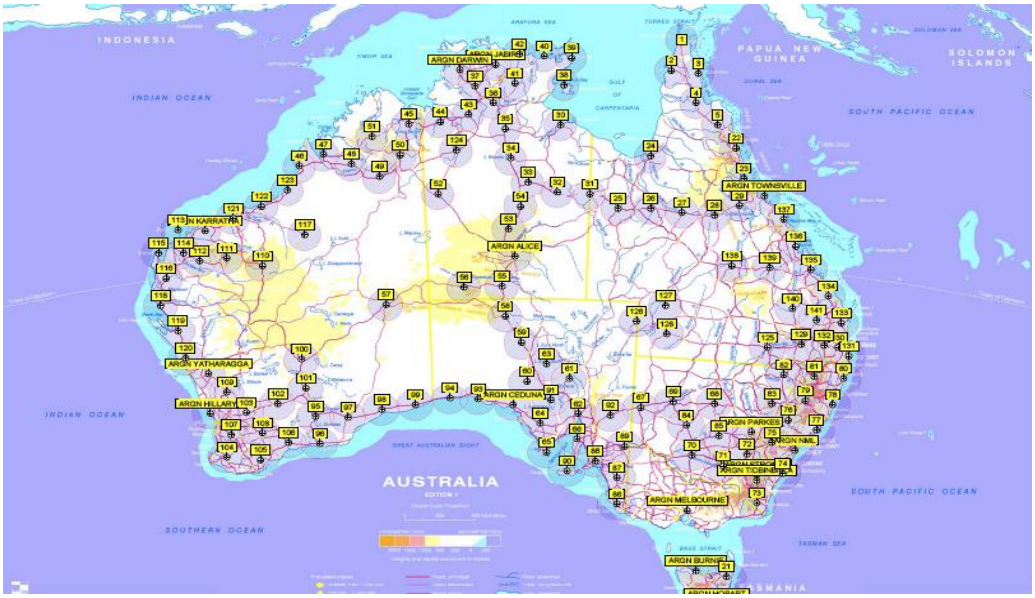

Figure 4
Sites of AuScope CORS

VI. Status of GNSS CORS in Thailand

The first GNSS CORS network in Thailand was set up by the Department of Public Works and Town & Country Planning (DPT) in 1996. The DPT CORS network now consists of 11 stations distributed over the entire country. The DPT CORS network was designed to serve as GNSS reference stations for both real-time and post-processed positioning applications. In 2005, the Royal Thai Survey Department (RTSD) also installed a new GNSS base station, called RTSD and designed for post-processed positioning applications. The Thai Meteorological Department (TMD) has established five CORS receivers as part of a tsunami and earthquake early warning system in Thailand and the installation was completed in late 2007. Subsequently, in early 2008, the Department of Lands (DOL) was the first organisation in Thailand to provide a Real Time Kinematic (N-RTK) GPS service using the Trimble VRS concept. Currently DOL's N-RTK network consists of 11 CORS receivers. With the full support from JPL and UNAVCO, Chulalongkorn University set up a new CORS, known as CUSV, to act as the only IGS station in Thailand and this station has been active since 2008. In addition, the National Institute of Information and Communications Technology (NICT) of Japan has installed four CORS receivers since 2005. Nevertheless, many Thai government agencies have plans to establish many more GNSS base stations in Thailand. Figure 5 shows the location of CORS networks currently operating in Thailand. The authors' observation is that the current distribution of Thai CORS sites is fairly poor, especially in the Greater Bangkok area. Our recommendation is to initiate a higher level of communication and collaboration among Thai agencies for the planning and sharing of planned and existing CORS installations so that duplication of CORS infrastructure can be avoided. *To gain maximum benefit from current and future GNSS technology, perhaps it is time for the Thai GNSS community to increase cooperation and discuss a strategic plan to move Thailand forward!*

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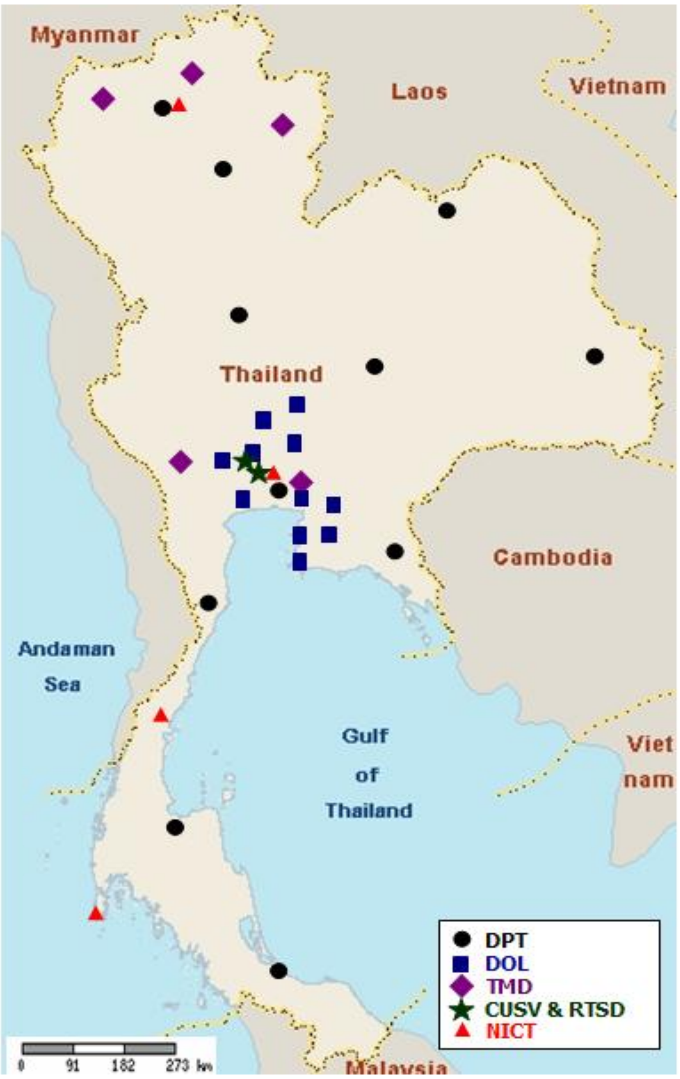

Figure 5
Thailand's CORS network

VII. Concluding Remarks

The following are a summary of the discussion points made in this paper:

(1) By the middle of the coming decade there may be four operational (or nearly so) Global Navigation Satellite Systems, all transmitting on several frequencies a variety of trackable signals:

- GPS will be upgraded, with several generations of satellites transmitting civilian signals on the L1, L2 and L5 frequencies.
- GLONASS will be revitalised, with a new generation of satellites transmitting signals on the G1, G2 and G3 frequencies (close though not identical to the GPS frequencies). There will also be a CDMA-type signal transmitted on the L1 frequency that would be very similar to GPS's L1 signal.
- GALILEO satellites will be transmitting a variety of frequencies and trackable signals. However only the E1 and the E5a/E5b will be coincident in frequency to the GPS L1 and L5, or close to the centre frequencies of the GLONASS G1 and G3 bands.
- COMPASS is the GNSS that currently has the most unknown factors associated with it. However there may be some COMPASS frequency overlap with the frequency bands at L1, and possibly L5, that will permit some degree of interoperability with the other three GNSSs. A COMPASS RNSS could be operating as early as 2012, with FOC of the COMPASS GNSS scheduled for 2020.

(2) By the end of the decade there may also be several Regional Navigation Satellite Systems launched by East or South Asian countries, with sufficient interoperability

with the GNSSs listed above to contribute extra satellites and signals to high accuracy users. Japan, India and South Korea have unveiled plans for RNSSs.

(3) Space Based Augmentation Systems constellations of satellites in geostationary orbits, although deployed for civil aviation applications by Japan, India and possibly Korea and Australia, will transmit additional GNSS-type signals (initially GPS, but also possibly GLONASS and GALILEO) in the L1 and L5 frequency bands.
(4) All proposed RNSS constellations, and several extra SBAS satellites, will be visible in the East Hemisphere region, significantly increasing total satellite visibility over what is currently available.
(5) The issues of *compatibility* and *interoperability* of the different GNSS/RNSS will loom large in the coming years. At the very least this would imply the same (or very similar) transmitted frequencies by all GNSS/RNSS.
(6) High accuracy users – for applications in surveying, geodesy, mapping, machine automation and precision navigation – will benefit from as much interoperability as possible so that carrier phase measurements may be made on several frequencies. The most common configurations of tracking/measurement processing will likely be:
    - Dual-frequency measurements of PR and CPH on the two frequencies common on all GNSS and most RNSS, i.e. L1/G1/E1 and L5/G3/E5a(/E5b?).
    - Triple/multiple-frequency GPS-only, or GLONASS-only, or GALILEO-only, etc., measurement processing using TCAR-type algorithms.
    - Some combination of triple-frequency GNSS, e.g. GPS+GALILEO, or GPS+GLONASS.
    - "All-in-view" tracking of all GNSS/RNSS signals for ultra-precise geodetic-type applications.
(7) A GNSS "system of systems" is a useful concept for analyses of: (a) transmitted GNSS/RNSS satellite frequencies and signals, (b) user receiver hardware and data processing algorithms, and (c) continuously operating reference receiver infrastructure to support differential GNSS positioning. However:
    - Only the two frequency bands L1/G1/E1 and L5/G3/E5a(/E5b?) will be common, or interoperable, across all GNSSs and RNSSs, and eventually the upgraded SBAS constellations.
    - Triple-frequency interoperability is not assured across all GNSS and RNSS.
    - Given the cost/complexity/power drain of full GNSS "system of system" receivers it is unlikely that there will be many portable user devices built with such capabilities.
    - There will be several different designs of "system of systems" receivers, basically falling into two categories: (a) multi-constellation GNSS dual-frequency (L1+L5) devices, and (b) devices that track the triple-frequency signals transmitted by all GNSS/RNSS constellations.
    - To support high accuracy users, future GNSS reference station networks must cater for the different classes of user equipment identified above.
(8) The "minimum interoperable configuration design" for a GNSS "system of systems" receiver for centimetre-level positioning accuracy will be a dual-frequency instrument, making pseudo-range and carrier phase measurements on the L1/G1/E1 and L5/G3/E5a/E5b frequencies. This will be relatively inexpensive, and offer users superior performance to current dual-frequency GPS+GLONASS receivers due to the massive increase in the number of tracked satellites (two frequencies each). However the density of reference stations to support differential positioning will be similar to current networks.
(9) The top-of-the-line full GNSS "system of systems" receiver that can track all broadcast frequencies/signals will likely only be used for specialist users, supporting geodetic research and perhaps mission-critical machine automation. The advantage is that the spacing of reference stations to support differential positioning can be much sparser than is the case for current networks.
(10) Many high accuracy users will continue to use the differential mode of positioning, taking advantage of permanent continuously operating reference stations. There will likely be a hierarchy of CORS networks, such as proposed in this paper (Tiers 1, 2 and 3)
(11) The density receivers within the CORS networks may therefore be variable:
    - The Tier 1 and Tier 2 CORS stations operating top-of-the-line, multi-frequency GNSS "system of systems" receivers will likely be established

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with relatively long inter-receiver separations, of the order of several hundred kilometres or more.

- The Tier 3 CORS stations operating the lower cost dual-frequency (L1+L5) “minimum interoperable configuration design” receivers, will likely be established at a variety of closer spacings, from just several kilometres apart (e.g. to support structural deformation monitoring, and single-base RTK applications), to perhaps up to several tens of kilometres (e.g. to support most DGNSS and network-RTK users).

In conclusion, GPS and GLONASS combined have already demonstrated the benefits of extra satellites for high accuracy users, and adding GALILEO and COMPASS satellites brings all that and more. In addition, if SBAS and RNSS satellites also transmit interoperable signals the system performance in terms of continuity, accuracy, efficiency, availability and reliability will improve even further. However, there are many design challenges to be addressed at the user hardware equipment and data processing algorithm level, as well as the deployment and management of next generation CORS networks to support all high accuracy users.

Modern Geodesy provides the foundation for all observations related to global change within the “*System Earth*”. The importance of Earth observations, provided with increasing spatial and temporal resolutions, better accuracy, and with decreasing turn-around time, should be seen in the context of not only scientific understanding of the Earth system, but also in support of fundamental societal activities, such as managing natural resources, environmental protection, human health monitoring, disaster prevention and emergency response. Global Navigation Satellite Systems such as the current GPS and GLONASS, together with “next generation” GNSS (and RNSS and SBAS), will play a vital role in fulfilling the mission of Modern Geodesy through an expansion of the capabilities of the International GNSS Service – by the upgrade of current Tier 1 CORS to GNSS “system of systems” receivers, and progression to real-time data products. The vehicle to deliver the ultra-high resolution (in the form of high accuracy, high reliability, low latency geodetic services) is the Global Geodetic Observing System (GGOS). GGOS requires the continued support of the IGS – a voluntary, non-commercial, confederation of about 200 institutions worldwide, self-governed by its members. The IGS does not own any CORS receivers, hence *the maintenance and upgrade of the global tracking network must be assured by the sustained commitment of national surveying/geodesy agencies around the world to invest in high quality CORS infrastructure*.

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