Platform Technologies for Space Atmosphere and Climate – A Benchmark Geospatial Project from the Australian Space Research Program

Kefei Zhang, Suqin Wu, Jizhang Sang, Robert Norman, Brett Carter, James Bennett

SPACE Research Centre,
School of Mathematical and Geospatial Sciences, RMIT University, GPO Box 2476
Tel: +61-3-9925 3272; Fax: +61-3-96632516;
Email: kefei.zhang@rmit.edu.au

Abstract. The multi-million-dollar Australian Space Research Program (ASRP) Project – "Platform Technologies for Space Atmosphere and Climate" was awarded to a consortium led by RMIT University in 2010. This benchmark geospatial research forms an important part of the Australian Government's recent space-related initiatives to support national strategic, economic and social objectives, and its aim is to enhance Australia's space capabilities by developing integrated and advanced space-based platform technologies through a multi-sensor satellite remote sensing approach.

In this contribution, the main objectives, primary research tasks, roadmap, work packages and anticipated outcomes for this project are introduced. The key issues and challenges confronting Australian space research and space industry are discussed, particularly those research tasks in the context of next-generation GNSS and their innovative applications in the areas of space weather, weather and climate, space situational awareness, positioning, navigation and timing (PNT) are emphasised. The key results and progress achieved so far in the areas of PNT, space-geodesy-based atmosphere remote sensing and atmosphere modelling, climate change, space weather and environment etc., are briefly reported.

Keywords: GPS/GNSS, space tracking, atmospheric sounding, space situational awareness.

Biography: Professor Kefei Zhang is Director of the SPACE Research Centre, RMIT University and he is the chief scientist of the ASRP project and leads a number of major Australian initiatives in the areas of algorithm development and new applications of frontier geospatial technologies. Dr Suqin Wu, Dr Brett Carter and Dr Robert Norman are research fellows at the SPACE Centre, RMIT University and their expertise areas are in GPS precise positioning, ionospheric scintillation and GPS signal ray tracing, respectively. Dr Jizhang Sang is Manager and Principal Research Engineer at EOSSS and he leads space situational awareness related research, in particular space debris tracking and laser-based space surveillance systems. Dr James Bennett is a research fellow at the SPACE Research Centre, RMIT University and is based at EOS Space Systems in Canberra. His expertise is in applied mathematics and orbit determination and prediction.

1. INTRODUCTION

In 2009, The Department of Innovation, Industry Science and Research (DIISR) in response to the 2008 Senate enquiry about the Australian capability in space, established the Space Policy Unit (SPU) as a core contract government unit to coordinate Australian space activities. $40 million was then allocated by SPU/DIISR to create the Australian Space Research Program (ASRP) Scheme to support space-related research, education and innovation activities through a competitive, merit-based funding program. The primary objectives of ASRP were to develop Australia's niche space capabilities by supporting space-related research, innovation and skills in areas of national significance or excellence. The program provided two types of grants: Stream A and Stream B. Stream A is for Space Education Development grants, and Stream B for Space Science and Innovation Project grants, which support collaborative space research and innovation projects involving the development of Australia's niche space capability in areas of strategic national priority. The ASRP grants support projects and link relevant Australian public and private research and development organisations with industry and international space agencies and organisations. For the Stream B grants, eligible consortia must comprise at least one university or research organisation and at least one industry partner. Eligible projects may include many research areas, such as development of application software and support systems for mapping, analysis, tracking and monitoring purposes from space-based information; development of new applications software or satellite payloads to gain an improved understanding of strategic issues, e.g. climate change; governance arrangements to support the operation of satellites such as the development, facilitation or participation in international fora on mitigating space debris (Australian Space Research Program, 2012).

To keep up with the pace of advanced international research and to play a leading role in the space-related research arena, an international research consortium led RMIT University was formed that involves major space players in Australia and selected

* Review Paper – accepted after double-blind review.
ISBN: 978-0-9872527-1-5
Melbourne: Geospatial Sciences, RMIT 2012

overseas space organisations. As one of the three projects funded (out of ~35 proposals) in the first round of the ASRP program, a three-year $7.5 million Platform Technologies project entitled "Platform Technologies for Space, Atmosphere and Climate" was awarded. The consortium consists of RMIT University, the University of New South Wales (UNSW), Curtin University of Technology (CUT), Bureau of Meteorology (BoM), Electro Optic Systems Space System (EOSSS), GPSat Systems Australia (GSA), NOAA's World Data Center for Meteorology (WDCM), USA and National Space Organisation (Center of Space and Remote Sensing Research, National Central University (NCU)), Taiwan which is a good mixture of government, academia, research organisations and industry.

The Global Navigation Satellite Systems (GNSS) have become a critical space-based infrastructure and rich space-information sources, which were mainly applied to geodesy and navigation in the past decades. Nowadays, due to the availability of all time, all weather, low cost and many other advantages of using GNSS techniques, the use of GNSS for space research has attracted great attention from all over the world. Geodesy and GNSS together play a critical role in many aspects of space research and its related research areas include, but not limited to, the following list:

- precise orbit determination (POD) of space objects, especially precise prediction of space objects in real-time or near real-time;
- precise positioning using space geodesy techniques such as GNSS, Satellite Laser Ranging (SLR) and Very Long Baseline Interferometry (VLBI);
- atmospheric modelling for high accuracy positioning, space weather monitoring and climatology, space object tracking etc.
- using the atmospheric satellite remote sensing technique, e.g. the Radio Occultation (RO) technique, to derive atmospheric parameters including temperature, pressure and water vapour in the stratosphere and the troposphere.

These research areas have made and will make significant contributions to space-related applications, e.g. space situational awareness, the orbit tracking and prediction of space objects including debris for space safety, which is vital for the maintenance and operation of satellites in service and the launch of new satellites, the monitoring of space weather and climate change etc.

2. AIMS AND OBJECTIVES

The aim of this project is to enhance Australia's space capabilities by developing integrated advanced space-based platform technologies through a multi-sensor satellite remote sensing approach, and the key objectives of this project include:

- to develop advanced algorithms for precise real-time or near real-time in-space tracking and navigation, and POD for current and future geo-environmental satellites;
- to investigate atmospheric mass density models for improving the accuracy and reliability of orbit determination and prediction of space objects
- to develop new algorithms and optimisation for precise ubiquitous positioning and mapping in the context of new generation GNSS;
- to investigate the effects of the Earth's magnetic field, the troposphere, the stratosphere and the ionosphere on the electro-magnetic L-band frequency ray paths by developing comprehensive 3D ray tracing application software packages;
- to study the atmosphere and space weather using GNSS and the low Earth orbit (LEO) radio occultation (RO) technique;
- to evaluate and assimilate remote sensing data from multi-sensor satellites for study of climate change and prediction of climatic hazards; and
- to improve the characterisation of climate in the Australian region, based on the new models and methodologies developed
- to investigate new algorithms adapted to new generation multi-frequency and multi-GNSS observations.

Apart from the above objectives, the new geo-environmental satellite programs (e.g. COSMIC II), coupled with the rapid development of the new generation GNSS, will provide critical additional space-related infrastructure for addressing the problems that Australia faces with climate change and natural hazards such as tropical cyclones, drought, extreme heat and bushfires, and also for addressing the issue of the insufficient density of ground-based meteorological observation stations in the southern hemisphere and the lack of meteorological observations over the world's oceans and polar regions. Thus in this project, it is proposed to explore the acquisition, processing and the analysis of more observation data, especially multi-sensor satellite remote sensing data, which the new geo-environmental satellite programs will offer for space, atmosphere and climate research, particularly in the Australian context.

3. RESEARCH ROADMAP

ISBN: 978-0-9872527-1-5
Melbourne: Geospatial Sciences, RMIT 2012

This project covers four key research themes which were categorised into eight work packages (WPs), for which a suite of software and system platforms were to be developed. These include the development of new algorithms, new models and comprehensive software packages to facilitate an optimal data acquisition, data processing and analysis, applications of space tracking, the best use of new generation GNSS and RO data as well as other meteorology- or climate-related measurements. The relationship among these four key research themes, the associated eight WPs, the specific research topics and the organisations undertaking the research tasks in each of the WPs are shown in Figure 1.

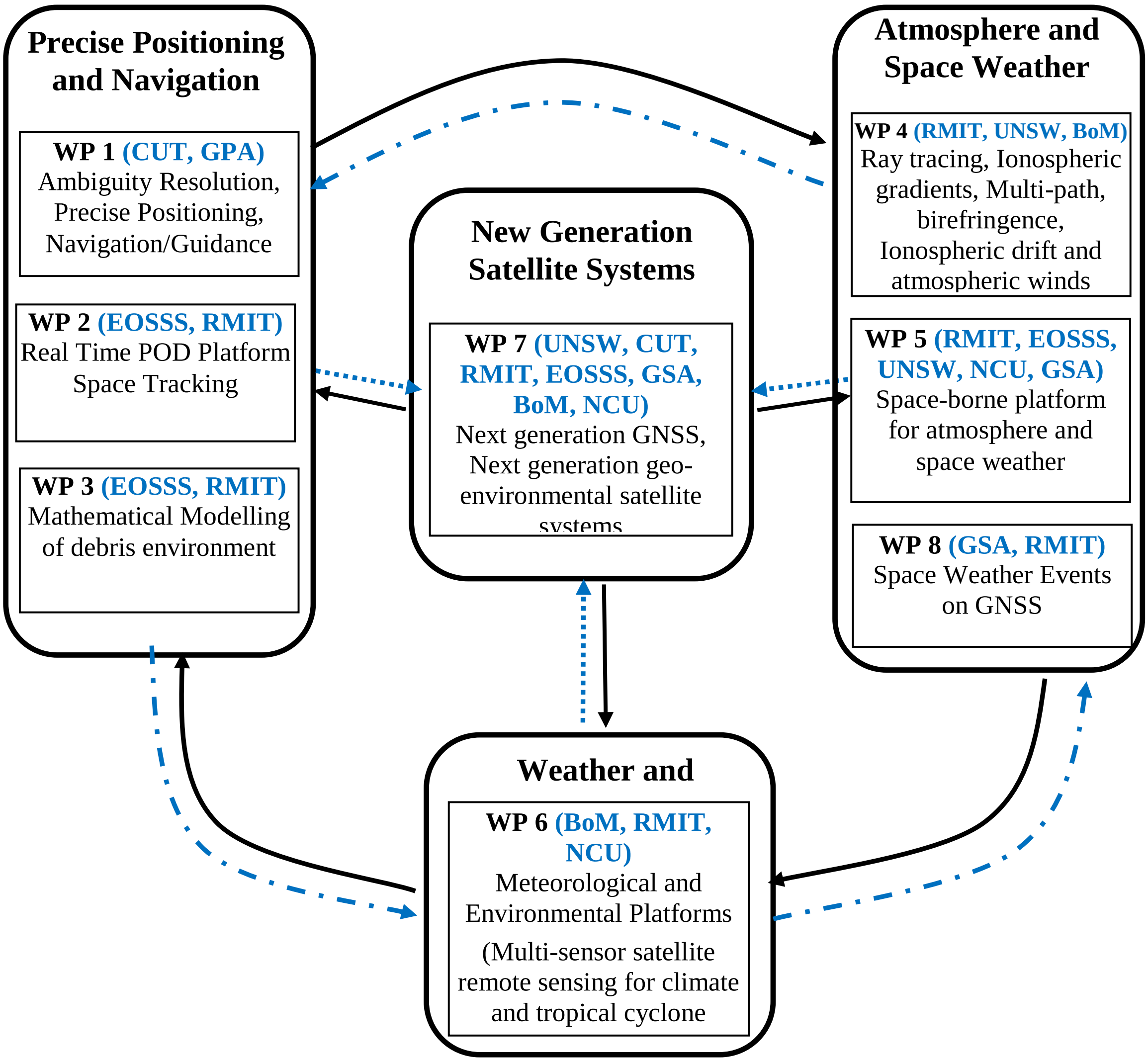

Figure 1. Four key research themes and their associated eight work packages, and the road map displaying their relationships.

4. RESULTS TO DATE

A large range of new developments across for this project have been achieved by the consortium in the past two years. The results outlined below are primarily from the RMIT team and EOSSS.

4.1 Atmospheric mass density modeling

Improving atmospheric mass density modeling is one of the main focuses of this project since the atmospheric drag is one of the main error sources in orbit propagation of space objects, including debris, at altitudes below 800 km. It is estimated, generally, that the long-term mean accuracy of all existing density models is about 15%. However, the accuracy of short-term models could be much worse (Doornbos et al. 2009). Significant progress has been made in the improvement of the accuracy of short-term mass density models (Yurasov et al. 2004; Storz et al. 2005; Doornbos et al. 2008) using the methods in which the corrections to the model-computed mass densities are estimated using space tracking data.

* Review Paper – accepted after double-blind review.
ISBN: 978-0-9872527-1-5
Melbourne: Geospatial Sciences, RMIT 2012

A new approach to improving the short-term mass density modelling accuracy has been developed recently (Sang & Zhang 2010; Sang et al. 2011). In this approach, the coefficients of an adopted mass density model are calibrated using the tracking data of space objects. Experimental results have demonstrated that accurate orbit predictions for debris objects below an altitude of 600 km are achievable by this method. For example, the reduction of the bias (along track) of the 72-hour orbit prediction from 17 km to 420 m for an object with an apogee altitude of 526 km was achieved when the calibrated density model coefficients, rather than the default ones, were used. Compared with other methods, this approach required fewer calibration satellites, i.e. about 30, instead of 70−80, which was reported in other methods, and it generated better orbit prediction for low altitude objects.

The other effort on the mass density modelling was the development of the method using precise orbit data to retrieve density information (Sang et al. 2012a, 2012b). The method is based on the fundamental perturbation equation of the semi-major axis due to air drag. Experiments of processing CHAMP GPS RSO (rapid science orbit) data of the first three months in 2009 show that, when the densities based on accelerometer data were used as the reference values, the mean relative accuracy/bias of the densities derived from this new method was about 2–3%. When POD (precise orbit determination) becomes a routine operation for many LEO spacecraft missions, this method can be used to retrieve accurate information about the mass density from the POD products, which is critically important for the development of long-term accurate density models.

These developments have provided a solid base for accurate short-term mass density modelling, and consequently resulted in better orbit predictions for low altitude debris objects and more reliable services for space situational awareness. A realistic and practical assessment of these methods would be made when tracking data from a global network are available.

In addition to the aforementioned developments, a new approach using publicly available historical two line element (TLE) data to estimate the area-to-mass ratio of debris objects is underway and some extremely encouraging results have been obtained (Bennet et al. 2012).

4.2 Space situational awareness (SSA) research

This research works towards improving the SSA through two areas: (i) modelling the evolution of the low-Earth orbit (LEO) debris population and (ii) providing better orbit predictions using TLE data.

4.2.1 Modelling the evolution of the LEO debris population

A model to simulate the long-term evolution of the low-Earth space debris environment has been developed (Bennett & Sang, 2011). In this model, the volumetric region between 200 and 2,000 km altitude above the earth was considered and discretised into spherical shells. It is a source-sink model and several factors including launches, release of orbital debris from launches, explosions, decay due to atmospheric drag and collisions were considered. The modelling results clearly showed the collisional cascading phenomenon, predicted by Kessler and Cour-Palais (1978). The model was also used to simulate the so-called “No Future Launches” scenario, which assumes there are no future launches into the environment from the specified initial epoch. The other assumption was that all explosions would cease in five years. The results of this scenario showed that over a simulation time span of 200 years, there was still an increase in the number of objects in some critical regions of the LEO environment which was consistent with other studies in the literature. This showed the dominant effect of the debris caused by collisions and suggests the need for remediation techniques to be employed to stabilise the environment.

4.2.2 Improving obit predictions using TLE data

A method, named as TLE-OD/OP, of applying the publicly available TLE data to orbit determination (OD) for better orbit predictions (OP) was also developed (Bennett et al. 2012). The TLE-OD/OP method is based on a method proposed by Levit and Marshall (2011), in which the positions derived from multiple TLEs using the simplified general perturbations (SGP) models algorithm are used as pseudo-observations in orbit determination processes. Usually, a 10-day orbit determination period is selected and all the TLEs that fall within this period are downloaded from www.space-track.org. By propagating backwards from the reference epoch of each of the TLEs, pseudo-observations are generated and used in the orbit determination process. The determined state is then propagated forwards using a highly accurate numeric integrator in which a full set of perturbing forces is considered. The result accuracy from this method has been assessed using satellites Starlette, Stella, Grace A and Grace B, where the TLE-OD/OP prediction results were compared with the standard SGP4 propagation. For all of the satellites considered, our TLE-OD/OP method was more accurate over 90% of the time and the results were less variable. Details can be found in Bennett et al. (2012).

One of the benefits of the TLE-OD/OP method is that the biases in the predicted orbit can be effectively estimated using simple functions. For example, we used two passes of satellite laser ranging (SLR) data to GRACE A satellite from a single station,

* Review Paper – accepted after double-blind review.
ISBN: 978-0-9872527-1-5
Melbourne: Geospatial Sciences, RMIT 2012

Mount Stromlo, Australia, to estimate its biases in the TLE-OD/OP prediction in the along, across track and radial directions (Bennett et al. 2012). The TLE-OD/OP orbit prediction result was then corrected to remove the biases so the better prediction accuracy was achieved. A 7-day prediction made for Grace A showed that the error in the absolute maximum along track direction was reduced from 16.6 km (SGP4) to 4.8 km using the TLE-OD/OP method, which was further reduced to 1.7 km when the bias correction approach was used.

Our current research focus is on refining the techniques discussed above and applying the TLE-OD/OP method to debris objects. Future work will focus on methods to provide reliable and robust orbit determination and prediction using sparse data from multiple sources.

4.3 Space weather effects on GNSS

One key focus area in this ASRP project is studying the effects of space weather on GNSS, in the context of developing a forecast capability in Australia. In this project, ionospheric scintillation (i.e. random fluctuations in phase and amplitude) has been the primary focus.

The detection of ionospheric scintillation is attributed to the presence of ionospheric plasma irregularities (also known as plasma waves) that can be detected using ground-based radar (e.g. Carter et al. 2012a), ionosondes (Carter et al. 2012c), in-situ satellites (e.g. Dao et al., 2011) and space-based radio occultations (Carter et al., 2011, 2012b). Ionospheric plasma waves, and hence scintillation, is most common in the equatorial and high-latitude regions, but is most pronounced in the equatorial region shortly after sunset.

The plasma instability that gives rise to equatorial plasma waves is the generalised Rayleigh-Taylor (R-T) instability, which requires a strong vertical plasma density gradient and a large upward plasma drift. The equatorial ionosphere is perfectly set up after sunset for the onset of R-T plasma waves, as the lower ionosphere (i.e. E region) depletes due to a lack of solar illumination, which is combined with the strong upward drift of the high-altitude (F region) ionosphere. The ionospheric waves generated severely affect the radio waves that propagate through it, e.g. the satellite telecommunications signals and the GNSS signals. For GNSS applications in particular, the amplitude and phase scintillations often result in loss of lock that strongly degrades the position determination accuracy of the receiver.

4.3.1 Equatorial plasma wave climatology

In order for a strong scintillation event to take place, a severe solar/geomagnetic event is not required to take place. As shown by Carter et al. (2011, 2012b), the generation of ionospheric plasma waves in any particular location is highly dependent on the magnetic latitude of the location, in addition to the time of day and the season. For example, it was shown by Carter et al. (2011, 2012b) that ionospheric scintillations are most common in the American sector for all times of the year, with the exception of the months surrounding the June solstice. Alternatively in the Australasian sector, ionospheric scintillations are most frequent in both the March and September equinox months and are least common during both solstices. The primary reason for this strong seasonal/longitudinal (s/l) dependence of the occurrence of equatorial plasma waves is due to a combination of the differences in the Earth's equatorial magnetic field strength, which is strongest (weakest) in the Australasian (American) longitude sectors, in addition to the magnetic declination with respect to the solar declination. The latter of these conditions for favourable plasma wave growth is due to the longitudinal conductivity gradients in the E region across the day-night terminator, as explained by Tsunoda (1985).

4.3.2 Tropospheric seeding of equatorial plasma waves

The Tsunoda hypothesis has been very successful in explaining most aspects of the s/l climatology of the occurrence of scintillation, however there are some aspects that still remain to be explained; e.g., the scintillation occurrence rates in the American sector, near Peru in particular, during the solstices. The issue with the occurrence of plasma waves in this part of the world is that the magnetic declination is 0 deg, and therefore the geometry of the background neutral wind, the magnetic field and the longitudinal conductivity gradient across the terminator is equivalent between the two solstices, and therefore should have comparable plasma wave occurrence rates. However, the observations are not in agreement with this notion and instead show a strong asymmetry between solstice plasma wave occurrence rates (e.g. Carter et al, 2012b). Recently, Tsunoda (2010) proposed that the difference between the solstices is due to the availability of atmospheric gravity waves in the lower atmosphere, that are expected to "seed" the generation of plasma waves via the R-T instability. Tsunoda (2010) supported this idea using the climatology of highly reflective cloud data, which showed higher activity near the magnetic equator during the solstice with higher plasma occurrence rates.

ISBN: 978-0-9872527-1-5

In a recent test of this hypothesis, Carter et al. (2012d) employed the world-wide lightning occurrence data and the COSMIC radio occultation (RO) scintillation data collected during 2007. For each RO event, a search was conducted for “coincident” lightning strikes that would have given an indication of atmospheric gravity wave activity in the troposphere that are expected to seed the R-T instability. It was found that the RO events that observed plasma waves did not show any significant difference in the occurrence of coincident lightning strikes compared to RO events for which plasma waves were not observed. Therefore, it was concluded that tropospheric seeding was not controlling the s/l climatology of the plasma wave occurrence and that another parameter, such as the upward plasma drift, was modulating the plasma wave generation. Similar conclusions were also reported by Su et al. (2008) using *in-situ* satellite observations.

4.3.3 Day-to-day variability in the occurrence of equatorial plasma waves

A more significant problem in the prediction of ionospheric scintillations is the day-to-day variability, which has puzzled scientists for decades. Recently, Carter et al. (2012c) investigated this issue using Ionospheric Scintillation Monitor data in the Australasian region. The most significant finding was that the occurrence of strong scintillation after sunset appeared to be correlated with the strength of the equatorial E-region electrojet at midday of the same day. Therefore, the electrojet strength at midday could potentially be used to accurately forecast the likelihood of strong ionospheric scintillation after sunset later that day. A correlation between the electrojet strength and the upward plasma drift after sunset has been reported in the past (e.g. Dabas et al. 2003), however a valid explanation of why this relationship exists has not yet been achieved.

4.3.4 Future research directions in ionospheric scintillation event prediction

Significant progress has been made in the understanding of equatorial plasma waves through the use of new observation techniques in the ASRP project. The climatology of ionospheric plasma waves that cause radio wave scintillations closely matches those reported previously using both ground-based and space-based measurement techniques. The method of RO has been shown in this project to be a powerful new tool for studying plasma waves, and has a great potential to fill the gap in our understanding and forecast capabilities. In the future, the potential to predict the occurrence of severe scintillation events will be explored further, and if successful, has the potential to make a significant impact on the industries and organisations that heavily rely on GNSS applications.

4.4 *Space weather platform*

Another area of research outlined in the ASRP project is the development of a space weather platform. The objectives are to develop ray tracing techniques, algorithms and programs based on geometrical optics and to use the programs to simulate GNSS L-band signal paths traversing the ionosphere and atmosphere. In particular, the GPS Radio Occultation signal paths have been simulated in order to test and validate and/or develop new atmospheric and ionospheric retrieval techniques.

Ongoing research is needed to improve our understanding of how best to process and assimilate the GNSS RO data. This research is innovative as there is currently no solution available that overcomes the problems encountered by GNSS RO techniques in the lower troposphere (LT), i.e. multi-path, receiver tracking error and super refraction, in order to provide atmospheric profiles of high accuracy in the LT. In addition there has been little research into determining birefringence effects on the GNSS signal or on horizontal refractive gradients on the GNSS signal path. The GNSS RO techniques assume spherical stratification of the refractive medium of both the ionosphere and atmosphere. Applying novel 3-D ray tracing techniques to simulate the GNSS RO signal will aid understanding of the RO signal paths and lead to improved GNSS RO techniques, and subsequently, improved weather forecasting.

4.4.1 GPS radio occultation

GPS RO is a space-based Earth observation technique with the potential for atmospheric profiling and meteorological applications. The GPS consists of about 30 satellites travelling at an altitude of ~20,200 km orbiting the Earth twice a day and continually transmit signals at the L-band frequencies 1.57542 GHz (L1), 1.2276 GHz (L2) and 1.17645 MHz (L5). GPS RO uses GPS receivers onboard Low Earth Orbit (LEO) satellites to measure the radio signals transmitted from GPS satellites. Refractive gradients in the ionosphere and atmosphere affect the paths of the L-band electromagnetic signals transmitted from GPS satellites, causing the signals to bend in accordance to Snell’s law. The bending of the ray paths in the ionosphere is due to electron density gradients. The ionosphere is a birefringent medium, due to the effects of the Earth’s magnetic field on the electrons, which means it has two distinct refractive indices and the electromagnetic signal will split in to as it traverses the ionosphere. The GPS signal is predominately right-hand circularly polarised, as such the signal will predominantly favour the extraordinary mode (this is not always the case). There exists a significant amount of structure in the ionosphere, which varies strongly with solar radiance. Like

* Review Paper – accepted after double-blind review.
ISBN: 978-0-9872527-1-5
Melbourne: Geospatial Sciences, RMIT 2012

the lower atmosphere the ionosphere can vary seasonally, spatially and diurnally. Refractivity in the lower atmosphere depends mainly upon the atmospheric pressure, temperature and the partial pressure of the water vapour.

4.4.2 Simulating GNSS radio occultation signal paths using ray tracing

As a result of this research new and novel ray tracing techniques have been developed. A new 3-D numerical ray tracing technique, enabling the tracing of ray tubes traversing inhomogeneous anisotropic media, such as the Earths ionosphere, has been developed (Norman et al. 2012a). This ray tracing technique has been written in general coordinates and can be easily adapted for other coordinate systems. Simulated high frequency ray paths using the Fully Analytic Ionospheric Model (FAIM) (Anderson et al. 1989) for the extraordinary case are presented. GPS RO paths showing the effects of the ionosphere, birefringence and horizontal gradients have also been simulated (Norman et al. 2012b) using the International Reference Model (IRI-2007) (Bilitza and Reinisch, 2008) to represent the ionosphere.

A new 3-D Segment Method Analytic Ray Tracing (3-D SMART) has been developed (Norman et al. 2012c). This is a pseudo analytic ray tracing technique and, as its name suggests, it uses explicit equations to represent the ionosphere and ray parameters in each atmospheric grid location and the directional component is determined based on the principles of geometrical optics. This ray tracing technique can simulate electromagnetic ray paths traversing complicated ionospheric profiles. Comparisons between corresponding ray parameter results determined using the 3-D SMART and 3-D numerical ray tracing show very good agreement (Norman et al., 2012c). Their results were determined using the IRI-2007 model. Analytic ray tracing is computationally considerably faster than numerical ray tracing, as such this program has the potential to be used in an operational system where near real-time simulations are required.

5. CONCLUDING REMARKS

Platform Technologies for Space Atmosphere and Climate, the 3-year $7.5 m project awarded to a consortium led by the SPACE Research Centre at RMIT University under the Australian government recent initiative of ASRP is introduced, and progress made mainly from RMIT and EOSSS are briefed in this paper. This is regarded a benchmarking project in geospatial science in terms of the prestige, scale and scope. The results are promising and they have paved the way for further developments towards the objectives of this project. This research is significant and has a profound impact on efficient and effective uses of space geodesy techniques for a wide variety of space-related applications including space tracking, precise satellite positioning, atmosphere and climate monitoring, especially in the Australian context.

ACKNOWLEDGEMENTS: The authors would like to acknowledge the Australian government's research grant support for this project through the Australian Space Research Program (ASRP) project.

References

Australian Space Research Program 2012, accessed 27 Sep 2012, http://www.space.gov.au.

Anderson, DN, Forbes, JM and Codrescu, M 1989, 'A Fully Analytical, Low- and Middle-Latitude Ionospheric Model', *J. Geophys. Res.* 94, p. 1520.

BENNETT, J & SANG, J 2011,'Modelling the evolution of the low-Earth orbit debris population', In: CAIRNS, I. & SHORT, W. (eds.), *Proceedings of the 11th Australian Space Science Conference*, Canberra, Australia, ISBN 13: 978-0-9775740-5-6.

BENNETT, J, SANG, J, SMITH, C & ZHANG, K 2012,'Improving low-Earth orbit predictions using two-line element data with bias correction', paper presented at the Advanced Maui Optical and Space Surveillance Technologies Conference, Maui, Hawaii, 11 – 14 September, 2012.

Bilitza, D and Reinisch, B 2008 'International Reference Ionosphere 2007, 'Improvements and new parameters', *J. Adv. Space Res.*, vol. 42(4), pp. 599 −609, 2008.

Carter, BA, Norman, R, Wang, C, Li, Y, Gordon, S, Hooper, G and Zhang, K 2011, 'Space weather effects of the GPS scintillation levels received from radio occultations', *Proceedings of the International Global Navigation Satellite System Symposium*, Sydney, Australia, paper #63.

Carter, BA, Makarevich, RA, Devlin JC, McDonald, AJ 2012a, 'Coincident multi-point observations of the E- and F-region decametre-scale plasma waves at high latitudes', *Journal of Atmospheric and Solar-Terrestrial Physics*, vol. 80, pp. 323−335.

Carter, BA, Zhang, K, Norman, R, Kumar VV, Kumar, S 2012b, 'On the occurrence of equatorial F-region irregularities during solar minimum using radio occultation', *Journal of Geophysical Research*, under review, manuscript #2012JA018127R.

Carter, BA, Francis, MJ, Terkildsen, M, Yizengaw, E, Marshall, R, Norman, R, McNamara, D, Yumoto, K, Zhang, K 2012c, 'Observations of equatorial plasma bubbles over northern Australia', paper presented at the Australian Space Science Conference, Melbourne, 24−26 September, 2012.

Carter, BA, Zhang, K, Norman, R, Kumar VV, Kumar, S 2012d, 'COSMIC observations of equatorial F-region irregularities', paper presented at the Australian Space Science Conference, Melbourne, 24−26 September.

Dabas, RS, Singh, L, Lakshmi, DR, Subramanyam, P, Chopra, P and Garg SC, 'Evolution of dynamics of equatorial plasma bubbles: Relationships to ExB drift, postsunset total electron content enhancements, and equatorial electrojet strength', *Radio Science*, vol. 38, no. 4, 1075, doi:10.1029/2001RS002586.

Dao, E, Kelley, MC, ROddy, P, Retterer, J, Ballenthin, JO, de La Beaujardiere, O, Su Y-J 2011, 'Longitudinal and seasonal dependence of nighttime equatorial plasma density irregularities during solar minimum detected on the C/NOFS satellite', *Geophysical Research Letters*, vol. 38, L10104, doi:10.1029/2011GL047046.

Doornbos, E, Klinkrad, H & Visser, P 2008, 'Use of Two-line Element Data for Thermosphere Neutral Density Model Calibration', *Adv. Space Res.* 41, pp. 1115 −1122.

Doornbos, E, Forster, M, Frische, B, van Helleputte, T, van den Ijssel, J, Koppenwallner, G, Luhr, H, Rees, D & Visser, P 2009, Air Density Models from Multiple-satellite Drag Observations, *DEOS/TU Delft Scientific Report 01/2009*, Delft, The Netherlands.

KESSLER, D & COUR-PALAIS, B 1978, 'Collision Frequency of Artificial Satellites: The Creation of a Debris Belt', *J. Geophys. Res.*, Vol. 83, pp. 2637−2646.

LEVIT, C & MARSHALL, W 2011,'Improved orbit predictions using two-line elements', *Adv. Space Res*, Vol. 47, pp. 1107−1115.

Norman, R, Bennett, J, Dyson, P, Le Marshall, J and Zhang, K 2012a, 'A ray-tracing technique for determining ray tubes in anisotropic media', *IEEE Transactions on Antennas & Propagation* (accepted) .

Norman, R, Le Marshall, J, Carter, B, Wang, C-S, Gordon, S, and Zhang, K 2012b, 'A new pseudo three-dimensional Segment Method Analytical Ray Tracing (3-D SMART) Technique', *IEEE Transactions on Antennas & Propagation*, Vol. 60, 12, (DOI: 10.1109/TAP.2012.2214194).

Norman, R, Le Marshall, J, Wang, C, Carter, B, Li, Y, Gordon, S and Zhang, K 2012c, '*Simulating GPS radio occultations using 3-D numerical ray tracing*', IEEE International Symposium on Geoscience and Remote Sensing Symposium IGARSS, (in press).

Sang, J, & Zhang, K 2010,'A New Concept of Real Time Improvement of Atmospheric Mass Density Models and Its Validation Using CHAMP GPS-Derived Precision Orbit Data', *Journal of GPS*, Vol. 9, No.2, pp. 104–111.

Sang, J, Smith, C& Zhang, K 2011, 'Modification of Atmospheric Mass Density Model Coefficients Using Space Tracking Data – A Simulation Study for Accurate debris orbit prediction', *Advances in the Astronautical Sciences*, Vol. 140, pp. 1479 −1493.

Sang, J, Smith, C& Zhang, K 2012a, 'Towards Accurate Atmospheric Mass Density Determination Using Precise Positional Information of Space Objects', *Adv. Space Res*, 49, pp. 1088−1096.

Sang, J, Smith, C & Zhang, K 2012b, 'A Method of Estimating Atmospheric Mass Density from Precision Orbit Solution', *AIAA/AAS Astrodynamics Specialist Conference*, Minneapolis, MN, USA, 13−16 August, 2012.

Storz, MF, Bowman, BR, Branson, JI, Casali, SJ & Tobiska, WK 2005, 'High accuracy satellite drag model (HASDM)', *Adv. Space Res*, 36, pp. 2497 − 2505.

ISBN: 978-0-9872527-1-5
Melbourne: Geospatial Sciences, RMIT 2012

Su, S-Y, Chao, CK, Liu, CH 2008, 'On monthly/seasonal/longitudinal variations of equatorial irregularity occurrences and their relationship with the postsunset vertical drift velocities', *Journal of Geophysical Research*, vol. 113, A05307, doi:10.1029/2007JA012809.

Tsunoda R 1985, 'Control of the seasonal and longitudinal occurrence of equatorial scintillations by the longitudinal gradient in the integrated E region Pederson conductivity', *Journal of Geophysical Research*, vol. 90, pp. 447−456.

Tsunoda R 2010, 'On seeding equatorial spread F during solstices', *Geophysical Research Letters*, vol. 37, L05102, doi:10.1029/2010GL042576.

Yurasov, VS, Nazarenko, AI, Cefola, PJ & Alfriend, KT 2004, 'Results and issues of atmospheric density correction', *J. Astronaut. Sci*, 52 (3), pp. 281−300.

* Review Paper – accepted after double-blind review.
ISBN: 978-0-9872527-1-5
Melbourne: Geospatial Sciences, RMIT 2012