

University of Southern Queensland  
FACULTY OF HEALTH, ENGINEERING & SCIENCES

EVALUATION OF THE PERFORMANCE OF DIFFERENT  
GLOBAL SATELLITE NAVIGATION SYSTEMS (GNSS)  
FOR AUSTRALIAN GNSS USERS

A dissertation Submitted by

**Kari Hautsalo**

in fulfilment of the requirements of Courses

ENG4111 and 4112 Research Project

Towards the degree of

Bachelor of Spatial Science (Surveying)

---

## **Abstract**

Satellite navigation has been available in the aviation and maritime worlds since GPS system was built in the 1970's and users were able to navigate anywhere in the world with unheard-of accuracy of less than a hundred meters. Since then other systems have emerged and a new term, Global Navigation Satellite System was born to generalise the concept.

Now that there are four different GNSS systems in a stage of development that includes satellites in orbit, it is prudent to ask the question: which GNSS system best suits the Australian user? This project took the task of finding information about all four GNSS systems that would enable an evaluation of performance of each system.

The project devised an evaluation framework for ranking the benefits and a methodology of assessing identified indicators of such suitability against that framework. As a result, differences were found, impacts of those differences were assessed and results tabulated in a matrix of ranking.

With limited resources and scope, the results can be seen as discussion enhancing rather than authoritative points of view and others may have other ideas of where the emphasis should lie.

The project report nevertheless covers a wide range of topics that would be included in any assessment into the needs of an Australian user.

---

# University of Southern Queensland

FACULTY OF HEALTH, ENGINEERING & SCIENCES  
SCHOOL OF ENGINEERING AND SURVEYING

## ENG 4111 & ENG4112 *Research Project*

### **Limitations of Use**

The Council of the University of Southern Queensland, its Faculty of Health, Engineering & Sciences, and the staff of the University of Southern Queensland, do not accept any responsibility for the truth, accuracy or completeness of material contained within or associated with this dissertation.

Persons using all or any part of this material do so at their own risk, and not at the risk of the Council of the University of Southern Queensland, its Faculty of Health, Engineering & Sciences or the staff of the University of Southern Queensland.

This dissertation reports an educational exercise and has no purpose or validity beyond this exercise. The sole purpose of the course pair entitled "Research Project" is to contribute to the overall education within the student's chosen degree program. This document, the associated hardware, software, drawings, and other material set out in the associated appendices should not be used for any other purpose: if they are so used, it is entirely at the risk of the user.

Assoc Prof Kevin McDougall  
Head of School (Civil Engineering and Surveying)  
Faculty of Health, Engineering & Sciences

---

# Certification

I certify that the ideas, designs and experimental work, results, analysis and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in other course or institution, except where specifically stated.

Kari Kauko Juhani Hautsalo

Student Number: 0050100245

---

Signature

---

Date

---

## **Acknowledgements**

I would like to take this opportunity to thank the following people for their assistance with this paper.

My University of Southern Queensland project supervisor, Dr Dev Raj Paudyal, for providing me with the direction of this topic and writing this project report.

Gassman Development Perspectives Pty Ltd, for allowances made towards studies.

My family and colleagues, not only for this project but for all the years of studies.

---

---

# Contents

Abstract.....	i
University of Southern Queensland .....	i
Acknowledgements.....	ii
Contents .....	iii
List of figures.....	v
List of tables.....	vi
Glossary .....	vii
Chapter 1 Introduction .....	1
1.1 Project background .....	1
1.1.1 GNSS background information .....	1
1.1.2 Project context .....	3
1.2 Project aims and objectives.....	4
1.2.1 Project aims.....	4
1.2.2 Project objectives .....	4
1.3 Scope and assumptions of the project.....	4
1.4 Evaluation framework.....	5
1.5 Structure and outline of the report .....	6
1.6 Chapter summary .....	8
Chapter 2 Literature review .....	9
2.1 Introduction.....	9
2.2 The physical perspective.....	9
2.3 The application perspective .....	13
2.4 The control perspective.....	17
2.5 Australian perspective.....	18
2.6 Conclusions.....	18

---

---

Chapter 3 Methodology .....	20
3.1 Introduction.....	20
3.2 Methodology of evaluation .....	20
3.3 General framework for evaluation .....	22
3.4 Evaluation framework structure.....	22
3.5 Risk Assessment .....	23
3.6 Ethics.....	23
3.7 Conclusions.....	23
Chapter 4 Evaluation.....	24
4.1 Introduction.....	24
4.2 Evaluation of physical aspects .....	24
4.2.1 Frequency bands .....	24
4.2.2 Signal structures.....	27
4.2.3 Signal strengths.....	29
4.2.4 Availability .....	30
4.2.5 Orbital differences .....	33
4.2.6 Geographical differences .....	34
4.3 Evaluation of application aspects.....	38
4.3.1 Available services .....	38
4.3.2 Supporting systems .....	40
4.3.3 Virtual Reference Station systems .....	42
4.4 Evaluation of control aspects .....	43
4.5 Conclusions.....	43
Chapter 5 Discussion and Conclusions.....	45
5.1 Introduction.....	45
5.2 Reviewing assumptions .....	45
5.3 Discussion .....	46
5.4 Conclusions.....	46
References:.....	48
Chapter 6 Appendix A .....	A-1
Chapter 7 Appendix B .....	B-1

---

---

## List of figures

Figure 2-1: SBAS system coverage .....	14
Figure 2-2: OmniSTAR/FUGRO coverage .....	15
Figure 2-3: MGEX stations.....	16
Figure 2-4: MGEX stations with Galileo tracking capability.....	16
Figure 2-5: MGEX stations with BeiDou-2 tracking capability.....	16
Figure 2-6: FUGRO stations with Galileo and BeiDou-2 tracking capability.....	17
Figure 2-7: CONGO tracking stations .....	17
Figure 4-1: GNSS frequency band L1 .....	25
Figure 4-2: GNSS frequency band L2 .....	25
Figure 4-3: GNSS frequency band L5 .....	26
Figure 4-4: Galileo E1 spectrum.....	29
Figure 4-5: BeiDou-2 orbits.....	32
Figure 4-6: Tasmanian user's GPS, Galileo and BeiDou-2 sky view North-South.....	33
Figure 4-7: Tasmanian user's GLONASS sky view North-South .....	34
Figure 4-8: GPS control segment.....	35
Figure 4-9: GLONASS ground segment.....	35
Figure 4-10: SDCM reference stations in Russia .....	36
Figure 4-11: SDCM reference stations global .....	36
Figure 4-12: Galileo Ground Segment.....	36
Figure 4-13: Stations capable of BeiDou-2 tracking .....	37
Figure 4-14: BeiDou-2 IGSO SV's ephemeris data age in hours .....	38
Figure 4-15: BeiDou-2 MEO SV's ephemeris data age in hours.....	38
Figure 4-16: QZSS and IRNSS coverage and orbits .....	41
Figure 4-17: Augmentation systems .....	41

---



## List of tables

Table 1-1: Evaluation Framework .....	7
Table 4-1: Frequency bands of different GNSSs .....	27
Table 4-2: GNSS signals and received signal strength on Earth .....	31
Table 4-3: GNSS orbital information .....	31
Table 4-4: BeiDou GEO satellites .....	32
Table 4-5: BeiDou IGSO satellites .....	32
Table 4-6: GNSS support in Australia for GNSS .....	42
Table B-1: Performance credit ranking.....	B-2

---

## Glossary

BOC	Binary Offset Carrier
BPSK	Binary Phase Shift Keying
CBOC	Composite Binary Offset Carrier
CDMA	Code Division Multiple Access
CS	Commercial Service
EGNOS	European Geostationary Navigation Overlay Service
EU	European Union
FDMA	Frequency Division Multiple Access
GAGAN	GPS Aided GEO Augmented Navigation
GBAS	Ground Based Augmentation System
GEO	Geostationary Earth Orbit
GLONASS	GLObal NAVigation Satellite System
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GRAS	Ground-Based Regional Augmentation System
GRR	Galileo Ground Reference Receiver
GSS	Galileo Sensor Station
GSO	GeoSynchronous Orbit
HP	High Precision
ICD	Interface Control Document
ICG	International Committee on GNSS
IGSO	Inclined Geosynchronous Orbit
IOV	In-Orbit Validation
IRNSS	Indian Radio-Navigation Satellite System
ISRO	Indian Space and Research Organisation
MBOC	Multiplexed Binary Offset Carrier
MEO	Medium Earth Orbit
MSAS	MTSAT Spacebased Augmentation System

---

OS	Open Service
PPS	Precise Positioning Service
PRN	Pseudo Random Noise
PRS	Public Regulated Service
PSK	Phase Shift Keying
QPSM	Quadrature Product sub-carrier Modulation
QZSS	Quasi-Zenith Satellite System
RNSS	Regional Navigation Satellite Systems
SA	Select Availability
SAR	Search and Rescue
SARSAT	Search and Rescue Satellite Aided Tracking
SBAS	Satellite-Based Augmentation Systems
SIS	Signal In Space
SV	Space Vehicle
TCAR	Tri Carrier Ambiguity Resolution
US	United States
WAAS	Wide Area Augmentation System

---

# Chapter 1 Introduction

## 1.1 Project background

### 1.1.1 GNSS background information

The current GNSS systems have been developed to provide competing alternate Global Navigation Satellite Systems (GNSS), largely overlapping in functionality but with limiting factors built into them to maintain strong control over who is able to use the systems and at which level of accuracy. Some systems, such as the US GPS system and Russian GLONASS are fully operational in terms of available satellites, whereas European Galileo, Chinese BeiDou-2 Navigation Satellite System (BDS) (formerly known as Compass/BeiDou-2), Japanese Quasi-Zenith Satellite System and Indian Regional Navigational Satellite System (IRNSS) are in their respective development and implementation phases.

The Global Positioning System (GPS), developed by the US Department of Defence in 1973, was the first Global Satellite Navigation System in operation. It was designed to provide the US military with a space based positioning service more accurate than previous satellite based TRANSIT system, later developed into project NAVSTAR (Eissfeller et al. 2001) and accurate enough to be used in ballistic missile navigation in an era when the cold war between the United States and the Soviet Union reached a stage of perceived threat of nuclear war. For that reason the design parameters initially restricted GPS for military use only. After an incident involving a civilian airliner invading then Soviet Union territory and being shot down caused the US Government to release the GPS system to civilian use in the belief that better tools would have helped to avoid such an incident (Pellerin 2006). This civilian use was however limited by the exclusion of certain information from the data content. This was established through coding and encrypting part of the exclusive information and even introducing a deliberate

degrading of data, called "Selective Availability", which needed to be removed by a decoding packet to achieve nominal accuracy.

The same perceived heightened threat of a nuclear war prompted the Soviet Union to replace its accurate but slow TSYKLON submarine navigation system (Ristić et al. 2010). This marked in 1976 the start of Globalnaya Navigatsionnaya Sputnikovaya Sistema (GLONASS), which was under the jurisdiction of the Russian Aerospace Defence Forces. GLONASS also, like GPS, incorporates deliberate error generation in its high precision signal in order to deny civilian users, or the enemy, the more accurate GNSS service.

The European Union initially started to develop their GALILEO system as a commercial enterprise for civilian use in 1999 (Roberts 2011) After some creative marketing estimates, giving the project much greater return on investment than was realistic, were discovered erroneous the project was close to being abandoned. This was given further discouragement by the US opposing to the Galileo project due to resulting inability to deny accurate positioning service in times of conflict (Dawoud 2012). Ironically, this resulted in decision makers realising that they cannot rely on GPS or GLONASS due to them being potentially shut off at any time. In 2002 the Galileo project was agreed upon (Dawoud 2012) by the European Union to be established and run by the European Space Agency (ESA).

Similar to GPS and GLONASS, Galileo also has services with different levels of accuracy available. The high precision data services are not, however, offered based on military involvement but instead are driven by commercial agreements.

Chinese BeiDou-1 project was initiated by the Chinese Government in 1980. It was initially developed as a regional system for the Chinese Government (Dawoud 2012). It was different in concept to other GNSS systems in that it was based on geo-stationary satellites positioned to service East Asia and Oceania. China joined the Galileo project in 2004 (Hongwei et al. 2010) in order to gain influence in a global civilian GNSS with some considerable funding. Soon after, however, Chinese Government realised that Galileo was not developing in the

direction that China wanted (Dawoud 2012) and made a decision to develop BeiDou further and enter into commercial, civilian market with it.

The resulting Compass/BeiDou-2, later renamed BeiDou-2, still maintains its geostationary satellites but introduces additional satellites in the medium earth orbit planes making it an autonomous global navigation satellite system.

The Indian Regional Navigational Satellite System (IRNSS) and Japanese Quasi-Zenith Satellite System (QZSS) are Regional Navigational Satellite Systems (RNSS), which both operate autonomously and use existing GNSS systems to add functionality in operating in challenging urban environments and mountainous regions. They use geostationary satellites and inclined geosynchronous orbit (IGSO) satellites to distribute their augmentation data (Roberts 2011). RNSS systems do not however fall under the scope of this project.

### **1.1.2 Project context**

Common to all GNSS systems is that long standing procedures and traditions do not exist and much of the international guidelines are based on agreements between nations and their respective agencies of authority. The resulting allocations of frequencies and bandwidths have been contested at times and space vessels have even been launched to confirm said frequencies to some extent (Dawoud 2012).

The concept of global navigation satellite system has been implemented in relatively similar fashions by all system designers. They are based on having an accurate clock in the satellite and broadcasting of orbital information with a time stamp down to receivers. This project, Evaluation of the performance of different Global Satellite Navigation Systems (GNSS) for Australian GNSS users, will focus on different physical and application details and specifications to evaluate them in terms of practical relevance.

As stated earlier, some of the GNSS systems are operational and some in development and implementation phase. This will make empirical testing of each of them either very difficult or impossible using available resources.

The evaluation of GNSS systems includes how each provides a service to an Australian user. This includes topics like physical parameters of the signals, the geographical and orbital characteristics and availability. Furthermore it includes topics about services, integrated and external, and applications such as integration and customisation potential, global positioning services as well as distribution of reliability and availability of service. It also seeks to uncover any Governmental policies and guidelines that may be relevant to the use of a GNSS system in national legislature and regulations.

## **1.2 Project aims and objectives**

### **1.2.1 Project aims**

This project aims to find tangible differences in GNSS systems currently available and in planning from an Australian GNSS user point of view. It seeks to uncover aspects of design or physical characteristics that will differentiate between GNSS systems, in particular when used in Australia.

### **1.2.2 Project objectives**

The project objectives include:

- Gain understanding of systems by performing a literature review
- Research technical specifications for differences in GNSS systems
- Research geographical differences of GNSS systems
- Develop evaluation assumptions, methods and criteria
- Draw conclusions

## **1.3 Scope and assumptions of the project**

This project will evaluate information on systems and designs against an evaluation framework. It determines that framework based on published work on feature relevancies.

This project will assess information and outcomes of studies published previously with focus on the relevance of those results but will not seek to verify them.

The project is supported by field tests when appropriate to verify theories and confirm behaviour estimates in the Australian context.

Assumptions will be formulated to both limit the scope in the context of "Australian User" as well as overcome the issues with non-verifiable information, such as system features that are published but not implemented and therefore subject to scrutiny.

The evaluation framework from an Australian perspective will be restricted to the use of GNSS for positioning purposes with emphasis on the surveying discipline. Furthermore, the framework is limited to include features and technical differences of the GNSS systems that provide a basis for evolutionary applications and are likely to be exploited by the surveying discipline.

#### **1.4 Evaluation framework**

Evaluation framework provides a focus on the evaluation by giving it a scope of particular issues of importance, a set of goals or desired outcomes within those issues and a set of criteria in determining the level of comparative impact to the topic.

Due to the rapid changes in implementation progress of particularly Galileo and BeiDou, some aspects of evaluation will be speculative as to the interoperability status with augmentation systems.

Overall, assumptions have to be made about exclusive use of any given GNSS system:

- The nature of comparative evaluation demands that features of individual systems be assessed on their stand alone merits even if that exclusive use is unlikely.
- Assumptions regarding the adoption of various supported services will have to be made to include the use of potential relevant technical advantages, regardless of their commercial viability in surveying industry.
- The user will be able to use only one GNSS system.
- The features of GNSS systems are assessed as if operational.
- Receiver design will allow use of all features.



Table 1-1 depicts the elements of each evaluation areas:

- Physical; features of the signals and equipment as well as methods and physical means of signal transmission.
- Application; services and applications that the signals enable and support.
- Control; characteristics of the system administration and user authorisation.

These areas as well as identified indicators have been derived from the perceived focus in review literature.

## **1.5 Structure and outline of the report**

This report starts off with the introduction to the project and its historical background regarding its major area of focus to conceive the objective of the project.

That is followed by the review of significant perspectives expressed by industry experts in the area of GNSS features and their practical effects on real life surveying. Consequently the evaluation framework was determined to enable comparative assessment and evaluation.

A literature review was conducted to ascertain the nature and trends of research in the area of GNSS development and future outlook. This revealed features that are the most likely to contribute to finding details of the identified indicators of comparative excellence.

The data collection was performed along with the literature review resulting in outlining of the features and respective relative strengths and weaknesses of each GNSS as well as attempting to classify the quality of that data. An evaluation framework table of these strengths, weaknesses and qualities of the source of the data was formulated to lay out the final assessment of the different GNSS systems.

Finally, these results were discussed and conclusions drawn.

**Table 1-1: Evaluation Framework.**

Evaluation area	Identified Indicators	Desired status
Physical aspect	Frequency bands	<ul style="list-style-type: none"> <li>• Multiple bands support TCAR and MCAR</li> <li>• Receiver design friendly</li> <li>• Multipath mitigation</li> </ul>
	Signal structure	<ul style="list-style-type: none"> <li>• Receiver design friendly</li> <li>• Multipath mitigation characteristic</li> <li>• Tracking ability</li> </ul>
	Signal strengths	<ul style="list-style-type: none"> <li>• Strong signal helps in challenging environments</li> <li>• Strong signal improves fix time</li> </ul>
	Availability	<ul style="list-style-type: none"> <li>• Maximum usable satellites</li> </ul>
	Orbital differences	<ul style="list-style-type: none"> <li>• Inclination angle to support all of target area</li> </ul>
	Geographical differences	<ul style="list-style-type: none"> <li>• Designed to support target area</li> </ul>
Evaluation area	Identified Indicators	Desired status
Application aspect	Available services	<ul style="list-style-type: none"> <li>• Services available for more than basic navigation</li> <li>• Integration with other positioning methods to widen scope</li> <li>• Augmentation and quality of service message</li> <li>• Ionospheric correction delivery</li> </ul>
	Supporting systems	<ul style="list-style-type: none"> <li>• SBAS support</li> <li>• Global tracking service support</li> </ul>
	Virtual Reference Station systems	<ul style="list-style-type: none"> <li>• Supported platform for VRS (CORS)</li> </ul>
Evaluation area	Identified Indicators	Desired status
Control aspect	Reliability of access	<ul style="list-style-type: none"> <li>• Access not conditional</li> </ul>
	Guaranteed service	<ul style="list-style-type: none"> <li>• Service guaranteed</li> </ul>

## **1.6 Chapter summary**

This project seeks to, by means of research, find aspects of design, physical limitations or advantages that will provide a level of differentiation between current GNSS systems. It further seeks to quantify the practical consequences of those potential differences in the context of Australian GNSS user.

## Chapter 2 Literature review

### 2.1 Introduction

*"In the next few years, surveyors using high productivity, real-time kinematic (RTK) positioning and indeed all other precision positioning users will be faced with a barrage of new global navigation satellite system (GNSS) signals from GPS, GLONASS, GALILEO and possibly COMPASS/Beidou2 as well as Satellite Based Augmentation Systems (SBAS) signals and Regional Navigation Satellite Systems (RNSS). New receivers with enhanced capabilities will enter the market and the old days of choosing which colour GPS receiver will be replaced by a myriad of new considerations." (Roberts 2011, p1)*

In the wake of the realisation that the high precision services from systems like GPS and GLONASS will not be reliable in times of conflict many national instances have decided to secure their navigation needs by implementing alternative systems. This has been done either by introducing completely self-contained GNSS systems like Galileo and BeiDou-2 or by implementing additional resources to GPS and GLONASS base services to form Regional Navigation Satellite Systems (RNSS) or Space Based Augmentation Systems (SBAS).

To assess the differences and advantages or limitations between any two or more systems we need to gain understanding of the development of each system.

### 2.2 The physical perspective

The GPS system employs 24 active satellites in 6 unevenly distributed orbital planes with 4 satellites in each plane. This provides with a better coverage of the northern hemisphere. Each orbit is inclined at an angle of  $55^\circ$  to the astronomical

equatorial plane. The orbits are ellipses (Cojocaru et al. 2009) with small eccentricity ( $e \approx 0.003$ ) with flight path length of the flight path for each satellite is 26,560 km at an orbital radius of approximately 26,600 km and the travel time is 11h 58min (Ristić et al. 2010). This design aims at having always a minimum of 4 satellites visible at any location at any point in time.

The GPS system uses Code Division Multiple Access (CDMA) technique, where each and every satellite transmits the same two carrier bands (Lewandowski et al. 2009). The satellites initially transmitted Coarse/Acquisition (C/A) code signals on the L1 (1575.42 MHz) band and the P(Y or Precise) code on the L2 (1227.60 MHz) band (Eissfeller et al. 2001). After a modernization phase began in 2005 more bands were utilised, L1M and L2M for military use and L2C for a new civil signal (Eissfeller et al. 2001) as well as new L5 band signal (1176.45 MHz) (Roberts 2011). The clock accuracy is one of the most important factors in achieving positioning accuracy and Larson et al. state (2000) "*The formal error for the carrier-phase clock estimates are on the order of  $125 \times 10^{-12} s$* ". GPS system uses WGS-84 coordinate reference frame which closely resembles the International Terrestrial Reference Frame (ITRF) and GPS time (Chen et al. 2009).

The Russian GLONASS system is currently fully operational with 24 active satellites in 3 evenly distributed ( $120^\circ$ ) orbital planes. The 8 satellites in each plane are also evenly distributed in their circular orbits with radii equal to approximately 25,480 km, which implies an orbital period of 11h15m (sidereal time) and a flight altitude of around 19,100 km (Cojocaru et al. 2009). This arrangement guarantees 5 satellites visible at any location at any point in time.

First generation GLONASS system uses Frequency Division Multiple Access (FDMA) technique in which two individual carrier frequencies are assigned to each satellite, but the PRN-codes are the same for all satellites (Lewandowski et al. 2009). The GLONASS system operates on same L1 and L2 bands as GPS with L1 frequencies between 1602 and 1615.5 MHz and L2 frequencies between 1246 and 1256.5 MHz (Dawoud 2012). The latest development introduces Glonass-K1 satellites in 2012 with CDMA technique on new L3 band (1202.025 MHz) and later in 2013 the Glonass-K2 satellite brings CDMA to existing L1 band (Stupak

2010). The GLONASS satellites initially carried Caesium clocks with daily frequency stability of  $5 \times 10^{-13}$  (Eissfeller et al. 2001) but with second generation implementation these were replaced by rubidium clocks.

The GLONASS system uses ParametryZemli 1990 (PZ90) coordinate reference frame which also closely resembles the International Terrestrial Reference Frame (ITRF) and UTC (SU) time (Chen et al. 2009).

The Galileo will, when fully operational, consist of a constellation of 27 active satellites. These satellites are spaced around the plane in three circular medium earth orbits with radii equal to around 29,600km and inclination of  $56^\circ$  to the equatorial reference plane. They have an orbital period of 14 sidereal hours (Cojocar 2009). Galileo constellation guarantees that at any point on the earth, there will be at least 6 satellites in the view (Dawoud 2012). The combination of the orbital inclination and the flight altitude of the satellites will considerably increase the coverage of the Polar Regions (Cojocar 2009).

Galileo will transmit its ten navigation signals in the frequency ranges of 1164 - 1215 MHz (for E5a and E5b), 1215 - 1300 MHz (for E6) and 1559 - 1592 MHz (for E2-L1-E1). The E2-L1-E1 range includes the GPS frequency band L1. An additional frequency range of 1544.05-1545.15 MHz is defined as Search and Rescue (SAR) uplink as well as frequency range of 406.0-406.1 MHz as SAR downlink frequencies. All Galileo satellites will transmit using the same nominal frequency, utilising Code Division Multiple Access (CDMA) which is compatible with the GPS approach (Dawoud 2012).

The Galileo satellites generate its signals using passive hydrogen masers. It is very stable and its accuracy can be stated by saying it would lose only one second in three million years (ESA 2012). They also carry rubidium atomic frequency standards for backup. The stability of the rubidium clock using the same analogy indicates it would lose three seconds in one million years.

The Galileo system uses Galileo Terrestrial Reference Frame (GTRF) which is compatible with ITRF2005 and it uses Galileo system time (GST). GST start epoch is 00:00 UT on August 22nd 1999. At this epoch, GST shall be ahead of

---

UTC by 13 s and will not apply leap seconds. GST is therefore “aligned” to GPST (Dalporte 2009)

The Beidou-2 system will consist of 35 satellites including 5 geostationary orbit (GEO) satellites, 5 in highly inclined (55°) geosynchronous orbits (IGSO) and 24 medium Earth orbit (MEO) satellites. The 24 satellites will be evenly distributed, 45° separated in argument of latitude, in 3 orbital planes with an inclination angle of 55° (Chen et al. 2009). They will offer complete coverage of the globe orbiting flying at an altitude with semi-major axis of 27840km (Dawoud 2012).

As at June 2012, 4 of the 5 GEO satellites are operating whilst one has ceased transmitting, all 5 IGSO satellites are fully operational and can already be employed for standalone positioning in South East Asia and Oceania. The only MEO satellite in orbit, whilst still transmitting, has developed a clock problem and cannot be relied upon for positioning (Montenbruck et al. 2012). The MEO satellites have an orbital period of 12h50m. The BeiDou-2 signals are transmitted in three bands; B1 (Equivalent of Galileo E2) at 1,561.098MHz, B3 (Equivalent of Galileo E6) at 1,268.520MHz and B2 (Equivalent of Galileo E5b) at 1,207.140MHz. The signal division technique for BeiDou-2 is CDMA.

The primary frequency standard of the Compass/Bei-Dou-2 navigation payload is based on Rubidium clocks (Malette et al. 2010). For redundancy purposes, all satellites are equipped with clocks of different origin, except for COMPASS-M1, which builds exclusively on Chinese technology (Montenbruck et al. 2012). Frequency Stability according to Gao et al. (2011) is  $8.47 \times 10^{-15}$  over 7 days.

The BeiDou-2 system uses Beijing 1954 for its coordinate frame. The COMPASS/BeiDou system time (BDT) adopts the length of a second in international atomic time as its basic unit and uses the continuous counting method with ‘week’ and ‘second of the week’. BDT is broadcast in the navigation message files. The starting point of BDT is at 00:00 UTC Jan 1st, 2006, and there is no leap second in the BDT system (Gao et al. 2011).

## 2.3 The application perspective

The GPS system transmits its navigation message in two codes, the Coarse/Acquisition (C/A) providing Standard Positioning Service (SPS) and the encrypted Precise-code (P) providing Precise Positioning Service (PPS). Furthermore, a new M-code incorporating the Selective Denial spoofing technique of the C/A code is included (Ristić et al. 2010). Although there are many services to complement the GPS system, no additional services are included in the GPS system itself and for instance augmentation services are completely external to the GPS architecture (Rizos et al. 2005).

Glonass runs a similar system to GPS with Standard Precision Service (SP) and High Precision Service (HP) with C/A and P-codes respectively. Importantly, each service is run on both L1 and L2 bands allowing dual frequency receiver civilian use (Ristić et al. 2010).

The Galileo runs five different services (ESA 2011):

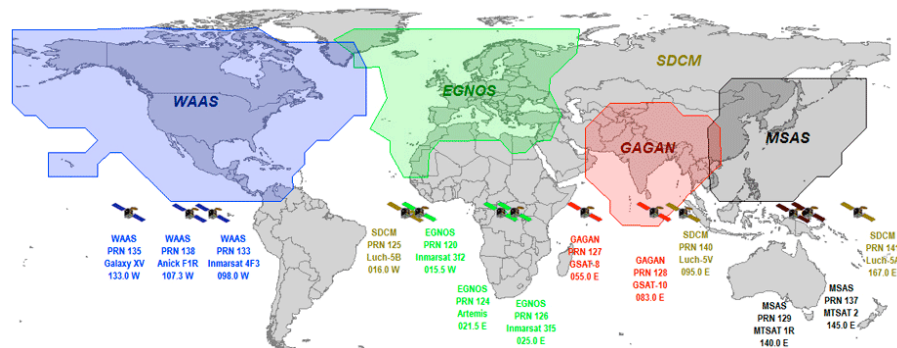
- Galileo Open Service (OS), open, free service with guaranteed accuracy but no quality or integrity information
- Galileo Commercial Service (CS), adds two encrypted and customer configurable signals to allow external service integration to CS
- Galileo Public Regulated Service (PRS) is an Access-Controlled service intended for law enforcement and government authorities of European Union offering improved continuity of service in the presence of interfering threats
- Galileo Safety of Life (SoL) contains signal integrity information at global level as opposed to other systems using SBAS to provide for integrity
- Galileo Search and Rescue Service (SAR/Galileo) provides SAR service via detection of Emergency Position Indicating Radio Beacons (EPIRBs) as well as via a return link from the SAR operator to the distress emitting beacon

BeiDou-2 supports both global worldwide services and regional services. Under the global services it offers Open Service similar to GPS and Authorized Service for Military use. Under the regional services users are provided with wide area



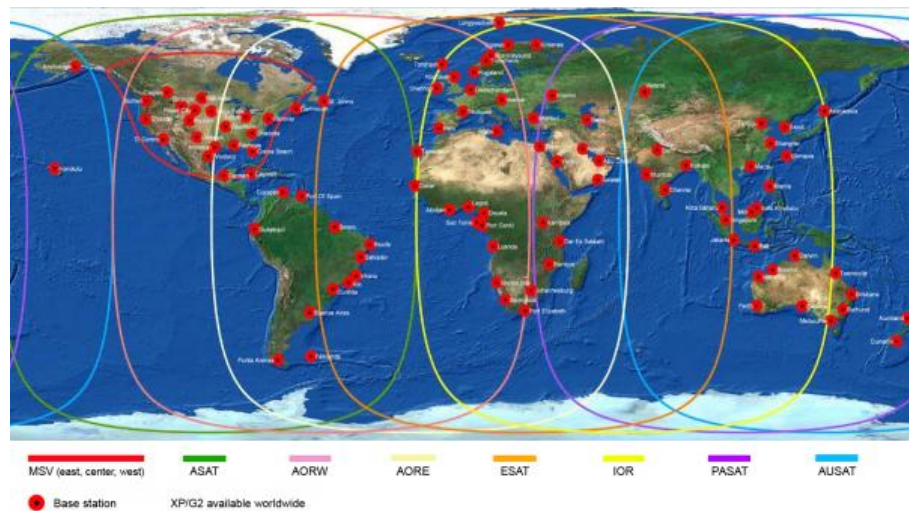
differential services including ionosphere grid data and intersystem time offsets (Montenbruck & Steigenberger 2013).

GNSS systems are widely supported and utilised by various commercial and non-commercial service providers. They are of both global and regional nature. Precise Point Positioning (PPP) service is an example of a global service where institutions around the world provide post processing of observation data gathered anywhere in the world, often free of charge, over the internet. Although it may be reasonable to expect that all systems will be supported at a later stage, according to Gakstatter (2013) the Australian AUSPOS PPP-service does not get a mention for support for other than GPS system, where most others are reported to include GLONASS data processing. No information was given on Galileo or BeiDou-2. Regional services include Space Based Augmentation Systems (SBAS) which although operate satellites, target specific regions of the globe. Figure 2-1 depicts coverage areas of some SBAS operations and although Australia is getting usable signals from MSAS and WAAS, it can be seen that coverage is not ideal for Australia.



**Figure 2-1: SBAS system coverage (GENEQ 2013).**

Commercial SBAS and Global Differential GPS service providers can operate more transmitting satellites, thus reaching wider areas for coverage. For instance OmniSTAR/FUGRO system covers virtually the complete globe as can be seen in Figure 2-1, along with locations of tracking stations. However Figure 2-6 shows that stations capable of tracking Galileo and BeiDou-2 is less densely populated.



**Figure 2-2: OmniSTAR/FUGRO coverage (OminSTAR 2013).**

Global tracking is also an aspect of support for a GNSS system. One of the purposes for global tracking is determination of inter-system biases (IGS 2013) and that implies tracking of all systems. The Multi-GNSS Experiment (MGEX) coverage map, Figure 2-3 below, depicts tracking stations around the world. Figure 2-4 and Figure 2-5 show stations capable of tracking Galileo and BeiDou-2 satellites respectively. Cooperative Network for GIOVE Observations (CONGO) is operated by Deutsches Zentrum für Luft- und Raumfahrt (DLR, The German Aerospace Center), Bundesamt für Kartographie und Geodäsie (BKG, The Federal Agency for Cartography and Geodesy), and Deutsches GeoForschungsZentrum (GFZ, German Research Centre for Geosciences). It provides tracking information for GIOVE satellites but some tracking stations also carry out tracking of GPS and GLONASS satellites. CONGO tracking stations are depicted in Figure 2-7 with GLONASS capable stations signified with red squares.

Virtual Reference Station systems, such as Continually Operating reference Station systems in Australia may or may not support other GNSS than GPS but literature is scarce with the smartnetaus twitter feed stating: "new Trimble firmware enables use of @smartnetaus CORS corrections with Glonass enabled units" (2013).



Figure 2-3: MGEX stations (IGS 2013).

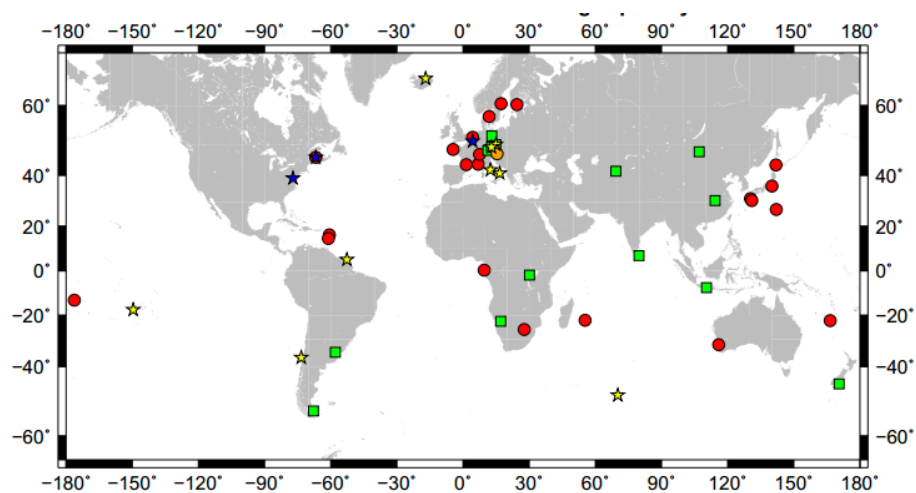


Figure 2-4: MGEX stations with Galileo tracking capability (Tegedor et al. 2013).

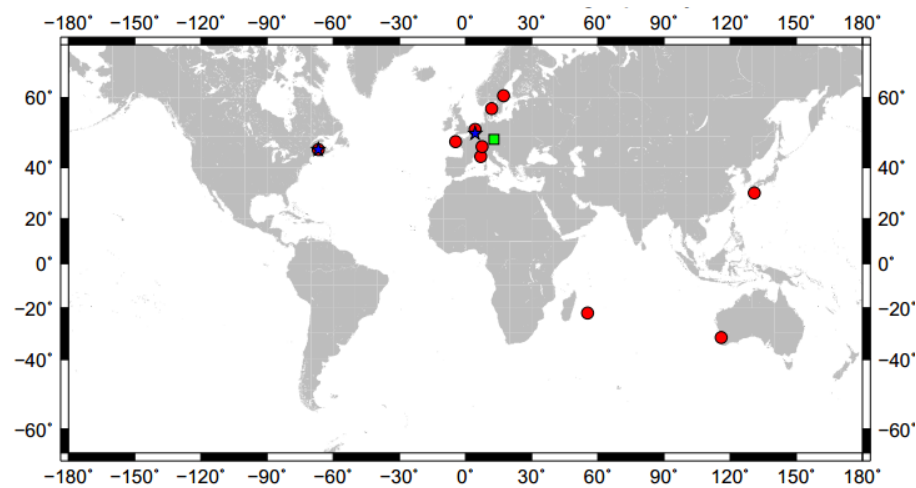
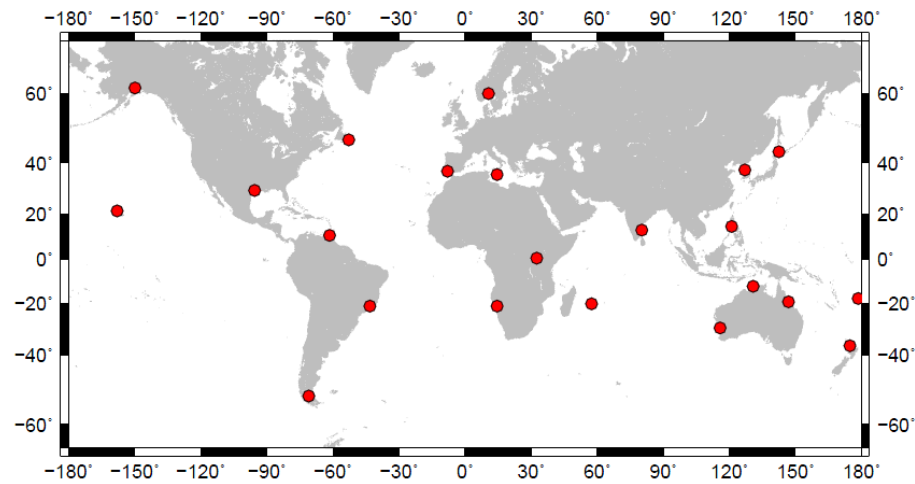
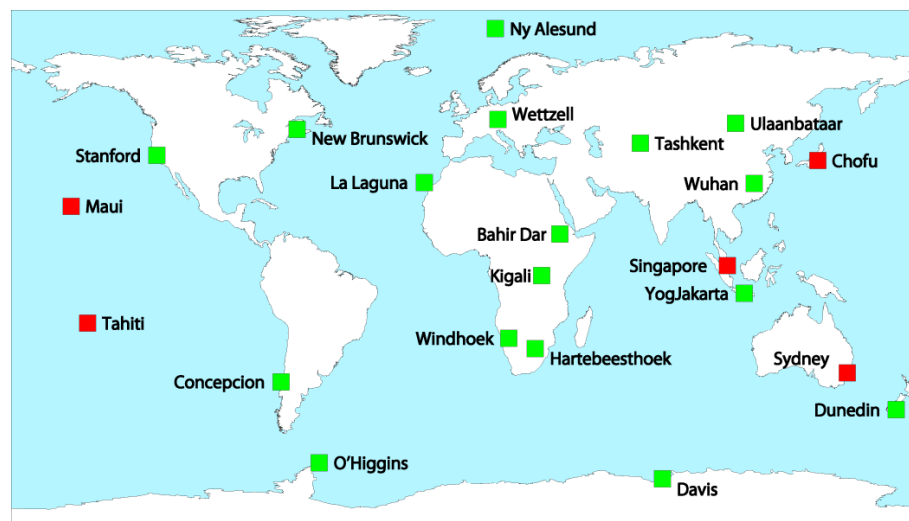


Figure 2-5: MGEX stations with BeiDou-2 tracking capability (Tegedor et al. 2013).



**Figure 2-6: FUGRO stations with Galileo and BeiDou-2 tracking capability (Tegedor et al. 2013).**



**Figure 2-7: CONGO tracking stations (TUM 2013)**

## 2.4 The control perspective

As Eissfeller et al. (2001) and Ristić et al. (2010) have stated GPS and GLONASS, respectively, have been developed with a sovereign military control. Dawoud (2012) mentions that BeiDou-2 is aimed at commercial markets whilst supremely run by the Government of China. Galileo on the other hand is a civilian enterprise (Roberts 2011) with dedicated services for Government use.

The previous statements imply, and in the case of GLONASS have been acknowledged, that service from a GNSS is not guaranteed, and indeed may be turned off at any time. This will have consequences in decision making for institutions which rely on un-interrupted reliable GNSS services.

## 2.5 Australian perspective

Literature about the impacts of different GNSS systems to Australian users seems focused on overall potential and real benefits provided by multiple GNSS systems employing new frequency bands. According to Roberts (2011), the new signals are more powerful and improve initialisation time in dual frequency RTK as well as suit Australian geographical location particularly well.

Reporting of benefits of an individual GNSS system over the others has been limited to outlining affiliations and partnerships between said GNSS and augmentation service providers such as the Japanese Quasi-Zenith Satellite system and the US WAAS supporting GPS whilst European EGNOS supports Galileo (Roberts 2011).

*"More signals however will mean a stronger solution as a result of improved dilution of precision and less likelihood of dropouts due to a lack of satellites. Australia is geographically well situated to benefit from the increase in new signals... Perhaps mission planning will become redundant" (Roberts 2011).*

From an Australian perspective the regional component of BeiDou-2 system offers advantages in improved availability and Geometry Dilution of Precision (GDOP), due to presence of additional, regional satellites, as well as availability of differential services (Chiang et al. 2010).

Literature about supporting services paint a picture of GPS-centric practice with some Glonass support as laid out in previous chapter covering application perspective.

## 2.6 Conclusions

The various systems use a multitude of frequency bands and coding systems but can operate in a compatible manner. Some of the current equipment can receive all signals but The US Department of Defence has stated that they will not support the legacy L1 (C/A) / L2 (P/Y) signals after 2020 which means that surveyors will have to upgrade to L2C or L5 capable equipment to guarantee high precision

performance (Roberts 2011). With GNSS systems still in development phase, BeiDou-2 is the only navigation satellite system offering a sufficient number of signals-in-space for continuous navigation in at least the Asia-Pacific region (Montenbruck et al. 2012).

## **Chapter 3 Methodology**

### **3.1 Introduction**

To ascertain how different characteristics of each GNSS system affect the Australian user the theoretical information is assessed to reveal any potential contributing factors. The prevailing profile of an Australian GNSS user needs to be clarified in terms of potential use of different navigation data available through the GNSS systems. A study of assessing this will be undertaken simultaneously with previous task due to likely overlapping of topics. Also a perspective of the professional GNSS bodies is outlined in this context.

The necessary field activities, if deemed useful given the availability of applications exploiting specific features is uncertain, were planned based on availability of equipment and necessary access to all GNSS information. As the information was gathered it became evident that field experiments would serve only a limited purpose due to two of the GNSS systems reviewed running in limited or test mode as well as, for testing probable differentiating features, an unrealistic need of resources such as experimental receivers and simulation equipment and software.

The project needed a methodology that could be implemented within the scope of the project, would fulfil the requirements of finding real and measurable differences and allow for the assumptions necessary to perform the evaluation.

### **3.2 Methodology of evaluation**

Given the limitations in access to real measurement data, some assumptions needed to be made. The task of formulating these, and any other, assumptions was required to both limit the scope and give the project a realistic context. This became the first step in the methodology of the project.

Assumptions made were:

- The Australian user is limited to one GNSS.
- The Australian user perspective was limited to surveying in Australia.
- All GNSS assessed are fully operational.
- Receiver technology does not pose any limitations.

The next step was to research literature for information that would contribute to identifying indicators that can be used in evaluating benefits and limitations of each GNSS, specifically from an Australian user's perspective. This was performed by researching papers from conferences and seminars for topics of special interest. This provided an insight into which areas of technology and applications the experts in the industry expected to be relevant when comparing the performance of each GNSS. Further research was conducted into thesis produced and reports on subjects that gave new evidence in theories and technological predictions. Furthermore, research was extended to international and national institutions and their work to gain understanding in the areas of compatibility and inter-operability of the GNSS. A list of identified indicators was compiled based on this research and will be put in a matrix for evaluation.

The data to be evaluated was gathered from previously mentioned literature research and no data collection from field experiments was performed.

Classifying the information by quality and by relevance was performed along with previous formulation of identified indicators. This was done by sorting the data into groups of:

- research on actual data and performance
- research on simulations of performance based on published data and known parameters
- research on theoretical implications of expected behaviour within known context

The relevance was derived to from weighting and emphasis given to various differentiators by experts in the field.



Evaluating the parameters against the evaluation framework was then performed to determine the effectual differences in the GNSS systems and the result of the evaluation, weighted by data classification, was formulated.

This was followed by review of the objectives and how the results contribute to achieving those objectives.

Review of assumptions was then overlaid to the results and objectives to identify any discrepancies as well as circular structures and multiplication of instances of weighting of results.

Finally, conclusions were formulated based on evaluation against the evaluation framework along with caveats regarding the objectivity of weightings.

### **3.3 General framework for evaluation**

The evaluation framework falls under 'competition benchmarking' (Stuedler & Kaufmann 2002). This means that rather than evaluate whether a system feature gives the best possible outcomes, an outline on how the outcome of that feature compares with other systems is given.

Historical review of evaluation frameworks reveals that an evaluation of GNSS systems is dominated by specific scenarios or the performance of combined GNSS systems. The evaluation framework for this project adheres to the competition benchmarking criterion but also looks at a broad range of topics.

The evaluation framework was chosen to provide a focus on the evaluation that reflects the needs of an Australian user. It was designed to focus on real outcomes and results of the various differentiating features and factors of each GNSS.

### **3.4 Evaluation framework structure**

The evaluation framework was given a structure that divides the topics into three categories based on the nature of those topics. The resulting categories, reflecting aspects of each, were physical, application and control. The physical aspect looks at features of the signals and equipment as well as methods and physical means of signal transmission. The application aspect considers what services and

applications each GNSS system enable and support. Finally, the control aspect looks at how the use of each GNSS system is governed and how that might affect decision making in Australia.

A matrix of identified indicators was built with ranking of features as well as rudimentary classification of the quality of the data collected. Quality was decided to be determined by the nature of study behind the data, real testing versus simulation or theoretical examination, as well as the consensus relating to the data amongst academics.

### **3.5 Risk Assessment**

Risk Assessment was performed on the basis that outside of everyday risks no specific risks were anticipated. The risk of consequences of misrepresentation of data and implied, unqualified recommendations was deemed to be low.

### **3.6 Ethics**

This project was not likely to encounter the topic of ethics either in its preparation and field work, nor its publication. The possible global political opinions of contributing literature were not relayed to the project output, nor were any offered by the author.

### **3.7 Conclusions**

As a conclusion, the methodology of evaluation is pragmatic and simplistic, with the aim of stating the outcomes in an un-ambiguous manner.

## Chapter 4 Evaluation

### 4.1 Introduction

Evaluating GNSS systems is about finding different features in each of them and assessing the impact they are likely to have on an Australian user. Many of the features impact same or similar aspect of the usability of a system. It was necessary to give the evaluation a structure that enabled evaluation to be divided into smaller entities that were logical and easy to understand. This resulted in division into physical, application and control aspects.

### 4.2 Evaluation of physical aspects

#### 4.2.1 Frequency bands

The various GNSS systems operate in the L - Band frequency range which sits between 1GHz and 2GHz. Figure 4-1, Figure 4-2 and Figure 4-3 show the distribution within that frequency range covering a number of different carriers and bandwidths. It is, however, fortunate from the receiver manufacturing point of view that they can be grouped to two bands. The first ranges from E5/L5 to E6 and the second from Compass L1 to Glonass G1. These two bands can be handled by a single receiver design. Using stacked patches in antenna design multiple bands can be received albeit with less gain and bandwidth (Dempster & Hewitson 2007).

This shared frequency range also lends itself to more interoperability of signals as well as manufacturers exploiting them all with mass produced devices. If anything, this seems to encourage multi-GNSS receivers, negating the need to choose between systems.

There are performance differences due to selection of carrier frequencies nevertheless. Three-carrier ambiguity resolution can be seen as an improvement to RTK baseline length for high accuracy surveying. With gap-bridging concept, TCAR uses two closely spaced (super-widelane) and two widely spaced (widelane) carrier frequencies to create virtual wavelengths and frequencies (Werner & Winkel 2003). These are then subjected to mathematical formulae along with first estimation of the satellite to receiver line-of-sight range from one code range measurement to obtain first a super-widelane and then widelane ambiguity fix.

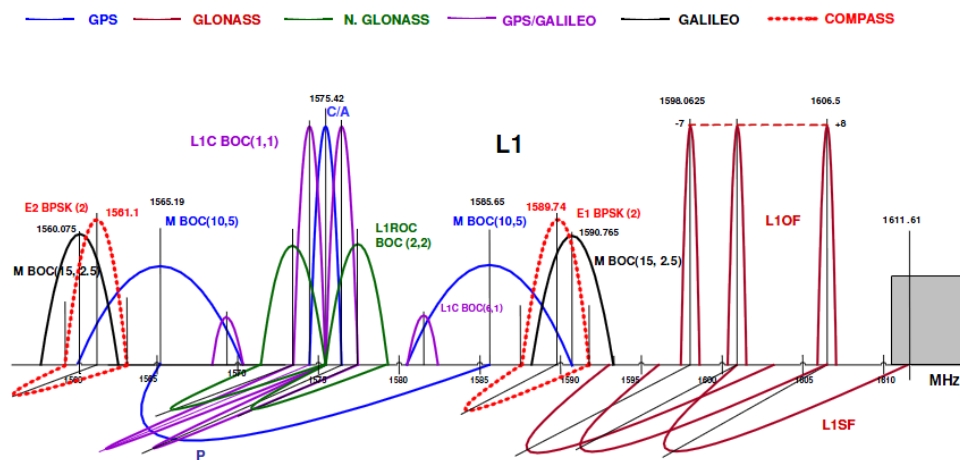


Figure 4-1: GNSS frequency band L1 (Stupak 2008)

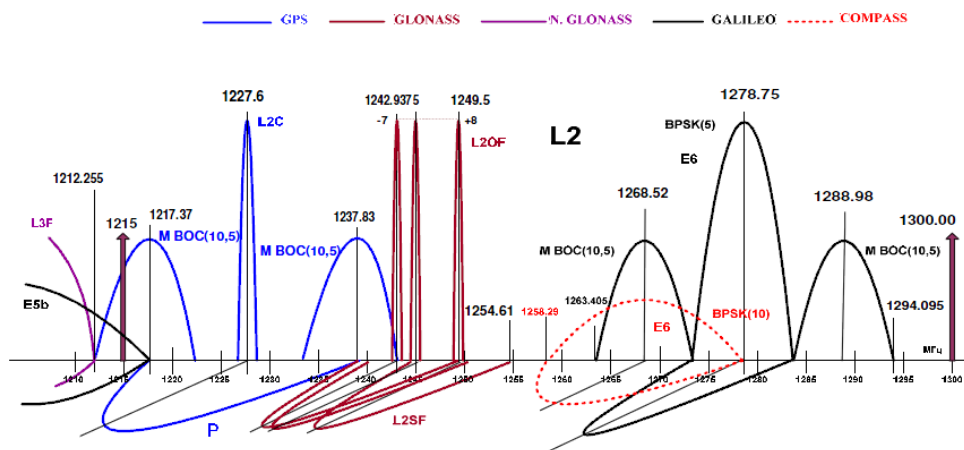
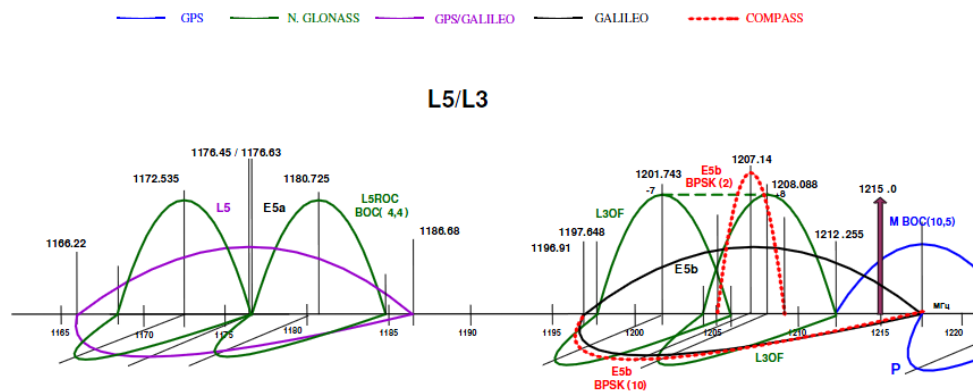


Figure 4-2: GNSS frequency band L2 (Stupak 2008)



**Figure 4-3: GNSS frequency band L5 (Stupak 2008)**

The separation of bands plays a part in the success rate of ambiguity resolution (AR). Werner and Winkel (2003) studied the theoretical AR success rate between GPS and Galileo systems and found that, of all possible band combinations and using specific set of assumptions regarding the signal structures, carrier-to-noise ratios and the multipath environment, using E5ab for code and base signal, E6-E5ab for Super-Widelane and L1-E5ab for Widelane yielded a 100% success rate overall. This compared favourably with GPS which only has three bands and therefore less potential combinations.

Werner and Winkel (2003) point out that "an important pre-condition for the performance of this algorithm is that there are no or only small multipath effects present, because otherwise, these systematic effects will destroy this 'gap-bridging' concept". This is likely to dilute the potential of TCAR, despite the lure of its distance independency, as a realistic alternative for other than wide open areas. Another limiting factor for TCAR is that at this time availability of mobile receivers capable of performing TCAR is to be announced.

In conclusion, all GNSS systems offer suitable frequency bands for current GNSS receivers. The lack of civilian signal in GPS L2 band has necessitated semi-codeless tracking development for receivers but this is a stable situation and should in fact disappear in the future. The Galileo enjoys an advantage in band distribution that enables better exploitation of some techniques, such as Tri Carrier Ambiguity Resolution (TCAR). The BeiDou-2 system lacks published information to formulate reliable conclusions but it shares the E6 band frequency with Galileo and may have an advantage in TCAR behaviour, see Table 4-1.

**Table 4-1: Frequency bands of different GNSSs (Rodríguez 2008).**

System	GPS	GLONASS	Galileo	Compass
Frequency Band	L1	L1	E1	B1
Centre Frequency	1575.42 MHz	1602 MHz	1575.42 MHz	1561.098 MHz (B1) 1589.742 MHz (B1-2)
Frequency Band	L2	L2	-	-
Centre Frequency	1227.60 MHz	1246 MHz	-	-
Frequency Band	L5	-	E5a	-
Centre Frequency	1176.45 MHz	-	1176.45 MHz	-
Frequency Band	-	-	E6	B3
Centre Frequency	-	-	1278.75 MHz	1268.52 MHz
Frequency Band	-	L3	E5b	B2
Centre Frequency	-	1201 MHz	1207.14 MHz	1207.14 MHz

#### 4.2.2 Signal structures

The signal structures of various GNSS systems vary substantially more than the frequencies. Three of the four GNSS, GPS, Galileo and BeiDou, use Code Division Multiple Access (CDMA) modulation to identify each space vehicle message within the broadcast stream. Glonass uses historically Frequency Division Multiple Access (FDMA) modulation (which is depicted as a group of frequencies in Figure 4-1), with each space vehicle allocated one out of 16 frequencies, thus providing identification to the control system. Even though there are 16 frequencies, the full constellation is planned to consist of 18 space vehicles (SV). This has been made possible by allocating same frequencies to antipodal SVs (Misra 2013). Glonass are modernising the SVs and is testing and will be implementing a CDMA method as well.

This distinction is historically due to FDMA providing (previously) better security protection thanks to the improved Spectral Separation Coefficient (SSC) of FDMA (Rodríguez 2008). This advantage has however vanished with improved security of CDMA via cross-correlation of the employed codes. Inclusion of FDMA will make receiver design more costly and move by Glonass towards use of CDMA is seen as part of their move to commercialising Glonass. From the user

---

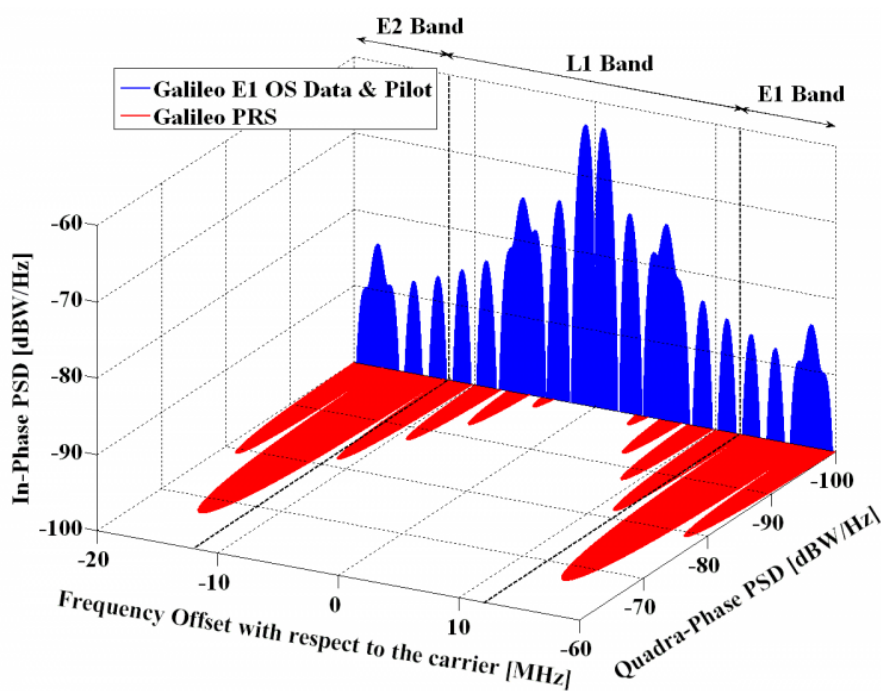
point of view, as long as receiver can decode both modulation methods, there is no practical difference.

Whilst the actual signal structures of different GNSS systems is beyond this report, some pieces of information can give insight into how they affect the user. The signal structure of each GNSS system contributes to some extent to the success of the tracking of the signal. For example, as Eissfeller et al. (2001) state, the navigation data in Galileo system is only modulated on the I-Component, leaving the Quadrature-Channel free of additional phase shifts (Galileo E1 In-Phase and Quadra-Phase channels can be seen in Figure 4-4). This leads to a coherent, i.e. more robust phase tracking at a lower Signal-to-Noise level.

Chipping rates (signal pulse rates) are to some extent decided with demands from the requirement for interoperability and legacy concerns between different GNSS systems in mind (Roberts 2011). The Galileo system, although free from compelling design restrictions, chose to make its E1-band compatible to GPS L1-band to enable use of legacy L1 receivers.

In general higher chipping rates are reported by each GNSS system literature to yield higher accuracy levels in positioning. To explain this Roberts (2011, p. 8) states: 'Chipping rate defines the resolution to which a raw measurement can be made. So the L5 (or E5) with a 10.23Mhz chipping rate will be a more precise measurement than the L1 C/A (or E1) at a 1.023Mhz rate'. He continues to add (citing Avila-Rodriguez et al, 2008; Dempster and Rizos, 2009) that higher chipping rates require more transmission power and more expensive receiver design.

With various Binary-Offset Modulation (BOC) types, however, spectral separation properties are reported to improve by lower chipping rates (Lohan et al. 2005). The main advantage of a BOC-modulated signal over binary phase shift keying (BPSK) signal is its spectral-shaping capability, which allows a good separation between old and new GPS and Galileo signals (Lohan et al. 2005). This is not however a point of difference since all four GNSS systems are either using or planning signals modulated by BOC and using similar chipping rates but may become a differentiator if receiver limitations exist in this respect.



**Figure 4-4: Galileo E1 spectrum, (Rodríguez 2011)**

In conclusion, signal structures lend themselves to various advantages in technique exploitation. Higher chipping rates are being introduced to all GNSS systems and Binary Offset Modulation in various forms is included in all GNSS systems, at least in some message types. The FDMA used by GLONASS no longer enjoys a security benefit due to the cross-correlation of codes modulated in CDMA. The FDMA modulation of some GLONASS SVs causes some cost burden towards receiver design. This has however stabilised with virtually every receiver manufacturer offering a product. The Quadrature-Channel, being free of additional phase shifts, leads to a coherent, i.e. more robust phase tracking at a lower Signal-to-Noise level and should prove a benefit.

#### 4.2.3 Signal strengths

Signal strengths for different GNSS systems reported by respective Interface Control Documents (ICD) are presented in User Received Power. See below in Table 4-2 the values compiled by de Bakker (2007) showing no significant differences between systems. The BeiDou data is not present in the table but the figures according to Rodríguez are -163dBW for all three bands B1, B2 and B3 (2011). As stated previously, signal structure may contribute to usability of signal and tracking characteristics in particular.



Table 4-2 shows also the improved user received signal power yielded by more powerful Galileo E5 and GPS L5 signals. This will improve the tracking of the signal in areas where obstacles hinder the reception (Roberts 2011).

GPS and Galileo are enjoying an advantage in received signal strength in L5 and E5-E6 bands respectively with a nominal difference.

#### **4.2.4 Availability**

GNSS availability is a concept that consists of the number and distribution of useful satellites, the required satellite elevations for a particular scenario and, with perhaps less significance, the potential authoritative control of the systems. In essence it means the percentage of time the signal is available to the receiver in any given scenario.

**Table 4-2: GNSS signals and received signal strength on Earth (de Bakker 2007)**

GNSS system	Signal	Centre frequency main lobe(s) (MHz)	Bandwidth main lobe(s) (MHz)	User received signal power (dBW)
GPS	L1 C/A	1575.42	2.046	-160 <sup>3</sup>
	L1 P	1575.42	20.46	-163 <sup>3</sup>
	L2 C/A	1226.60	2.046	-166 <sup>3</sup>
	L2 P	1227.60	20.46	-166 <sup>3</sup>
	L5	1176.45	20.46	-157.9 <sup>3</sup>
Galileo	L1A	1560.075 1590.765 <sup>1</sup>	5.115	-157 <sup>4</sup>
	L1BC-P	1574.397 1576.443 <sup>1</sup>	2.046	-160 <sup>4</sup>
	L1BC-D	1574.397 1576.443 <sup>1</sup>	2.046	-160 <sup>4</sup>
	E5a-P	1176.45	20.46	-158 <sup>4</sup>
	E5a-D	1176.45	20.46	-158 <sup>4</sup>
	E5b-P	1207.14	20.46	-158 <sup>4</sup>
	E5b-D	1207.14	20.46	-158 <sup>4</sup>
	E5AltBoc P	1176.45 1207.14 <sup>1</sup>	20.46	-155 <sup>4</sup>
	E6A	1268.52 1288.98 <sup>1</sup>	10.23	-155 <sup>4</sup>
	E6BC-P	1278.75	10.23	-158 <sup>4</sup>
E6BC-D	1278.75	10.23	-158 <sup>4</sup>	
GLONASS	L1 standard accuracy	1602.56- 1615.50 <sup>2</sup>	1.022	-161 <sup>3</sup>
	L1 high accuracy	1602.56- 1615.50 <sup>2</sup>	10.22	-161 <sup>3</sup>
	L2 standard accuracy	1240.00- 1269.00 <sup>2</sup>	1.022	-167 <sup>3</sup>
	L2 high accuracy	1240.00- 1269.00 <sup>2</sup>	10.22	-167 <sup>3</sup>

3. Minimum received power with a 3dBi gain linearly polarized antenna for a satellite with a minimum of 5 degrees elevation.

4. Minimum received power with a 0dBi gain ideally matched antenna for a satellite with a minimum of 10 degrees elevation.

**Table 4-3: GNSS orbital information, source Chen et al. (2009)**

	GPS	GLONASS	Galileo	BeiDou (MEO)
Number of SV	31	24	27	27
Orbital planes	6	3	3	3
Inclination	55°	64.8°	56°	55°

Table 4-3 above outlines the basic orbital characteristics of each GNSS (in case of BeiDou, the Medium Earth Orbit (MEO) satellite component). BeiDou also has 5 Geostationary Satellites positioned strategically in the region (see Table 4-4) and 3 Inclined Geosynchronous Orbit (IGSO) satellites (see Table 4-5).

**Table 4-4: BeiDou GEO satellites, source Chen et al. (2009)**

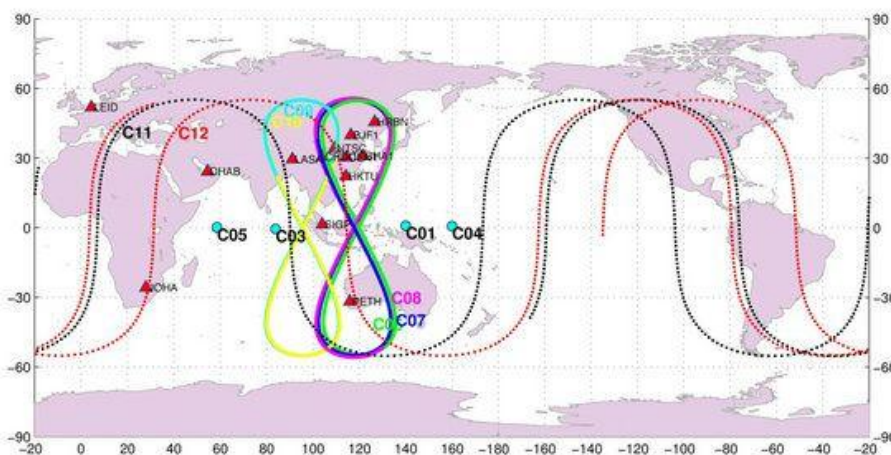
Satellite	Launch Date	Position
BeiDou-1A	31-Oct-2000	140°E
BeiDou-1B	21-Dec-2000	80°E
BeiDou-1C	25-May-2003	110.5°E
BeiDou-1D	3-Feb-2007	58.75°E
BeiDou-1E	TBD	160°E

**Table 4-5: BeiDou IGSO satellites, source Chen et al. (2009)**

Semi-major Axis [Km]	42164
Inclination [Deg]	55
Eccentricity	0
RAAN	0°, 120°, 240°
Argument of perigee	187.6°, 67.6°, 307.6°

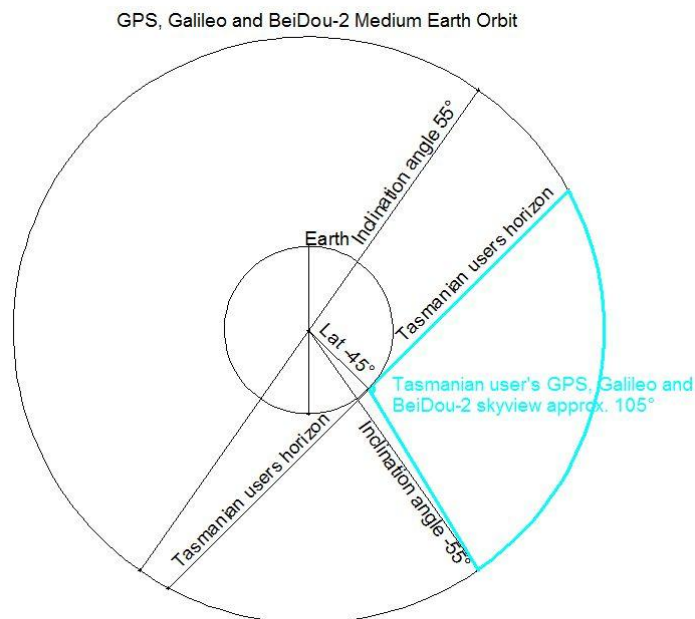
From an Australian user's perspective availability is determined by available satellites in Australian sky. This varies according to the number of satellites as stated above and their orbits.

BeiDou-2 enjoys a particular advantage in having a regional component to it. This, in the form of satellites in Geo Stationary (GEO) and Inclined Geo Synchronous (IGSO) orbits provide significant increase in total available satellite in areas where those are visible. As can be seen from Figure 4-5, Australia is very conveniently situated to get almost full benefit from them, thus adding up to 8 satellites to sky view to complement the Medium Earth Orbit (MEO) satellites in view.

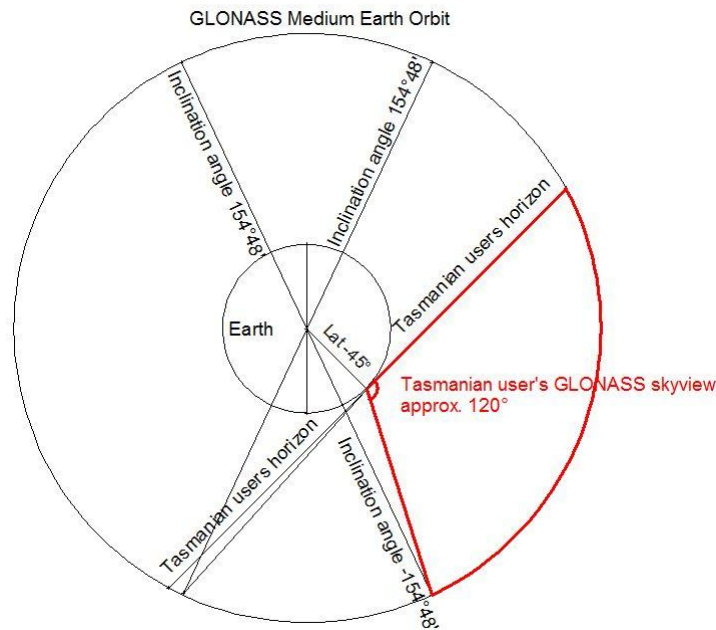
**Figure 4-5: BeiDou-2 orbits (He et al. 2013)**

#### 4.2.5 Orbital differences

Users in higher latitude areas, such as areas in the North of Canada, Alaska, Europe, Russia as well as Antarctica, even Southern parts of Australia to some extent, obtain better GLONASS availability and consequently better derived dilution of precision (DoP) than users of GPS, Galileo or BeiDou-2 (Eissfeller et al. 2001). This is due to the high inclination angle of GLONASS; 64.8 degrees compared to 55 degrees for GPS and BeiDou-2 as well as 56 degrees for Galileo. This will obviously affect an Australian user depending on the latitude they are in. For GPS, Galileo and BeiDou-2 a user slightly south of Tasmania, at latitude -45 degrees, would be able to observe satellites all the way to northward masking angle of, say, 10 degrees but would be subjected to a de facto southward masking angle of approximately 76 degrees and the north-south sky view is approximately 105 degrees (see Figure 4-6). Using GLONASS the scenario changes so that the de facto southward masking angle is approximately 63 degrees and the north-south sky view is approximately 120 degrees (see Figure 4-7).



**Figure 4-6: Tasmanian user's GPS, Galileo and BeiDou-2 sky view North-South**



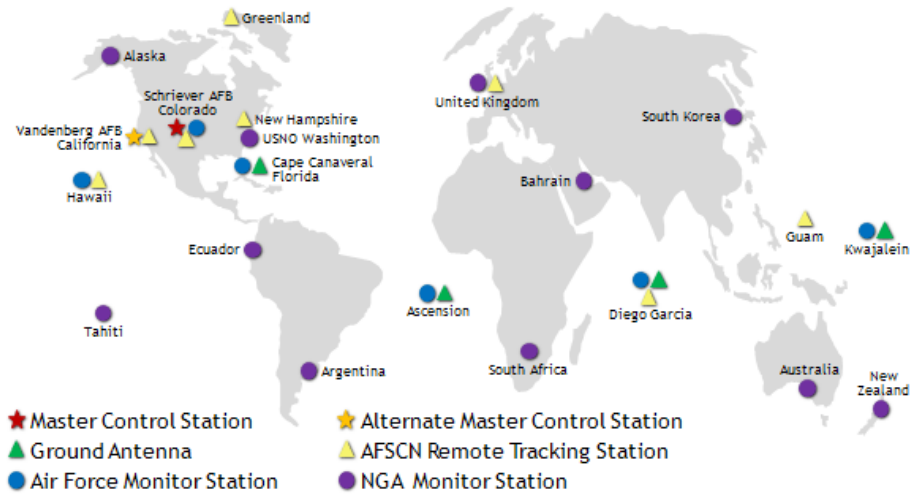
**Figure 4-7: Tasmanian user's GLONASS sky view North-South**

#### 4.2.6 Geographical differences

Geographically, the focus of each GNSS system has been in the areas of controlling bodies, North America for GPS, Russian Federation for GLONASS, Europe for Galileo and China for BeiDou-2. This is evident in the distribution of control stations.

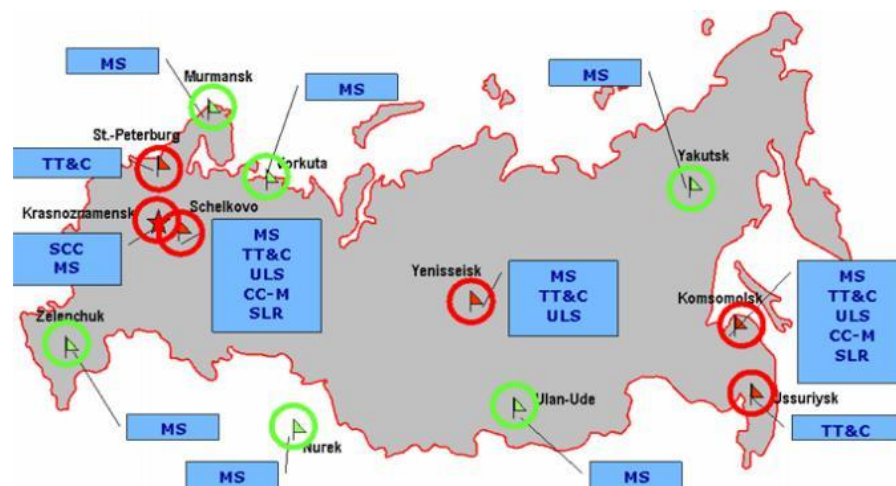
The GPS control segment, depicted in Figure 4-8, is distributed well around the globe and the Ground Antennas, green triangles in the map, enable continuous data and update upload capability. In general the GPS service is available all around the globe with Australia enjoying the full geographical advantage.

The GLONASS system has all its ground control stations in Russian mainland, see Figure 4-9, although the differential service aligned with GLONASS, System of Differential Correction and Monitoring (SDCM) has monitoring stations in neighbouring, ex USSR countries, Ukraine and Kazakhstan as well as planned reference stations all around the globe, one of which is in Sydney, see Figure 4-10 and Figure 4-11.



**Figure 4-8: GPS control segment (NCO 2013)**

The Galileo ground segment consists of two Galileo Control Centres (GCCs), located at Fucino (Italy) and Oberpfaffenhofen (Germany) five telemetry, tracking and control stations, 10 uplink stations (ULSs), and up to 40 Galileo Sensor Stations (GSSs). The ULSs transmit navigation signals to the satellites and the GSSs receive the navigation signal from the constellation for transmission to the GCCs (Telespazio 2010). The coverage is worldwide with Noumea the nearest location to Australia, see Figure 4-12.



**Figure 4-9: GLONASS ground segment (ESA 2013)**

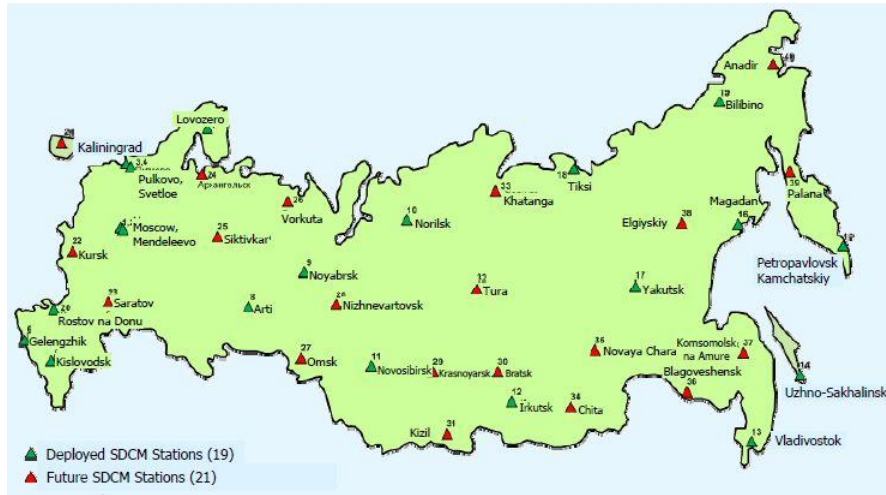


Figure 4-10: SDCM reference stations in Russia (Stupak 2012)

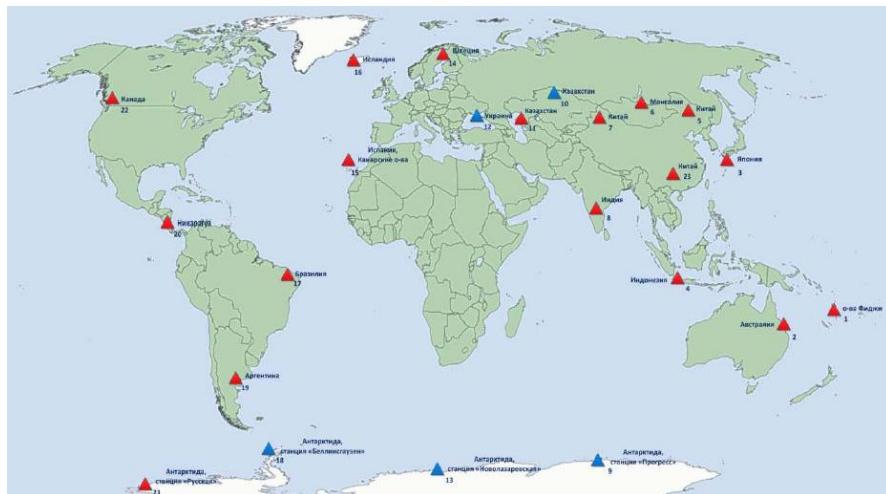
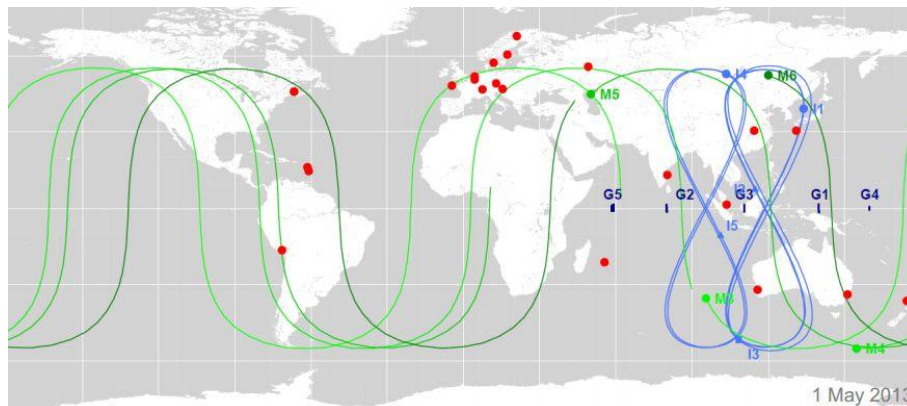


Figure 4-11: SDCM reference stations global (Stupak 2012)



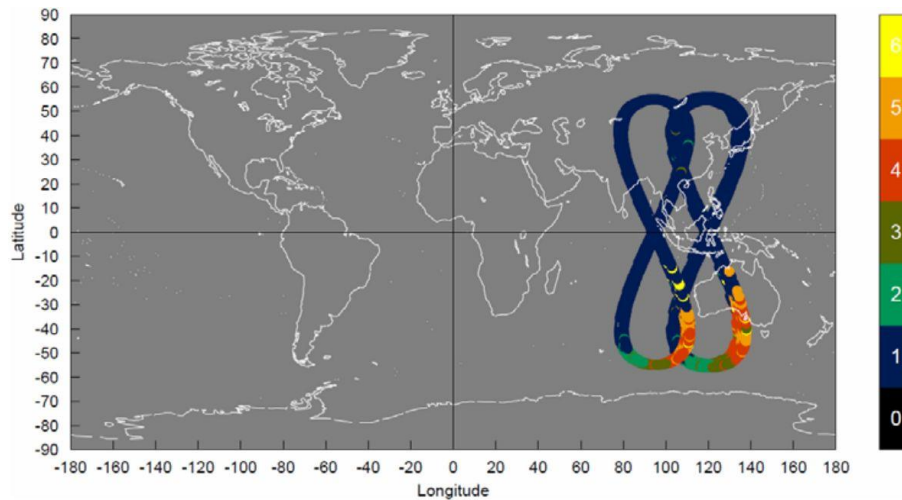
Figure 4-12: Galileo Ground Segment (Telespazio 2010)

The BeiDou-2 ground segment consists of one Master Control Station, two Upload Stations and 30 Monitor Stations. The locations are believed to be in mainland China, although, as BeiDou-2 capable tracking is performed by MGEX and CONGO (Montenbruck et al. 2013), see Figure 4-13. Australia is not only in with two tracking stations, but benefits from the contributions of the IGSO and GEO satellites of the regional component. A minor disadvantage compared to northern parts of the IGSO orbits stem from the fact that satellite ephemeris data gets updated when a satellite is in range of the control stations on Chinese mainland and therefore the issue-of-data-ephemeris parameter (IODE), measured in hours, is up to 6 hours old when that same satellite services Australian skies (see Figure 4-14). As can be seen in Figure 4-15, this characteristic of data updates from mainland China control stations affects the MEO satellites as well, even more so, with IODE values between 8 and 23 hours from the Americas to Indian subcontinent on the satellites journey eastward, until they reach the range of update centres.

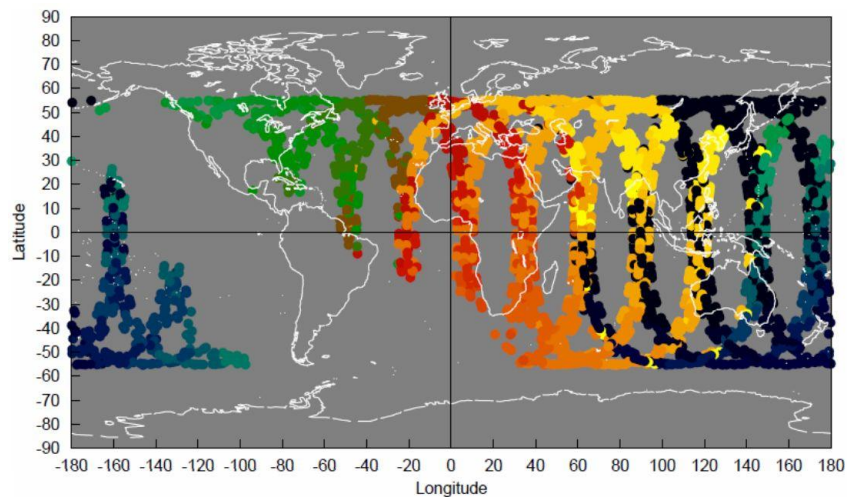


**Figure 4-13: Stations capable of BeiDou-2 tracking**





**Figure 4-14: BeiDou-2 IGSO SV's ephemeris data age in hours (Montenbruck & Steigenberger 2013)**



**Figure 4-15: BeiDou-2 MEO SV's ephemeris data age in hours (Montenbruck & Steigenberger 2013)**

## 4.3 Evaluation of application aspects

### 4.3.1 Available services

The basic function of a GNSS system is to provide navigation data to the GNSS user via a receiver. This is done via the navigation signal within the broadcast signal from the GNSS Space Vehicle.

The GPS system transmits its navigation message in two codes, the Coarse/Acquisition (C/A) providing Standard Positioning Service (SPS) and the encrypted Precise-code (P) providing Precise Positioning Service (PPS). The Precise-code on L2-band has only encrypted navigation message for military use

making it P(Y) and cannot be used on its own in a dual frequency scenario. This has been overcome by employing semi-codeless tracking techniques, which is not a feature of the GPS system. Furthermore, a new M-code incorporating the Selective Denial spoofing technique of the C/A-code is included (Ristić et al. 2010).

Glonass also has Standard Precision Service (SP) and High Precision Service (HP) with C/A and P-codes respectively. Each service is included on both L1 and L2 bands allowing dual frequency receiver civilian use (Ristić et al. 2010). The P-code navigation message has never been published but instead was distributed to the scientific community making the P-code fully available. This was apparently done to reserve the right to change code at will at any time (ESA 2011).

The Galileo runs five different services:

- Galileo Open Service (OS), open, free service with guaranteed accuracy but no quality or integrity information (ESA 2011).
- Galileo Commercial Service (CS), adds two encrypted and customer configurable signals to allow external service integration to CS (ESA 2011).
- Galileo Public Regulated Service (PRS) is an Access-Controlled service intended for law enforcement and government authorities of European Union offering improved continuity of service in the presence of interfering threats (ESA 2011).
- Galileo Safety of Life (SoL) contains signal integrity information at global level as opposed to other systems using SBAS to provide for integrity
- Galileo Search and Rescue Service (SAR/Galileo) provides SAR service via detection of Emergency Position Indicating Radio Beacons (EPIRBs) as well as via a return link from the SAR operator to the distress emitting beacon (ESA 2011).

BeiDou-2 supports both global worldwide services and regional services. Under the global services it offers Open Service similar to GPS and Authorized Service for Military use. Under the regional services users are provided with wide area differential services including global ionosphere grid data and intersystem time offsets (Montenbruck & Steigenberger 2013).

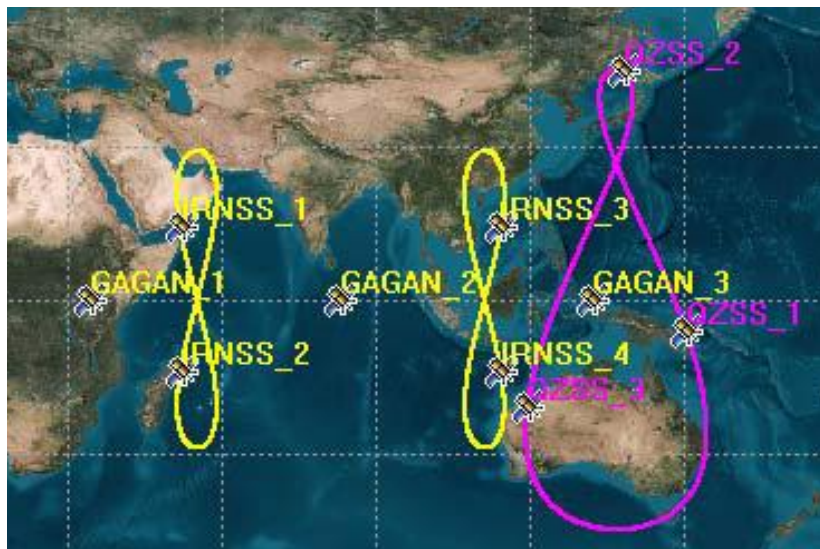
As a conclusion, and regardless of the common use of external services, The Galileo is the most attractive proposition for particularly applications where user has additional services to integrate to the Commercial Service signal. This could implementation of networks of different technologies combined with GNSS signals.

BeiDou-2 has both global worldwide services and regional services. Under the global services it offers Open Service similar to GPS and Authorized Service for Military use. Under the regional services users are provided with wide area differential services including ionosphere grid data and intersystem time offsets (Montenbruck & Steigenberger 2013). The China Satellite Navigation Office has been slow to publish navigation message content and the BeiDou Navigation Satellite System Signal In Space Interface Control Document Open Service Signal B1I (Version 1.0) was published only in late 2012.

#### **4.3.2 Supporting systems**

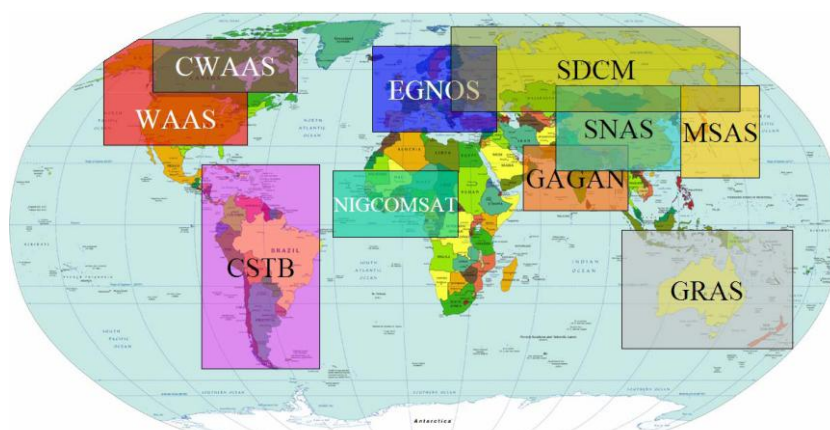
Regional Navigation Satellite Systems (RNSS) use existing GNSS systems and add to the satellite fleet using GEO satellites targeting regional areas, thus giving more available satellites and better urban area performance. Figure 4-16 shows that Australia is well within the operating area of the Japanese Quasi Zenith Satellite System (QZSS) as well as the Indian IRNSS (Rodríguez 2008). The QZSS is highly compatible with GPS, whilst the IRNSS seeks to be compatible with all GNSS systems. In reality it is a matter of receiver technology to be able to utilise these signals so no advantage or disadvantage can be given to any GNSS.

A Satellite Based Augmentation System (SBAS) is a system that provides augmentation of any GNSS in a region by using GEO satellites. Another augmentation system is Ground Based Augmentation System (GBAS). Typically GBAS could be for flight approach systems to complement other approach system as in the case of the planned Australian Ground-based Regional Augmentation System (GRAS) which provides service to the Australian continent (Rodríguez 2008). GBAS transmits augmentation data from ground stations in the same frequency bands as the GNSS itself.



**Figure 4-16: QZSS and IRNSS coverage and orbits (Rodríguez 2008).**

Figure 4-17 shows the target areas for some SBAS systems as well as GRAS, but it is worth noting that the Australian user can receive signals from satellites that service areas far away. Because the augmentation data is optimised for the target area, the quality of those services is questionable in Australia. Table 4-6 shows the respective GNSS support of the SBAS systems with GPS clearly most supported with GLONASS and BeiDou-2 and even Galileo, through Russian SDCM, also supported. Future plans for SBAS systems stated on their respective websites did not reveal any changes to the above.



**Figure 4-17: Augmentation systems (Rodríguez 2008)**

**Table 4-6: GNSS support in Australia for GNSS (Rodríguez 2008).**

SBAS	GPS	GLONASS	Galileo	BeiDou-2	Aust cover
Wide Area Augmentation System (WAAS)	<input checked="" type="checkbox"/>				
European Geostationary Navigation Overlay Service (EGNOS)	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/> *	<input checked="" type="checkbox"/> *		
Chinese Satellite Navigation Augmentation System (SNAS)				<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
MTSAT Space-based Augmentation System (MSAS)	<input checked="" type="checkbox"/>				<input checked="" type="checkbox"/>
System of Differential Correction and Monitoring (SDCM)	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>		<input checked="" type="checkbox"/>
GPS and GEO Augmented Navigation system (GAGAN)	<input checked="" type="checkbox"/>				<input checked="" type="checkbox"/>
Nigerian Communications Satellite System (NIGCOMSAT)	<input checked="" type="checkbox"/>				
Canadian Wide Area Augmentation System (CWAAS)	<input checked="" type="checkbox"/>				
South American Satellite Augmentation System (CSTB)	<input checked="" type="checkbox"/>				

\*according to Wikipedia but not EGNOS or others

Global tracking systems are predominantly trying to include all GNSS systems in their service with an increasing number of stations with receiving capabilities of GNSS systems other than GPS, which is the dominant GNSS. No differentiators to be found in that area.

Post-processing services are also clearly moving towards multi-GNSS support but for the moment GPS is the default system with GLONASS support available with some but according to Gakstatter (2013) the Australian AUSPOS PPP-service does not get a mention for support for other than GPS system.

### 4.3.3 Virtual Reference Station systems

The Virtual Reference Station systems are providing differential positioning services in real time and in Australia SmartnetAUS has stated: "new Trimble firmware enables use of @smartnetaus CORS corrections with Glonass enabled units" (2013). The NSW CORS network is not making a mention of support for any other GNSS than GPS.

#### 4.4 Evaluation of control aspects

*"The GLONASS P-code never was published by the system operators, but it was made known to the scientific community. This means, the GLONASS P-code is fully available. However, along with the P-code not being published by the system operators, it neither was officially released for use outside the Russian Armed Forces. Instead, they reserve the right to alter the code in future."*(ESA 2011)

This statement is typical description of a GNSS system developed under the premise of military threats, real or perceived, controlling governmental decision making.

In short, Galileo is the only GNSS controlled by civilians, the European Union. In times of conflict the choice of GNSS may come under some regret if the system shuts down, or more realistically the US employs the M-code to deny GPS signals from anyone else.

In Australia, individuals make their own choice of GNSS and carry the consequences in case of service denial and have no real material to use for evaluating that risk.

Director of Aviation Safety, on behalf of The Australian the Civil Aviation Safety Authority (CASA), has made an instrument under regulations 174A and 179A of the Civil Aviation Regulations 1988 (CAR 1988) as Instructions — use of Global Navigation Satellite System (GNSS) (CASA 2012). It makes a mention of GPS but not any other GNSS system. Whether this implies an alignment to GPS or not, or is just pragmatic about the dominance and current availability of GPS is not clear.

#### 4.5 Conclusions

Each GNSS has strengths and weaknesses, but an effort had to be made to rank them. Table B-1 in Appendix B, ranks the GNSS systems according to identified indicators of difference, weighted, perhaps subjectively, by quality and relevance.

It seems reasonable to put a heavier weight on features and outcomes that help the surveyor in his/her work as well as contribute towards making it easier to use GNSS with higher accuracy in surveying work. History has shown, on the other hand, that even though technology progresses to resolve issues of accuracy and ease of use quickly, the foundation of sustainable progress lies in openness and collaboration. Thus the future is undoubtedly in the path that Galileo is going.

## Chapter 5 Discussion and Conclusions

### 5.1 Introduction

This project sought to evaluate the available GNSS systems from an Australian user's perspective. To get an understanding of the potential factors contributing to the benefit of one GNSS over another, some literature research was necessary. This resulted in a vast array of aspects that would need to be processed and assumptions were made to limit the scope of the project. A sub-research about what an Australian GNSS user might appreciate most was conducted along the main task of literature review and related data collection.

An evaluation framework was also needed and the author decided to formulate his own based on views expressed in literature about GNSS in relation to surveying.

The conclusions are somewhat subjective without empirical data on user preferences and the matrix of performance credits is limited as in being more a discussion provoker than absolute ranking method.

### 5.2 Reviewing assumptions

- The Australian user is limited to one GNSS.
  - This may be unlikely due to receivers capable of multi-GNSS operation but conceivable nevertheless.
  - Enables relevant comparative assessment.
- The Australian user perspective was limited to surveying in Australia.
  - Necessary to limit the scope of the project.
- All GNSS assessed are fully operational.
  - Enables relevant comparative assessment and reflects the likely scenario in the near future



- No indications found that any GNSS would be halting progress.
- Receiver technology does not pose any limitations.
  - This is market driven and is limited only by cost.
  - Cost of equipment is not within the scope of the project.

### **5.3 Discussion**

Although these assumptions were made, the scenarios assessed are relatively realistic and even likely. The trend towards multi-GNSS is prevalent and expressed by prominent authorities within each GNSS organisation but they each still are and are seen to strive for better systems, better the other GNSS. The differences are in some cases small, even marginal. For instance, the real impact of signal strength is difficult to ascertain, with literature avoiding the voicing out of real tangible results and preferences.

Some differences, on the other hand, are significant and in the final ranking of performance credits may not get the weight they deserve due to lack of confidence from the author.

Data collected for the project is from numerous scholarly as well as commercial sources over a relatively long time, considering the concept is relatively new and progress is made rapidly and continuously. The data has taken new shapes as the concepts expressed mature and clarification is provided. Therefore the possibility of existence and reporting of conflicting data is real.

The features assessed as significant contributors to the results are subject to constant change and support from external or additional sources and may lose their significance accordingly. So even though each GNSS is judged as finalised, some aspects were needed to be judged by the current status.

### **5.4 Conclusions**

In terms of achieving project objectives, the project sought to gain understanding and to find if there are differences between the four GNSS systems that would have practical impacts on the work of an Australian user. The answer is yes, even though differences are changing by the day.

In general, GNSS systems are headed to more compatibility and interoperability. Superiority and advantages in an area or other are ebbing and flowing from one system to another but it was rather surprising to realise that the fate of the GNSS future is in the hand of soldiers with scenarios of threat painted to justify decisions to keep the *crème de la crème* in GNSS technology away from public use.

The result of the evaluation is laid out in the matrix in Table B-1 but that is heavily distorted by the dominance of GPS in the market. More interestingly, Galileo seems to be hitting the targets in terms of services and applications people want, BeiDou-2 has promise in particular in our region and GLONASS is desperately seeking partners in its future plans for augmentation.

## References:

Avila-Rodriguez, J, Hein, G, Wallner, S, Issler, J, Ries, L, Lestarquit, L, de Latour, A, Godet, J, Bastide, F, Pratt, T, & Owen, J 2008, 'The MBOC Modulation: The Final Touch to the Galileo Frequency and Signal Plan', *NAVIGATION*, vol. 55, no. 1, pp. 14-28.

de Bakker, PF 2007, 'Effects of Radio Frequency Interference on GNSS Receiver Output ', Masters Thesis, Delft University of Technology Faculty of Aerospace Engineering, Delft University of Technology, The Netherlands.

Chen, H-C, Huang, Y-S, Chiang, K-W, Yang, M, & Rau, RJ 2009, 'THE PERFORMANCE COMPARISON BETWEEN GPS AND BeiDou-2/COMPASS: A PERSPECTIVE FROM ASIA', *Journal of the Chinese Institute of Engineers*, vol. 32, no. 5, pp. 679-689.

Cojocaru, S 2009, 'GPS-GLONASS-GALILEO: A Dynamical Comparison', *The Journal of Navigation*, vol. 62, pp. 135–150, The Royal Institute of Navigation.

Dalporte, J 2009, 'The Definition and Implementation of Galileo System Time (GST)', *Proceedings of ICG-4 WG-D on GNSS time scales*, United Nations Office for Outer Space Affairs.

Dawoud, S, 'GNSS principles and comparison', Potsdam University, Potsdam, [http://www.snet.tu-berlin.de/fileadmin/fg220/courses/WS1112/snet-project/gnss-principles-and-comparison\\_dawoud.pdf](http://www.snet.tu-berlin.de/fileadmin/fg220/courses/WS1112/snet-project/gnss-principles-and-comparison_dawoud.pdf).

Dempster, AG & Hewitson, S 2007, 'The “System of Systems” receiver: An Australian opportunity?', paper to be presented at IGNSS2007 Symposium on GPS/GNSS, 4-6 December 2007, Sydney, Australia.

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

---

Eissfeller, B, Ameres, G, Kropp, V, Sanroma, D 2001, *Performance of GPS, GLONASS and Galileo*, University of Stuttgart, viewed 28 May 2013.

Gakstatter, E 2013, A Comparison of Free GPS Online Post-Processing Services, report, 7 October, GPS World, North Coast Media LLC, viewed 16 October 2013, <<http://gpsworld.com/a-comparison-of-free-gps-online-post-processing-services>>.

Gao, W, Jiao, W, Xiao, Y, Wang, M & Yuan, H 2011, 'An Evaluation of the Beidou Time System (BDT)', *The Journal of Navigation*, vol. 64, pp. 31-39, The Royal Institute of Navigation.

He, L, Maorong, G, Wang, J, Wickert, J, & Schuh, H 2013, 'Experimental Study on the Precise Orbit Determination of the BeiDou Navigation Satellite System', *Sensors*, vol. 13, Issue 3, 1 March 2013, pp. 2911-2928.

Hongwei, S, Haibo, Y, Hong, Z 2010 'The impact of navigation satellite ephemeris error on common-view time transfer', *Ultrasonics, Ferroelectrics and Frequency Control*, vol.57, January 2010, pp 151-153.

Larson, KM, Levine, J, Nelson, LM & Parker, TE 2000, 'Assessment of GPS Carrier-Phase Stability for Time-Transfer Applications', *Proceedings of the IEEE Trans Ultrason Ferroelectr Freq Control 2000*, vol.47(2), pp. 484-94.

Lewandowski, W, Jiang, Z 2009, 'USE OF GLONASS AT THE BIPM', presentation to be presented at the 41st Annual Precise Time and Time Interval (PTTI) Meeting, 16 - 19 November 2009, Santa Ana Pueblo, New Mexico, USA.

Lohan, ES, Lakhzouri, A & Renfors, M 2005, 'Benefits of using lower chip rates for Galileo OS and PRS signals', *ENC-GNSS 2005*, Munich, Germany.

Malette, LA, White, J & Rochat, P 2010, 'Space qualified frequency sources (clocks) for current and future GNSS applications', *Proceedings of Position location and navigation symposium (PLANS)*, IEEE/ION, 4-6 May 2010, Indian Wells, CA, USA, pp. 903-908.

Misra, P 2013, 'Multi-GNSS Future: GPS, GLONASS, Galileo, BeiDou, ...', lecture to be presented at Sogei Workshop, GNSS Technology Advances in a Multi-Constellation Framework, April 22-23, Rome, 2013.

Montenbruck, O & Steigenberger, P 2013, 'The BeiDou Navigation Message' paper to be presented at International Global Navigation Satellite Systems Society IGNSS Symposium, 16-18 July 2013, Gold Coast, Qld, Australia.

Montenbruck, O, Steigenberger, P, Hauschild, A 2013, 'From China with Love – The BeiDou Navigation System ', presentation to be presented at the Satellite Navigation Seminar, 14 May 2013, Munich, Germany.

Montenbruck, O, Hauschild, A, Steigenberger, P, Hugentobler, U, Teunissen, P & Nakamura, S 2012, 'Initial assessment of the COMPASS/BeiDou-2 regional navigation satellite system', published online, Springer.

Pellerin, C 2006, *United States Updates Global Positioning System Technology*, media release, 03 February 2006, U.S. Department of State, viewed 28 May 2013, <<http://www.america.gov/st/washfile-english/2006/February/20060203125928lcnirellep0.5061609.html>>.

Ristić, A, Govedarica, M, Petrovački, D 2010, 'GNSS – Status and Perspective', *Journal on Processing and Energy in Agriculture*, vol. 14, 2010, pp. 6-10.

Rizos, C, Higgins, M, Hewitson, S 2005, 'New GNSS Developments and their Impact on Survey Service Providers and Surveyors', paper to be presented at SSC2005 Spatial Intelligence, Innovation and Praxis: The national biennial Conference of the Spatial Sciences Institute, September 2005, Melbourne.

Rodríguez, J 2008, 'On Generalized Signal Waveforms for Satellite Navigation', Doctoral Thesis, FAF University of Munich, Munich.

——— 2011, GALILEO Signal Plan, European Space Agency Navipedia, viewed 8 September 2013, <[http://www.navipedia.net/index.php/GALILEO\\_Signal\\_Plan](http://www.navipedia.net/index.php/GALILEO_Signal_Plan)>.

Roberts, C 2011, 'How will all the new GNSS signals help RTK surveyors?', *Proceedings of the SPATIAL SCIENCES & SURVEYING BIENNIAL CONFERENCE 2011*, 21-25 November 2011, Wellington, New Zealand, pp. 40-51.

Stuedler, D & Kaufmann, J 2002, *Benchmarking Cadastral System*, International Federation of Surveyors FIG, Denmark.

Stupak, G 2010, 'GLONASS status and development plans', presentation to be presented at the 5th Meeting of the International Committee on GNSS, presentation, Turin, Italy, 18 – 22 October 2010.

—— 2012, 'SDCM status and plans', presentation to be presented at the Seventh Meeting of the International Committee on Global Navigation Satellite Systems, 4 – 9 November 2012, Beijing, China.

Tegedor, J, Melgard, T, Øvstedal, O & Vigen, E 2013, 'Multi-constellation Precise Point Positioning including GPS, Glonass, Galileo and BeiDou', presentation to be presented at GNSS Precise Point Positioning Workshop: Reaching Full Potential, 12-14 June 2013, Ottawa, Canada.

Werner, W & Winkel, J 2003, 'TCAR and MCAR Options With Galileo and GPS', *Proceedings of 16th Tech. Meeting of the Satellite Div. of the U.S. Institute of Navigation*, Portland, Oregon, 9-11 September 2003, pp.790-800.

Yates, G 2013, Grant Yates: twitter feed, viewed 16 October 2013, <<https://twitter.com/smartnetaus>>.

CASA 356/12 - Instructions - use of Global Navigation Satellite System (GNSS) - F2012L02141, (instrument under regulations 174A and 179A of the Civil Aviation Regulations 1988) 2012 (Director of Aviation Safety, on behalf of CASA).

*Control Segment* 2013, National Coordination Office (NCO) for Space-Based Positioning, Navigation, and Timing, Washington, D.C. USA, viewed 17 October 2013, <<http://www.gps.gov/systems/gps/control/>>.

*COoperative Network for GIOVE Observations (CONGO)* 2013, Technische Universität München, Munich, Germany, viewed 17 October 2013, <<http://www.iapg.bv.tum.de/190749-bD1lbg~iapg~forschung~gnss~congo.html>>.

*DGNSS Services* 2012, OmniSTAR brochure, OmniSTAR, Leidschendam, The Netherlands, viewed 16 October 2013, <[http://www.omnistar.com/Portals/0/downloads/brochures/DGNSS%20Service%20UK%20A4-spread%20\(3-5-2012\)%20Web.pdf](http://www.omnistar.com/Portals/0/downloads/brochures/DGNSS%20Service%20UK%20A4-spread%20(3-5-2012)%20Web.pdf)>.

*GALILEO CONTROL CENTRE* 2012, Telespazio brochure, Telespazio, Rome, Italy, viewed 17 October 2013, <[http://www.telespazio.com/docs/brodoc/GCC\\_eng.pdf](http://www.telespazio.com/docs/brodoc/GCC_eng.pdf)>.

*Galileo Terrestrial Reference Frame* 2012, ESA, Prague, Czech Republic, viewed 28 May 2013, <<http://www.oosa.unvienna.org/pdf/icg/2012/template/GTRF.pdf>>.

*GLONASS Ground Segment* 2012, ESA, Czech Republic, viewed 17 October 2013, <[http://www.navipedia.net/index.php/GLONASS\\_Ground\\_Segment](http://www.navipedia.net/index.php/GLONASS_Ground_Segment)>.

*How the Galileo atomic clocks work* 2012, ESA, Czech Republic, viewed 28 May 2013, <[http://www.esa.int/Our\\_Activities/Navigation/How\\_the\\_Galileo\\_atomic\\_clocks\\_work](http://www.esa.int/Our_Activities/Navigation/How_the_Galileo_atomic_clocks_work)>.

*SBAS Made Easy* 2013, GENEQ Inc, Montréal, Canada, viewed 16 October 2013, <<http://sxbluegps.com/technology/sbas-made-easy/>>.

## Appendix A

# Project Specification



**University of Southern Queensland**

Faculty of Engineering and Surveying

## **ENG4111/4112 Research Project - Project Specification**

**For:** Kari Hautsalo

**Topic:** Evaluation of the performance of different Global Satellite Navigation Systems (GNSS) for Australian GNSS users.

**Supervisor:** Dr Dev Raj Paudyal

**Project Aim:** To evaluate the accuracy, reliability and performance of GNSS using GPS, Glonass, Galileo and Beidou respectively for Australian GNSS users.

**Sponsorship:** Gassman Development Perspectives

**Programme:** Issue B, 21<sup>th</sup> April 2013

1. Study the differences in principle in respective GNSS systems.
2. Study the different evaluation frameworks in spatial science domain.
3. Develop a methodology to quantify performance differences in different GNSS systems.
4. Perform evaluation and review methods.
5. Formulate conclusions.

Supplementary TBA  
programme:

Agreed:

\_\_\_\_\_ (Student)

\_\_\_\_\_ (Supervisor)

\_\_\_/\_\_\_/\_\_\_

\_\_\_/\_\_\_/\_\_\_

## Appendix B

# Performance credit ranking

**Table B-1: Performance credit ranking**

Legend			False	Significant	True	Confident	Inconclusive			
Evaluation area	Identified Indicators	Desired status	GPS	GLONASS	Galileo	BeiDou-2				
			Performance Credit	Data Quality	Performance Credit	Data Quality	Performance Credit	Data Quality		
Physical aspect	Frequency bands	Multiple bands support TCAR and MCAR	Significant	Confident	Significant	Confident	Significant	Inconclusive		
		Receiver design friendly	True	Confident	Significant	Confident	True	Confident		
		Multipath mitigation	Significant	Inconclusive	Significant	Inconclusive	True	Inconclusive		
	Signal structure	Receiver design friendly	Significant	Confident	Inconclusive	Inconclusive	Significant	Confident	Confident	
		Multipath mitigation characteristic	Significant	Inconclusive	Significant	Inconclusive	True	Inconclusive	Inconclusive	
		Tracking ability	Significant	Inconclusive	Significant	Inconclusive	True	Inconclusive	Inconclusive	
	Signal strengths	Strong signal helps in challenging environments	True	Inconclusive	Significant	Inconclusive	True	Inconclusive	Inconclusive	
	Availability	Maximum usable satellites	Significant	Confident	Significant	Confident	True	Confident	Confident	
	Orbital differences	Inclination angle to support all of target area	Significant	Confident	True	Confident	Significant	Confident	Confident	
Geographical differences	Designed to support target area	Significant	Confident	Inconclusive	Confident	Significant	Confident	Confident		
Evaluation area	Identified Indicators	Desired status								
Application aspect	Available services	Services available additional to navigation	Inconclusive	Confident	Inconclusive	Confident	Significant	Confident	Confident	
		Integration with other technologies	Inconclusive	Confident	Inconclusive	Confident	True	Confident	Inconclusive	
		Quality of service message	Inconclusive	Confident	Inconclusive	Confident	Inconclusive	True	Confident	
		Differential service	Inconclusive	Confident	Inconclusive	Confident	Inconclusive	True	Confident	
		Ionospheric correction delivery	Inconclusive	Confident	Inconclusive	Confident	Inconclusive	True	Confident	
	Supporting systems	SBAS support	True	Confident	Significant	Confident	Significant	Confident	Significant	Confident
		Global tracking service support	Inconclusive	Confident	Significant	Confident	Significant	Confident	Significant	Confident
Virtual Reference Station	Supported platform for VRS (CORS)	True	Confident	Inconclusive	Confident	Inconclusive	Confident	Inconclusive		
Evaluation area	Identified Indicators	Desired status								
Control aspect	Reliability of access	Access not conditional	Inconclusive	Confident	Inconclusive	Confident	True	Confident	Inconclusive	
	Guaranteed service	Service guaranteed	Inconclusive	Confident	Inconclusive	Confident	True	Confident	Confident	
<b>Overall suitable</b>			Significant	Inconclusive	Significant	Inconclusive	True	Inconclusive	Inconclusive	