Impact of Next Generation GNSS on Australasian Geodetic Infrastructure

Chris RIZOS, Matt HIGGINS and Gary JOHNSTON, Australia

Key words: geodesy, GPS, GNSS, CORS instructure

SUMMARY

Global Navigation Satellite Systems (GNSSs) involve satellites, ground stations and user equipment, and are now used to support many activities within modern societies. Among them, precise positioning for geodetic, surveying and critical real-time machine guidance applications requires a substantial investment in ground infrastructure in the form of continuously operating reference stations (CORS) and associated ICT components. The federal government, state governments and the government of New Zealand are currently establishing CORS networks to address several precise positioning 'markets'. The foundation infrastructure in Australia is funded under the AuScope initiative and, together with other geodetic CORS will by mid-2011 see well over 250 stable CORS across Australia and New Zealand to support national datum and global geodesy goals. The latter include support for the International GNSS Service (IGS) and the Global Geodetic Observing System (GGOS).

The Global Positioning System (GPS) from the U.S. is the best known, and only currently fully operational, GNSS. Russia has deployed its own GNSS called GLONASS which will be fully operational within one or two years. 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 modernised GPS-IIF and planned GPS-III, the revitalised (and later to be modernised) GLONASS, Europe's planned GALILEO system, and China's COMPASS system. Furthermore, a number of Space Based Augmentation Systems (SBASs) and Regional Navigation Satellite Systems (RNSSs) will add extra satellites and signals to the multi-constellation GNSS/RNSS 'mix'.

This paper explores some of the implications of next generation GNSS from the perspective of precise positioning. In particular, issues such as the different "tiers" of CORS, unification of CORS infrastructure, capabilities of the next generation CORS receiver, and deployment strategies for future CORS will be discussed.

Impact of Next Generation GNSS on Australasian Geodetic Infrastructure

Chris RIZOS, Australia

1. NEXT GENERATION GNSS

1.1 From GPS to Multi-GNSS

Global Navigation Satellite Systems (GNSSs) involve satellites, ground stations and user equipment, and are now used to support many activities within modern societies. The U.S. *Global Positioning System* (GPS) is the best known, and only currently fully operational GNSS. Russia also operates its own (not yet fully deployed) GNSS called *Glonass*, to be fully operational 2010-2011. Fuelling growth in applications during the next decade will be next generation GNSSs that are currently being developed and deployed (see Rizos, 2008 for details). Europe is developing *Galileo*, for deployment 2013-2015, and China launched *Beidou* – which was the first Regional Navigation Satellite System (RNSS) – and then announced *Compass*, a GNSS to be deployed in the time period 2015-2020. Japan will launch in 2010 the first satellite of its own regional augmentation to GPS and Galileo known as the *Quasi-Zenith Satellite System* (QZSS). India has proposed the *Indian RNSS* (IRNSS) to be operational in the next decade (although details are still scant). In addition there are a number of Space-Based Augmentation Systems (SBAS) that are already deployed (such as the U.S.'s Wide Area Augmentation System – WAAS, The E.U.'s European Geostationary Navigation Overlay System – EGNOS, and Japan's MTSAT Satellite Augmentation System - MSAS), or will be soon (India's GPS Aided Geo Augmented Navigation – GAGAN, and Russia's System of Differential Correction & Monitoring – SDCM), that broadcast extra navigation signals primarily intended for aviation users (though only in the protected aeronautical frequency spectrum bands). Hence most of the big space players all now have, or will in the coming decade launch, a GNSS, RNSS or SBAS. In this paper these ”next generation” navigation satellite systems, combined with the current and modernised GPS, will be collectively referred to as ”multi-GNSS” systems. We may distinguish between the multi-GNSS satellite systems (the space infrastructure), the user equipment and the ground augmentation infrastructure (the ground infrastructure) needed to support high accuracy applications such as geodesy, surveying and machine automation.

The main advantage that the multi-GNSS era will bring is *more satellites*. It is estimated that by 2015, if the planned deployments go ahead, there will be up to 3 times the number of satellites and 4-6 times the number of individual signals on which measurements can be made, compared to today's number (50 satellites, on which two-frequency measurements can be made). It is generally conceded that the more satellites and signals there are, the better the positioning performance is – in terms of accuracy, availability, reliability and integrity.

1.2 Multi-GNSS and an Increase in Satellite Availability

Figure 1 shows the average visibility – the number of satellites above a 15° elevation cutoff angle – of the current 31 satellite GPS constellation on a worldwide basis over a 24 hour period on 20 June 2009 (Dempster & Rizos, 2009). A similar analysis can be performed for the current 20 satellite Glonass constellation. Surprisingly the average number of visible satellites is 8-10 for both constellations, and hence tracking *both* GPS and Glonass would on *average* effectively double the number of trackable GNSS satellites. (Of course the incomplete Glonass constellation would result in times of the day when there would be significantly less visible satellites than the case for GPS.)

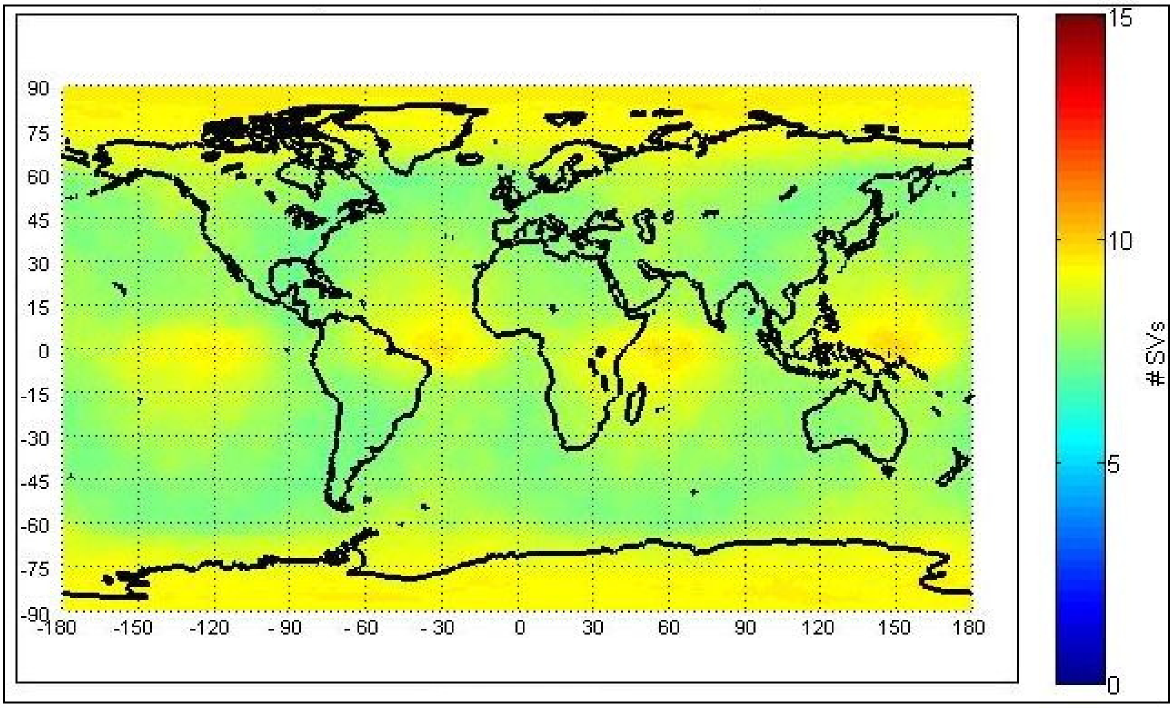


Figure 1: Average number of visible satellites (15° elevation cutoff angle) of the 31 satellite GPS constellation on a worldwide basis over a 24 hour period (Dempster & Rizos, 2009).

Compare this to the average worldwide next generation GNSS satellite visibility in Figure 2 for the GPS (the current 31 satellite constellation), Glonass (planned 24 satellite constellation), Galileo (planned 30 satellite constellation), Compass (possible 27 satellite constellation), IRNSS (possible 7 satellite constellation) and QZSS (3 satellite constellation), assuming an elevation cutoff angle of 15°, calculated over a 24 hour period. In the Australasian region the average number is over 40. The maximum number of visible satellites is close to 60.

1.3 Multi-GNSS and an Increase in Satellite Measurements

An important aspect of the ”richness” of multi-GNSS is the number of transmitted frequency bands (Figure 3), and the different modulated signals on those carrier frequencies. In principle, a receiver can be designed to track any of the individual signals (and some frequencies will have multiple signals on which measurements could be made, in an analoguous manner that an appropriately configured GPS receiver can track the open C/A-code or the encrypted Y-code on the L1 frequency). A receiver that could track all of the transmitted frequencies and signals is sometimes referred to as a ”system of systems” (SoS) receiver (Dempster & Rizos, 2009). Such a SoS receiver would be built using ”software receiver” principles, and has been proposed for future ultra-precise geodetic applications of the International GNSS Service (Humphreys et al, 2008). In reality, commercial off-the-shelf multi-GNSS receivers developed for the high accuracy positioning market will track a particular sub-set of all possible signals, as is currently the case with the first multi-GNSS receiver products available today.

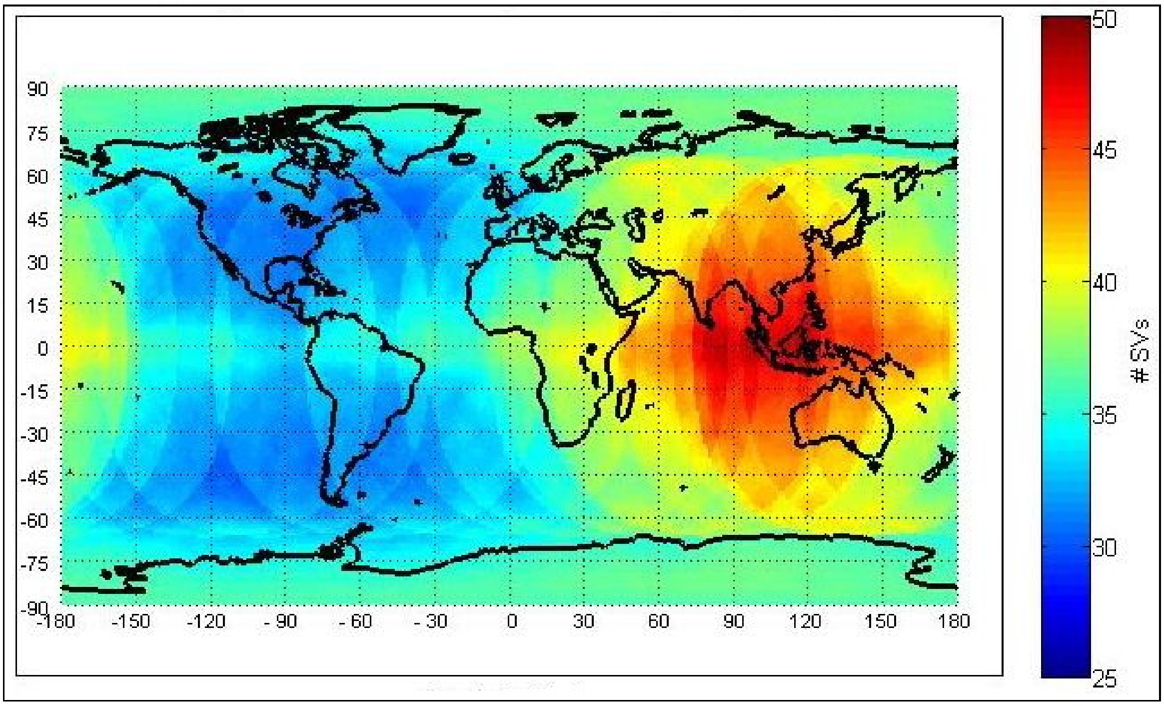


Figure 2: Average number of visible satellites (15° elevation cutoff angle) of the GPS, Glonass, Galileo, Compass, WAAS, EGNOS, QZSS, MSAS, IRNSS and GAGAN constellations on a worldwide basis over a 24 hour period (Dempster & Rizos, 2009).

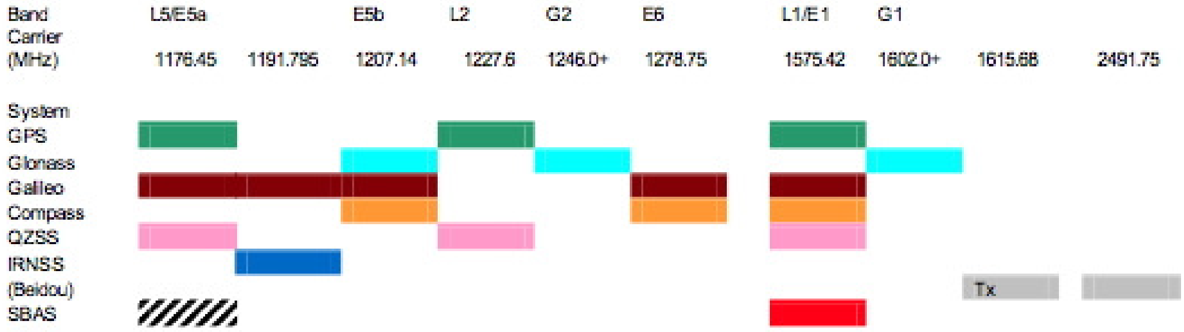
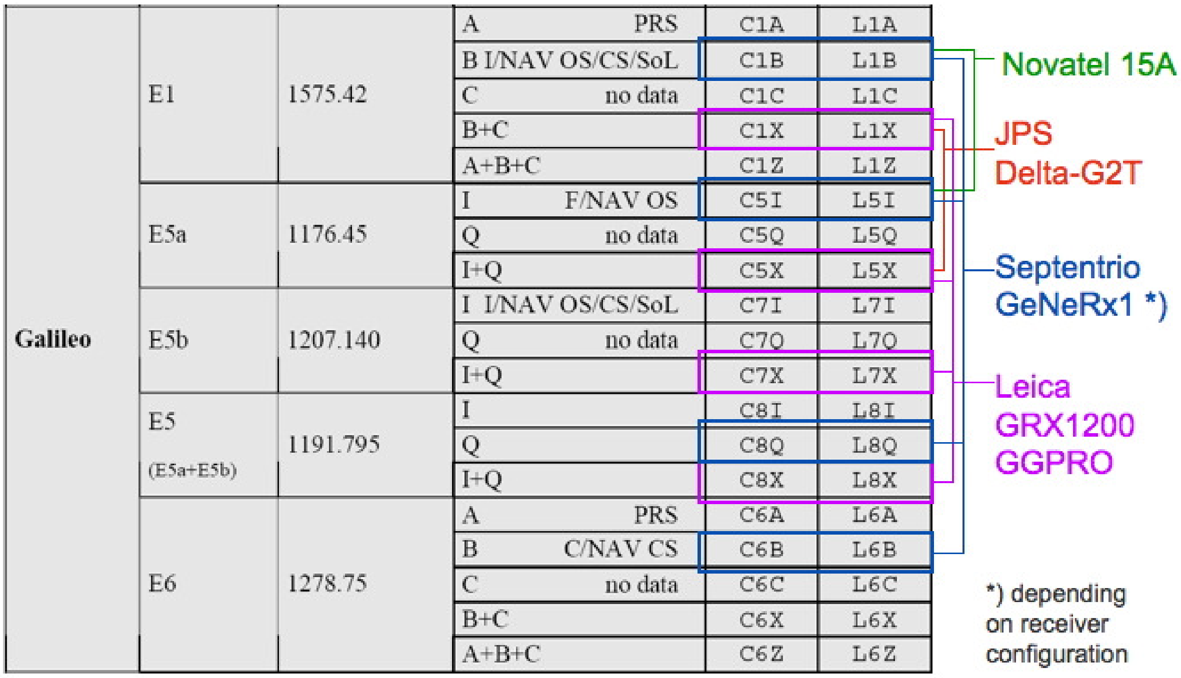


Figure 3: Multi-GNSS frequency bands (Dempster & Hewitson, 2007).

To illustrate the challenges of *interoperability* of top-of-the-line multi-GNSS receivers, consider the case of four brands of receiver on the market today that claim to be “Galileo-ready”. The different Galileo frequencies and signals are illustrated in Table 1. Each row is a different trackable signal. The last two columns refer to the pseudorange and carrier phase observable for that signal. Although each multi-frequency Galileo receiver claim to make pseudorange and carrier phase measurements on the different frequency bands, and the measurement functional model is assumed to be the same (e.g. in the case of L1, the same model is assumed, no matter whether the C1A, C1B, C1C or C1X signals are tracked), there are likely to be *differences in the stochastic models* of the measurements due to subtle inter-channel biases, different susceptabilities to multipath disturbance, etc. This is likely also to be the case for “Compass-ready” receivers. The complexity increases manyfold in the case of true multi-GNSS receivers (i.e. capable of tracking multiple signals of all four GNSSs) and data processing software (of the resulting pseudorange and carrier phase measurements).

Table 1: Galileo signals and different receiver observables (Hugentobler, 2009).



Galileo	E1	1575.42	A	PRS	C1A	L1A
			B	I/NAV OS/CS/SoL	C1B	L1B
			C	no data	C1C	L1C
			B+C		C1X	L1X
			A+B+C		C1Z	L1Z
	E5a	1176.45	I	F/NAV OS	C5I	L5I
			Q	no data	C5Q	L5Q
			I+Q		C5X	L5X
	E5b	1207.140	I	I/NAV OS/CS/SoL	C7I	L7I
			Q	no data	C7Q	L7Q
			I+Q		C7X	L7X
	E5 (E5a+E5b)	1191.795	I		C8I	L8I
			Q		C8Q	L8Q
			I+Q		C8X	L8X
	E6	1278.75	A	PRS	C6A	L6A
			B	C/NAV CS	C6B	L6B
			C	no data	C6C	L6C
			B+C		C6X	L6X
			A+B+C		C6Z	L6Z

It is not yet clear whether this “non-interoperability” issue with respect to the trackable signals (and resulting measurements) for multi-GNSS receivers will impact on any but the most critical geodetic applications. However, given that high accuracy GNSS requires ground infrastructure for differential operations, such signal non-interoperability when combined with multiple available GNSS and frequency tracking options may be an issue in the multi-GNSS era (see section 3.1.5).

2. GEODETIC INFRASTRUCTURE

Next generation GNSS will have a significant impact on the ground infrastructure of permanent Continuously Operating Reference Station (CORS) networks that support high accuracy positioning. CORS nowadays provide the fundamental infrastructure required to meet the needs not only of *geodesy* and the geosciences, but also of many professional GNSS *surveying*, *mapping* and *navigation* users. Furthermore, the widespread use of the GNSS-RTK ("real-time kinematic") technique 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* and *precision agriculture*, and perhaps in future for advanced *Intelligent Transport System* (ITS) applications The discussion below has been adapted from Rizos (2007).

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 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 kilometres, 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 modern geocentric geodetic datums at the national level, and (c) the extension and increasing density of the geodetic control (groundmark) networks using GPS techniques.

2.1 The IGS Infrastructure

2.1.1 The IGS Today

The *International GNSS Service* (IGS – http://igs.org) was established in January 1994 as a service of the International Association of Geodesy (IAG – http://www.iag-aig.org). Since June 1992 the IGS – originally known as the "International GPS Service for Geodynamics", from 1999 simply as the "International GPS Service", and finally since March 2005 as the "International GNSS Service" – has been making freely available to all users raw GNSS tracking data from its global network, and high accuracy satellite ephemerides and other derived products (http://igs.org/components/prods.html). The mission of the IGS is "to provide the highest-quality GNSS data and products in support of the terrestrial reference frame, Earth rotation, Earth observation and research, positioning, navigation and timing and other applications that benefit society" (Dow et al, 2007). The IGS activities are fundamental to scientific disciplines concerned with monitoring the earth's geodynamics (or more correctly its "geokinematics") and solid earth geophysics, climate and surface weather, sea level change and ocean dynamics, gravity, space weather, geohazard precursors, and more. However, the IGS also supports many other non-scientific applications including precise navigation, machine automation, time transfer, and surveying and mapping, by providing easy access to the International Terrestrial Reference Frame (ITRF) through its IGS stations and precise GNSS products.

The IGS operates as a voluntary, non-commercial, confederation of over 200 institutions worldwide, self-governed by its members. The IGS collects, archives, and distributes GPS and Glonass observation datasets – datasets which are analysed and combined to form the various IGS products. A distinguishing characteristic of the IGS is its globally distributed CORS network (Figure 4), currently (early 2010) numbering approximately 415 stations. 132 of these are incorporated as core stations in the latest realisation of the ITRF (ITRF2005); 25, 37 and 55 stations are co-located with VLBI, SLR and DORIS space geodetic instruments respectively; 103 are co-located with tide gauges; 93 are combined GPS+Glonass receivers; and about 120 are operating as real-time data streaming stations. Note the Australian and New Zealand stations.

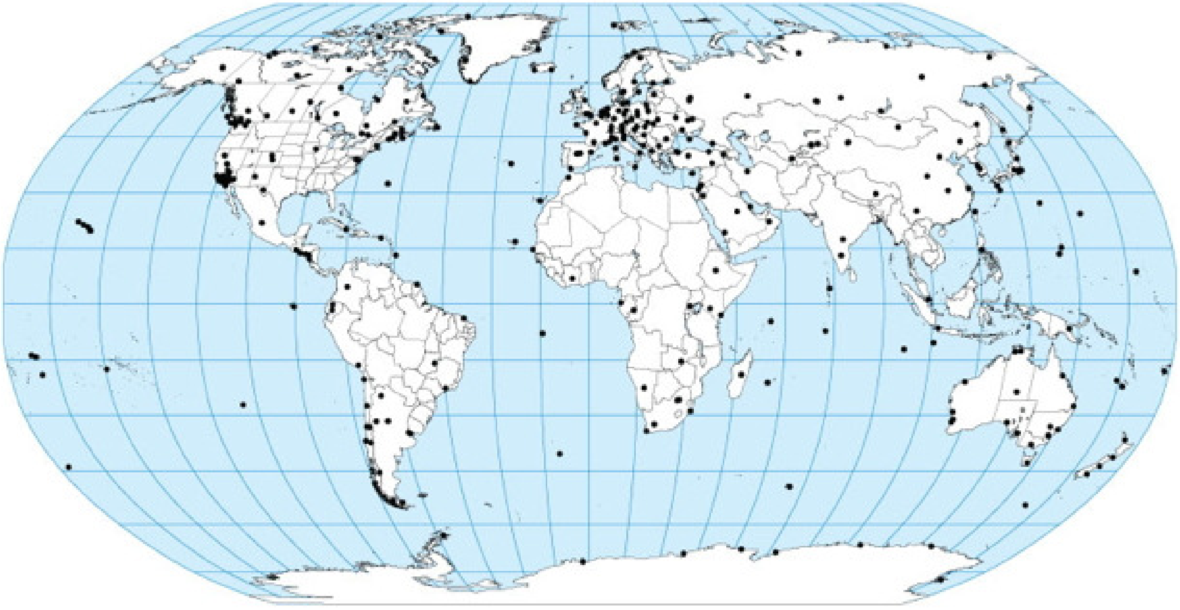


Figure 4: Global distribution of IGS stations (http://igs.org/network/netindex.html).

While the IGS product range has been mainly concerned with GPS, since 1998 Glonass products were also developed, and nowadays the raw data and derived products have been integrated into the mainstream IGS product flow (http://igs.org/components/prods.html). In fact, over its 15 year lifetime the IGS has demonstrated a remarkable ability to both improve the *quality* of its core products (such as satellite orbits, satellite and CORS clocks) and to *diversify* its range of products (e.g. Glonass products, atmospheric models). *The IGS will therefore be the first of the scientific GNSS user/product communities to take advantage of the multi-GNSS signals-in-space, CORS receivers and ground infrastructure.*

2.1.2 The IGS in the Future

It should be noted that all, or even most, of the signals from next generation GNSS constellations will not be transmitted before 2013-2015 at the earliest, hence the current investment in CORS infrastructure for the IGS (and national CORS networks) will continue to be in GPS+Glonass capable receivers. However, the upgrade of the CORS infrastructure at or after 2015 will have to incorporate multi-GNSS tracking capability. In 2008 the IGS launched a Real-Time Pilot Project (http://www.rtigs.net), with the following core objectives :

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

Within the next few years new RT IGS products will be generated on a continuous basis, to augment the current set of post-processed products. In parallel with this internal development, the IGS is working with its parent organisation – the IAG – to transition its service into part of the *Global Geodetic Observing System* (GGOS) (http://www.ggos.org). GGOS will be the geodetic component of the Global Earth Observing System of Systems (GEOSS) now being established by the inter-governmental Group on Earth Observations (GEO) (http://www.earthobservations.org/). This contribution will be vital to *global change* studies, and necessitates an upgrade of the global geodetic capability to deliver positioning capability *ten times more accurate* than at present. 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 play a key role in GGOS. To satisfy these internal (RT services) and external (GGOS) goals, the IGS global tracking network and its analysis capability will need to be significantly enhanced. New GNSS receivers, stable monumentation, and improved communications links will be required, as will improved modelling and data processing methodologies. Such a GNSS/CORS upgrade strategy may also be followed by many countries with respect to their own CORS networks. Australia is making an important contribution to the current IGS operations, and will also support future GGOS/IGS operations with upgraded geodetic infrastructure (section 3.1.3).

2.2 National CORS Infrastructure

2.2.1 CORS Today

In the 1990s, when the establishment of 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 RINEX files, and sent to an archive or data centre. From there the GNSS observation 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 will continue to be, available free-of-charge to all users.

With the advent of GPS-RTK techniques in the early 1990s (and later GNSS-RTK, incorporating Glonass data), carrier phase-based positioning finally could be seriously considered a *surveying tool*. However, to ensure high *productivity* GNSS-RTK there are several constraints, including: (1) that all GNSS receivers must have dual-frequency tracking capability, and (2) the inter-receiver distances should ideally be less than ten or so kilometres. These operational constraints placed cumbersome limits on many applications and drove the development of *network-based techniques* (e.g. Rizos, 2002) that have enabled cm-accuracy positioning with less dense reference receiver spacing requirements (on the order of 50-100km) and which could operate in real-time. Such relaxed specifications on CORS receiver spacing has encouraged many more countries to establish real-time CORS networks as an investment in *surveying infrastructure.*

2.2.2 Future Multi-GNSS CORS

There are proposals in Australia and New Zealand currently under consideration for the establishment of a National Positioning Infrastructure (NPI) to satisfy the cm-level real-time accuracy requirements of most major GNSS user communities. *Next generation GNSS*, with many more signals and frequencies, will have important implications for the development of the CORS network(s) that will form the foundation of a nation's NPI. For example, with the benefits of extra satellite visibility (or availability), and carrier phase tracking of three or more different transmitted L-band frequencies, the inter-receiver separations within GNSS CORS networks can be relaxed even further (section 3.1.2). 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" techniques. Furthermore, if decimetre-level coordinate accuracy is adequate, the CORS separation can be relaxed to several hundreds of kilometres for dual-frequency receivers, significantly reducing the necessary ground infrastructure investment required. However, many issues in relation to density and distribution of CORS are as yet unresolved. Even the specifications of the CORS receivers is unclear. See discussion in section 3.1.5.

No discussion on the NPI would be complete without addressing questions such as "Who will establish and maintain future CORS networks, government or private service providers?" Government agencies and organisations which typically justify the costs of implementing CORS networks by citing the principle of "preventable costs". This is similar to the strategy used to finance the establishment of classical geodetic groundmark networks decades earlier. The return on the original investment is not measured in terms of revenue earned, but justified as a means of keeping the costs borne by the community lower than the alternative (i.e., having no geodetic control infrastructure). This approach also encourages network standardisation and avoids the establishment of a patchwork of private, ad-hoc networks for project-specific purposes. There are already several different *business models* for CORS services (real-time positioning, or raw GNSS measurements) in different countries around the world. In some cases the government CORS infrastructure (even capable of supporting GNSS-RTK) is offered free, analoguous to road infrastructure, and service providers are encouraged to sell value-added services. In other cases the government agencies directly market GNSS CORS-based services themselves. However, it is very likely that the rollout of *uncoordinated* networks of CORS, operated by government agencies *and* private companies will be the norm, with considerable redundancy in ground infrastructure. Furthermore, such issues will be even more complex as we enter the era of multi-GNSS. Nevertheless to deliver on the vision that the NPI implies (an incomplete list): a single governance framework, coordinated CORS rollout, quality assurance procedures and operational guidelines, and one (or more) business model, that deliver a *seamless* (or at the very least interoperable) positioning service across the nation. This discussion is introduced in section 3.2.

3. IMPLICATIONS OF MULTI-GNSS TO CORS INFRASTRUCTURE

3.1 The Technical Issues

By about 2015, when the majority of multi-GNSS constellations are transmitting L-band signals, appropriately equipped users would benefit from (Rizos, 2008):

- enhanced *accuracy* (more observations, greater measurement redundancy, faster differential GNSS filter convergence, lower PDOP, etc.),
- improved *availability* (approximately three times more visible satellites, dual- and triple-frequency signal availability, more rapid on-the-fly ambiguity resolution, lower constraints on user-CORS receiver separations, etc.), and
- higher *integrity* (increased measurement redundancy, reduced interference vulnerability, enhanced QC algorithms, etc.).

Let us assume that 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. Current users of high accuracy GNSS techniques 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. With the coming of multi-GNSS a range of technical issues will need to be resolved, including upgrading of industry data standards such as RTCM (for real-time correction broadcasts) and RINEX (for archiving and exchange of recorded raw GNSS measurements), design of multi-GNSS antennas that have high phase centre stability and low multipath vulnerability, new guidelines and procedures for high accuracy positioning. Discussion of these issues is beyond the scope of this paper. However, some remarks in relation to the *rollout* of the appropriate CORS infrastructure to support high accuracy user communities are made below.

3.1.1 Tiers of CORS

Rizos (2008) has suggested that CORS infrastructure could be *heirarchical*: (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 IGS is currently in the process of defining the specifications (principally in terms of which signals will be tracked) of the next generation ”system of systems” GNSS receiver (e.g. Humphreys et al, 2008). It is likely that

Tier 1 CORS will ultimately be equipped with software-reconfigurable SoS GNSS receivers. Tier 2 CORS probably will deploy off-the-shelf multi-GNSS receivers – although it will be necessary to have a consistent definition of observables (to prevent scenarios such as Table 1 in the case of the Galileo signals tracked by different brands of commercial GNSS receivers). But what about Tier 3 CORS? That is not an easy question to answer.

3.1.2 CORS Rollout

Consider the following characteristics of high productivity, cm-level accuracy techniques:

(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 network-RTK operational mode will be used, with extra satellites providing quicker and more reliable 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 kilometres or more (Feng & Rizos, 2005).

One strategy may be to simply install Tier 2 type multi-GNSS receivers at Tier 3 sites as well, and the distinction between the "tiers" is the *stability* of the monumentation (the former being much more stable than the latter) and not the type of receiver. Another possible scenario is to 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, or a combination of both. The ratio between the former and the latter[1] is likely to be between 1:10 and 1:20. However, such planned rollout would be possible if there was *coordination* between CORS operators within the context of an overarching NPI. Nevertheless, such an outcome may, in reality, be difficult to achieve, as investment in CORS infrastructure will be spread across many companies and agencies, upgrading or establishing CORS at different times over the coming decade (see section 3.1.5).

3.1.3 Australia's Geodetic CORS

Australia is well regarded for its contribution to global geodesy above and beyond that would be expected of a country with Australia's modest population and economic influence. This contribution is attributable to, amongst other things, a unique environment where a large land mass with very sparse geodetic infrastructure has led to government geodetic surveyors being receptive to the development and use of new geodetic techniques. For example, since the mid-1990s Australia has hosted two SLR stations, operated several VLBI antennas for geodetic experiments, and established the Australian Regional GPS Network (ARGN) of permanent GPS receivers. The most recent boost to investment in Australian geodetic infrastructure commenced in mid-2007, as part of the Geoscience Capability, funded by the federal government's National Collaborative Research Infrastructure Strategy (NCRIS) known as

---

[1] A rule-of-thumb that is consistent with the inter-receiver spacings of the two classes of receivers, and a suggested ratio of Tier 2 to Tier 3 CORS.

AuScope (http://www.auscope.org.au). A key component of AuScope is the Geospatial Framework, which includes the building of three VLBI antennas, an upgrade of Mt Stromlo's SLR station, and establishment of almost 100 permanent GNSS stations, with the rollout to be completed by mid-2011. *AuScope Geospatial* may therefore be considered part of Australia's contribution to the upgraded GGOS ground station network (section 2.1.2). Australia will continue to support the IGS, especially as it moves to real-time operations. Furthermore, Geoscience Australia (http://www.ga.gov.au/geodesy) is working with state governments to ensure that a heirarchy of GNSS CORS will be established that conforms to the multi-tier concept introduced in section 3.1.1, such that the Tier 1 and 2 CORS form the stable foundation to the Australian NPI.

3.1.4 Interoperable CORS

Interoperability across multiple GNSS constellations is a complex issue – consider the following:

- Dual-frequency systems will be *more interoperable* than triple-frequency ones, as no GNSS has frequency plans that exactly match other GNSSs. Hence we will have TCAR-based GPS-only processing, combined with MCAR-based Galileo-only processing, possibly combined with TCAR-based Glonass processing and TCAR-based Compass processing – implying expensive receivers and complex data processing software.
- The "minimum interoperable configuration design" for multi-constellation GNSS will be a dual-frequency receiver tracking the L1 and L5 frequencies (or equivalent E5a/E5b bands).
- The L1-L5 dual-frequency receiver configuration is likely to be the least expensive of the dual-frequency carrier phase-tracking GNSS receivers useful for precise positioning.
- SBAS satellites will only transmit on L1 and L5 frequencies, hence these signals will only contribute to dual-frequency data processing, although this is unlikely to occur until well into the next decade.
- In the case of RNSSs there may be regional markets/products that will take advantage of signals only broadcast over specific area. However this raises many interesting questions, as the world has only, to date – with the exception of the few Beidou terminals in China – been using "global" GNSS products. How the various RNSS and SBAS signals will be incorporated into user products and services is still unknown.
- Dual-frequency receivers have already shown they can support cm-level accuracy under conditions of sufficient trackable satellites, good geometry, low multipath disturbance, and constrained baseline lengths (user-CORS distances of ten to several tens of kilometres).
- GPS will have many legacy issues through to the year 2020 and beyond, with a mixed heritage of GPS-IIRM, GPS-IIF and GPS-III satellites, with only the GPS-IIF and GPS-III satellites (none of which have as yet been launched) transmitting on three frequencies. While new receivers will likely be able to track all GPS signals ("backward compatibility"), older receivers will not be able to track the newer L2C, L5 and L1C signals ("foreward compatibility"). *Making sure the NPI can service the*

needs of users with the latest generation of multi-frequency receivers will be a significant challenge.

- There will be an increasing number of CORS established that will *not* necessarily support other users, but are intended to operate as GNSS 'arrays' for either deformation monitoring (e.g. dense receiver networks on buildings and other structures) or atmospheric remote sensing (e.g. tropospheric sounding to support weather forecasting). They will require low-cost receivers, though they will use data from other high-tiered CORS networks. *Integration of these CORS networks into the NPI will also be a challenge.*

Whatever the mix of CORS receiver types that will be used (and they will vary over time), ground CORS infrastructure investment is likely to continue to grow significantly. 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 government agencies and the private sector. But can the level of coordination or integrated CORS operations across a nation or region be raised sufficiently to deliver on the visions of the Australian and New Zealand NPIs? This is briefly dicussed in section 3.2.

3.1.5 Technical Issues Associated with Multiple GNSS Constellations

There are a range of technical issues that need to be addressed by national and state government agencies, working with universities and the private sector, as an NPI based on multiple GNSS contellations is rolled out over the coming decade. Many of them are (directly or indirectly) related to two ”messy” characteristics of next generation GNSS: (1) there is *no 100% signal or frequency interoperability across the four GNSSs* (Figure 3), and (2) the deployment of the 24-30 satellite constellation of each GNSS has a *different start date and duration* (typically 3-5 years from first launch to Full Operational Capability when a minimum of 24 satellites are broadcasting signals). The former implies that most next generation GNSS receivers will likely track only a *sub-set* of all possible signals and frequencies, while the latter implies that there will be many years of *incomplete* GNSS contellations (with associated issues of legacy signals, multi-year CORS infrastructure investment and upgrade challenges, sub-optimal data processing algorithms, etc.). The following three challenges therefore arise:

- The minimum specifications of Tier 1, 2 and 3 CORS receivers – this is of course a ”moving target” as tracking capability will necessarily change with time as we progress from the current GPS+Glonass, to GPS(modernised)+Glonass, GPS+Glonass+Galileo, G+G+G+Compass, and so on, over the next decade.
- The ratio of Tier 1 to Tier 2 to Tier 3 CORS, *and* their geometric pattern of deployment – defining the so-called *spatial deployment strategy* (SDS) across a country, or city or region.
- The timeline for the deployment of the various CORS receivers – the so-called *temporal deployment strategy* (TDS) over the coming decade – so as to minimise gaps in GNSS user positioning capability as progressive upgrades of GNSS receiver capability are introduced into the market.

With the abovementioned challenges in mind, an incomplete list of associated technical issues includes the following:

- The definition of a consistent set of GNSS observable types, the use of which would allow different GNSS receiver capabilities to be assessed.
- Definition of preliminary specifications of CORS receivers (for all three tiers) for the first and second ”waves” of CORS networks, able to track modernised GPS+Glonass and GPS(mod)+Glonass+Galileo signals.
- ”Strawman” proposals for SDS and TDS for Tier 1 and Tier 2 CORS, for the first two waves of CORS deployments.
- It is critical that the upgrade of current Australian and New Zealand IGS, ARGN, PositioNZ, and AuScope GNSS CORS over the next 5-10 years ensures that the long term continuity of coordinate time series are not disrupted. This is an issue that the entire IGS must address as it progressively upgrades to multi-GNSS over the next decade. This is because the current antennas will have to be replaced, resulting in ”jumps” in the station’s coordinate time series. A phased upgrade (both geographically and over time) will be necessary.
- In parallel with upgrading GNSS receiver tracking capability, and further ’in-filling” of gaps in coverage with additional CORS, it will be opportune to implement techniques and procedures to deliver sub-cm accuracy for the ”backbone” of the NPI – the Tier 1 and 2 CORS. This includes refinements to monumentation, improved characterisation of the multipath environment at each CORS site, and increased co-location with other geodetic instrumentations (including ”clusters” of GNSS receivers, perhaps of different ”generations”).
- Associated upgrades to data communications, quality assurance processes, and archiving and data handling procedures, to ensure that the integrity of the NPI can be assured.

These are challenging issues that are not only relevant to Australian and New Zealand CORS. The IGS and many other countries will face the same challenges, hence there will be a considerable body of literature and research findings that can be referred to as the NPIs based on multi-GNSS are rolled out in the coming decade. However, for an NPI to be realised there are also many non-technical issues that must be addressed.

3.2 The Organisational Issues

A useful framework for considering organisational issues as we move to a multi-GNSS future is to set out some clear principles for the positioning infrastructure. Higgins (2008) recently developed the following list of principles to inform the development of a policy for a National Positioning Infrastructure for Australia:

- **Public Good**: Meet public good needs such as strengthening rather than fragmenting Australia’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, including science which is a requirement in the case of AuScope stations but could be extended to others;
- **Beneficial**: Allow full realisation (by users and operators) of the economic, environmental and societal benefits for Australia;
- **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 within the Australia & New Zealand land Information Council (ANZLIC), the approach should encourage participation by non-ANZLIC 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**: Recognise that availability of resources to build the positioning infrastructure may vary in time, location and across sectors. Therefore, extensibility is desirable to take advantage of funding injections when available.

Higgins (2008) has also proposed a model for understanding and facilitating discussion of the roles that a given organisation 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 organisation might play (Figure 5):

- ***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 centre 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 organisation 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.

Ibid (2008) also points out that if different organisations 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 organisation and setting agreed levels of service within and between each of the roles outlined above. The organisation 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 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 centimetre-level accuracy.
- 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. For example, consider the following:
    - Most mass market users will not need access to all signals from all GNSS. Taking into account the technical issues outlined earlier in this paper, the complexity of such equipment is not likely to be warranted for the mass market. A more likely scenario for mass market users is to evolve in the short term from using single-frequency GPS receivers to using single-frequency, multi-GNSS receivers. Then over time their needs may evolve to dual-frequency, multi-GNSS receivers.
    - On the other hand, the high precision end of the market may well need multi- frequency, multi-GNSS solutions and will expect existing precise positioning services to evolve to supply those solutions and to do so with ever increasing levels of reliability.

These are two extremes of a possible range of scenarios and it is difficult to predict how a given organisation should evolve its involvement in CORS to react to such a range of scenarios. However, the organisational model and underlying principles outlined by Higgins (2008), along with the concepts of *spatial deployment strategies* and *temporal deployment strategies* outlined in section 3.1.5 can at least give a systematic framework for an organisation to analyse and evolve its role.

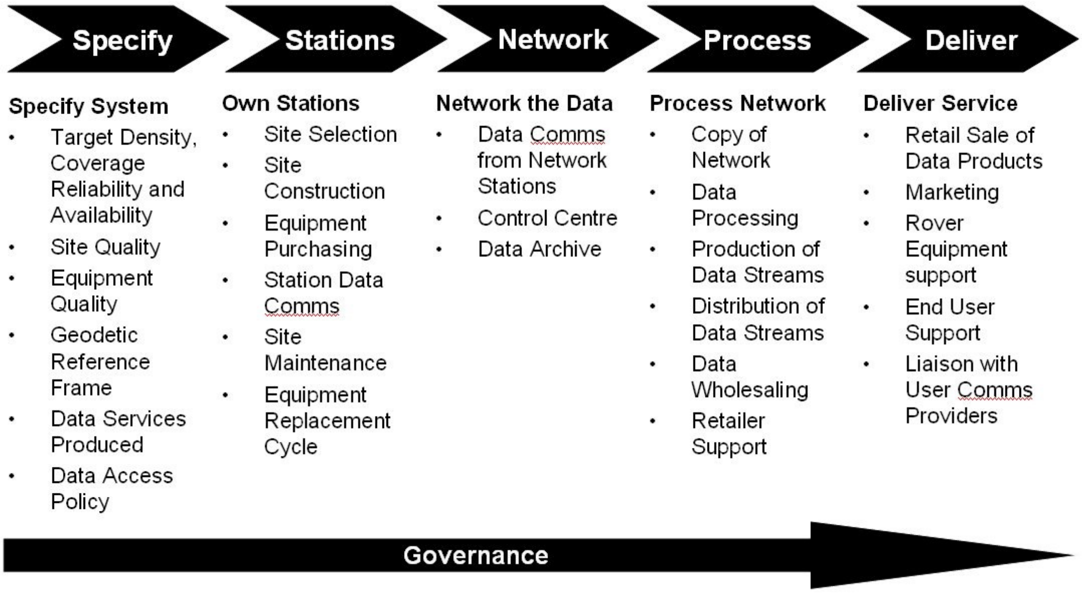


Figure 5: A model for organisational roles within a National Positioning Infrastructure (Higgins, 2008).

4. CONCLUDING REMARKS

The future of multi-GNSS is an exciting one, with improvements in a number of metrics. However the increased complexity in GNSS signals will impact on receiver design, with new classes of receivers developed for different user markets. The top-of-the-line receiver is likely to be embraced only by the geodesy and scientific users. However, very significant impacts will be felt by owners and operators of Continuously Operating Reference Station (CORS) networks. The type of receiver equipment to be used, the design of the CORS networks, and a host of other technical issues will need to be addressed. It is likely that a “multi-tier” model of CORS will evolve, with different receiver technologies (tracking some or all GNSS signals), to service different markets. However, the challenge is also to organise the patchwork of different CORS networks, over the next decade as new GNSS signals are broadcast, into a single National Positioning Infrastructure that is able to address all GNSS users in as efficient a manner as possible.

REFERENCES

Dempster, A.G., & Hewitson, S. (2007), The “System of Systems” receiver: An Australian opportunity? *IGNSS2007 Symp. on GPS/GNSS*, Sydney, Australia, 4-6 Dec, available from http://www.gmat.unsw.edu.au/snap/publications/dempster&hewitson2007.pdf, accessed 25 December 2009.

Dempster, A.G., & Rizos, C. (2009), Implications of a "system of systems" receiver, *Surveying & Spatial Sciences Institute Biennial International Conference*, Adelaide, Australia, 28 September – 2 October, CD-ROM procs.

Dow, J., Neilan, R., & Rizos, C. (2007), The International GNSS Service (IGS): Preparations for the coming decade, *20th Int. Tech. Meeting of the Satellite Division of the U.S. Inst. of Navigation*, Fort Worth, Texas, USA, 25-28 September, 2136-2144.

Feng, Y., & Rizos, C. (2005), Three carrier approaches for future global, regional and local GNSS positioning services: Concepts and performance perspectives, *18th Int. Tech. Meeting of the Satellite Division of the U.S. Institute of Navigation,* Long Beach, California, 13-16 September, 2277-2287.

Higgins, M.B. (2008), An organisational model for a unified GNSS reference station network for Australia, *Journal of Spatial Science*, 53(2), 81-95.

Hugentobler, U. (2009), The International GNSS Service in a challenging field of developing Global Navigation Satellite Systems, pres. *EUPOS Symp*., Berlin, Germany, 1 December.

Humphreys, T., Young, L., & Pany, T. (2008), Considerations for future IGS receivers, *IGS Analysis Center Workshop*, Miami, Florida, USA, 2-6 June, available from http://igscb.jpl.nasa.gov/overview/pubs/IGSWorkshop2008/docs/recDev-positionpaper.pdf, accessed 25 December 2009.

Rizos. C. (2002), Network RTK research and implementation: A geodetic perspective, *Journal of Global Positioning Systems*, 1(2), 144–150.

Rizos, C. (2007), Alternatives to current GPS-RTK services and some implications for CORS infrastructure and operations, *GPS Solutions*, 11(3), 151-158.

Rizos, C. (2008), Multi-constellation GNSS/RNSS from the perspective of high accuracy users in Australia, *Journal of Spatial Science*, 53(2), 29-63.

BIOGRAPHICAL NOTES

Chris Rizos is currently Head of the School of Surveying & Spatial Information Systems at the University of New South Wales, Sydney, Australia. Chris has been researching the technology and applications of GPS since 1985, and established over a decade ago the Satellite Navigation and Positioning group at UNSW, today the largest academic GPS and wireless location technology R&D laboratory in Australia. Chris is the Vice President of the International Association of Geodesy (IAG), and a member of the Executive and member of the Governing Board of the International GNSS Service (IGS). Chris is also the Chair of the joint IAG/IHO Advisory Board on the Law of the Sea (ABLOS).

Matt Higgins is Manager of Geodesy and Positioning with the Department of Environment and Resource Management in the Queensland Government, Australia. He holds Bachelor and Masters Degrees in Surveying. From 2007 to 2010, Matt is a Vice President of the International Federation of Surveyors (FIG) and their representative on the UN mandated International Committee on GNSS. He also leads a GNSS related project in Australia's Cooperative Research Centre for Spatial Information. He is a Fellow of the Surveying and Spatial Sciences Institute (SSSI). Matt received SSSI's highest award in 2005 for Professional Eminence and Excellence. He was elected President of the Australia-based International GNSS (IGNSS) Society in 2008, when GPS World magazine also named him among the 50+ leaders to watch in GNSS business.

Gary Johnston is the Project Leader of the National Geospatial Reference Systems Project within Geoscience Australia (GA). GA is a key contibuter to Australian Geodesy and leads the Auscope Geospatial Project. Gary chairs the Geodesy Technical Sub-Committee of the Intergovernmental Committee on Surveying and Mapping. He is also a member of the Governing Board of the International GNSS service (IGS) and a member of the Steering Committee of the International Association of Geodesy's (IAG) Global Geodetic Observing System (GGOS). Gary was also recently elected to chair the Geodetic Infrastructiure of Antarctica (GIANT) working group under the Scientific Committee on Antarctic Research (SCAR).

CONTACTS

Professor Chris Rizos
School of Surveying & Spatial Information Systems
University of New South Wales
Sydney NSW 2052
AUSTRALIA
Tel. +61-2-93854205
Fax +61-2-93137493
Email: c.rizos@unsw.edu.au
Web site: http://www.ssis.unsw.edu.au

Matt Higgins
Spatial Information Group
Department of Environment & Resource Management
Locked bag 40, Coorparoo DC QLD 4151
AUSTRALIA
Tel. +61-7-38963754
Fax +61-7-38963697
Email: matt.higgins@derm.qld.gov.au
Web site: http://www.derm.qld.gov.au

Gary Johnston
Earth Monitoring Group
Geoscience Australia
GPO Box 378 Canberra ACT 2601
AUSTRALIA
Tel. +61-2-62499049
Fax +61-2-62499969
Email: gary.johnston@ga.gov.au
Web site: http://www.ga.gov.au