Craig Roberts GPS for Cadastral Surveying – Practical Considerations
Proceedings of SSC 2005 Spatial Intelligence, Innovation and Praxis: The national Biennial Conference of the Spatial Sciences Institute, September 2005. Melbourne: Spatial Sciences Institute. ISBN 0-9581366-2-9

GPS FOR CADASTRAL SURVEYING – PRACTICAL CONSIDERATIONS

C. Roberts

School of Surveying and Spatial Information Systems, University of New South Wales

c.roberts@unsw.edu.au

KEYWORDS: GPS, RTK, Cadastral

ABSTRACT

GPS technology, in particular real-time kinematic (RTK) GPS, has matured to the stage where it has become another tool for the professional surveyor. Commercial products offer user-friendly hardware/software and suggest techniques that can improve productivity at a high accuracy. Government services such as SCIMS in NSW and AUSPOS (Geoscience Australia) support improved GPS positioning and surveying for the user community. However, even though some professional surveyors have embraced GPS survey methods into their businesses, mainly for a range of engineering and topographic detail tasks, many practitioners are still reluctant to invest in the technology. This has been due to a number of reasons such as prohibitive cost, a lapsed understanding of geodesy, confusion about GPS surveying capabilities and best practice techniques, uncertainty over how to best utilise existing GPS services and infrastructure, lack of time/resources to invest into GPS surveying training, and for the cadastral surveyor uncertainty over what is acceptable practice to satisfy current survey regulations in their particular state or territory. This last point is of particular importance because if a professional surveyor can justify using RTK-GPS for engineering, detail *and* cadastral surveying then suddenly RTK-GPS does indeed become "just another tool" like the ubiquitous total station.

This paper seeks to investigate a number of practical issues faced by the cadastral surveyor using RTK-GPS. A brief introduction on how RTK GPS works is presented followed by a range of issues including the impact of GPS errors for the cadastral surveyor, initialisation, radio links, marks under trees and future GNSS augmentations. Survey regulations differ between states and impact on acceptable practices. As the author lives in NSW, this paper will have a NSW flavour.

As State Governments increasingly encourage professional surveyors to provide at least MGA control (and sometimes even MGA coordinates) on modern cadastral surveys, RTK-GPS, being a high precision coordinate generator, seems and obvious tool to use (in favourable conditions). It is hoped that this paper will encourage professional surveyors to trial GPS and/or use it more effectively.

BIOGRAPHY

Craig Roberts is a Lecturer in Surveying/GPS/Geodesy at the University of New South Wales, Sydney, Australia. He has lectured at RMIT University in Melbourne for two years. He graduated from the University of South Australia with a Bachelor of Surveying in 1988. He began his career as a private surveyor in Adelaide. He has since worked as a Geodetic Engineer at UNAVCO, Colorado, USA involved with GPS for geodynamic studies in Nepal, Ethiopia, Argentina and Indonesia. Later he was employed by the GeoForschungsZentrum, Germany where his main focus was orbit determination and prediction for a number of geodetic research satellites. He completed his PhD thesis at the School of Surveying and Spatial Information Systems, the UNSW in March 2002 supervised by Prof. Chris Rizos. His thesis was entitled, "A continuous low-cost GPS-based volcano deformation monitoring system in Indonesia".

1 OVERVIEW OF GPS THEORY

The Global Positioning System (GPS) was designed and developed by the US Department of Defence (US DoD) primarily for navigation purposes giving positions in real time to around 5-20m accuracy. A constellation of 28 satellites broadcasts position and time using ranging codes modulated onto two L1 and L2 band carrier signals. Geodesists and surveyors realised that by simultaneously measuring the GPS satellite signals at two antennas and combining the data, differential or relative positioning with respect to one base station was possible at higher accuracy; a few metres or better when using code or pseudo range observations and cm-level when using the carrier signal phase observations. However, differential positioning required data to be post-processed and as a result high accuracy positioning was not available in real-time.

The next advance came by incorporating a radio link between the base and rover enabling cm-level positioning of a static or moving user. This is known as real-time kinematic RTK GPS and nowadays is considered a mature and reliable technology. In reality the time between receiving GPS data at the base, sending to the rover, decoding, combining with the rover GPS measurements and computing a new coordinate introduces a time delay called “latency”. For modern systems this is typically less than 1 second and for static users, such as surveyors measuring discrete points, latency is not a problem.

The cm-level precision of RTK GPS relies on a process often referred to as “initialisation”. The faster the initialisation process is carried out, the faster the surveyor can get on with the job. But what is initialisation?

1.1 Initialisation

To answer this question some GPS theory needs to be revised. Differential GPS relies on a process called double differencing. Simultaneous “one-way” carrier phase measurements are logged at two antennas to the same constellation of satellites.

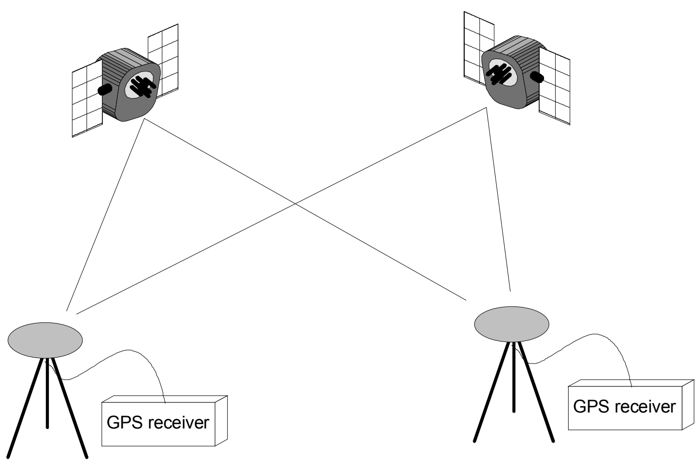

Figure 1 – Double differencing

The procedure identifies a base satellite and forms pairs comprising two satellites and two antennas with the base satellite common to all pairs (see figure 1). For example with two stations and five satellites, four pairs would be formed.

One-way carrier phase measurements are similar to EDM measurements in that the distance between a satellite and antenna is the sum of an unknown number of wavelengths (in this case the L1 GPS signal with a wavelength of 19 cm) plus a fractional part which is measured and continuously tracked by the GPS receiver. Separate channels in the GPS receiver “lock on” to separate satellites and count the number of wavelengths either increasing or decreasing for a setting or rising satellite respectively. Any interruption to this counting procedure, such as when a satellite tracks behind an obstruction, is called a “cycle slip”. Combining four one-way phase measurements is the process of double differencing and serves to eliminate the largest error sources namely receiver and satellite clock bias.

Double differencing is used to aid the computation of the unknown number of wavelengths between a satellite and receiver (called the “ambiguity”) at the moment of the first simultaneous measurement of both GPS receivers. This process is known as “ambiguity resolution” (AR). Han (1997) gives a thorough account of AR techniques. Initialisation therefore is the result of a successful AR procedure and therefore can produce cm-level positioning with respect to a known base station thereafter. If a cycle slip occurs AR must be recomputed for that satellite receiver pair. If all satellites experience a cycle slip, initialisation is repeated.

AR was the subject of vigorous research efforts in the 1990s but in recent times has become a more routine, but none-the-less complex procedure. AR can also refer to a range of different "linear combinations" of the double differencing process. The most precise double difference combination is the L1 fixed solution. If the AR procedure can compute the fixed number of L1 wavelengths for a particular baseline then this is the best solution achievable. However as the baseline length increases atmospheric biases not common to both ends of the line restrict successful AR. Other biases such as multipath and orbit errors also contribute. Therefore the L1 fixed solution is limited to baseline lengths of around 10-15 km depending on conditions. Rizos (1997) presents a range of linear combinations suitable for longer baseline lengths.

Standard RTK initialisation techniques seek to resolve ambiguities for the highest precision L1 fixed linear combination. Recently new firmware includes improved techniques to initialise RTK GPS over longer baselines. Perhaps other, less precise linear combinations are utilised during this procedure.

1.2 Why dual frequency?

Modern RTK GPS kits are all dual frequency instruments measuring both L1 and L2 carrier phase measurements. However the most precise GPS baseline result achievable is an L1 only fixed solution. So why not use just a single frequency instrument and still achieve the same accuracy? Indeed this is possible, but not feasibly in real-time. Single frequency GPS is certainly of identical precision over short baselines but must be post-processed.

The AR procedure is highly statistical and requires a number of GPS epoch measurements to achieve successful initialisation. Dual frequency receivers measure twice as much data and therefore reduce the time to initialisation. Additionally, in the realistic scenario that a surveyor experiences a total loss of lock and must re-initialise, then the faster re-initialisation is carried out the faster the surveyor can continue.

Early techniques to perform re-initialisation included an antenna swap method, re-observing a known point or simply waiting at a new point to re-initialise. Recent more sophisticated algorithms allow a procedure known as on-the-fly (OTF) initialisation. If the surveyor has lost lock, re-initialisation is performed automatically as they move to the next mark and often in less than 20 seconds. This technology relies on dual frequency data and significantly five or more visible satellites.

1.3 Survey planning

Full operational capability (FOC) was declared by the US DoD in 1995. FOC guarantees that four satellites (usually five) are visible anywhere on the Earth at anytime. Consequently, survey planning, that is checking that enough satellites will be available prior to a job, was considered obsolete. However the OTF requirement for a minimum of five visible satellites particularly in difficult environments requires that RTK surveyors should always consider the best time to work.

Figure 2 shows the number of satellites available over Melbourne on 14 September 2005 for an elevation mask angle of 15° (upper) and 20° (lower) which could simulate a difficult environment with many obstructions. Note that from the period from around 1pm until 2:30pm, only five satellites are available most of the time. This paucity of available satellites limits the effectiveness of OTF initialisation and can render this period impossible for RTK surveying. It is possible to log data during these periods and post-process later but this is not the intention of real-time surveying.

Survey planning software also allows "masking" of large obstructions in the local environment to refine the true number of satellites likely to be visible on a job. As a general rule in Australia, most GPS satellites are in the northern sky. During reconnaissance on a job, it is useful to avoid working near obstructions to the north if possible.

Despite FOC being available for a decade now, the number of GPS satellites can still be restrictive for high productivity applications. In the mid-1990s the first GPS/GLONASS receiver was produced commercially. GLONASS is the Russian equivalent system to GPS. At its peak in the mid-1990s, 16 satellites were operating in the constellation. This meant users could seamlessly track up to 40 satellites effectively negating survey planning except for the most difficult environments. However, due to a number of political and financial difficulties, the number of useable GLONASS satellites decreased and by 2000 only a handful were still operational. Recently the number of GLONASS satellites is on the rise and currently there are 13 operational GLONASS satellites (May 2005). The President of the Russian

Federation has indicated that he would like to see FOC for the GLONASS constellation by 2010 [Interfax, 2004]. For RTK applications relying on OTF algorithms, 40 available satellites is a significant advantage.

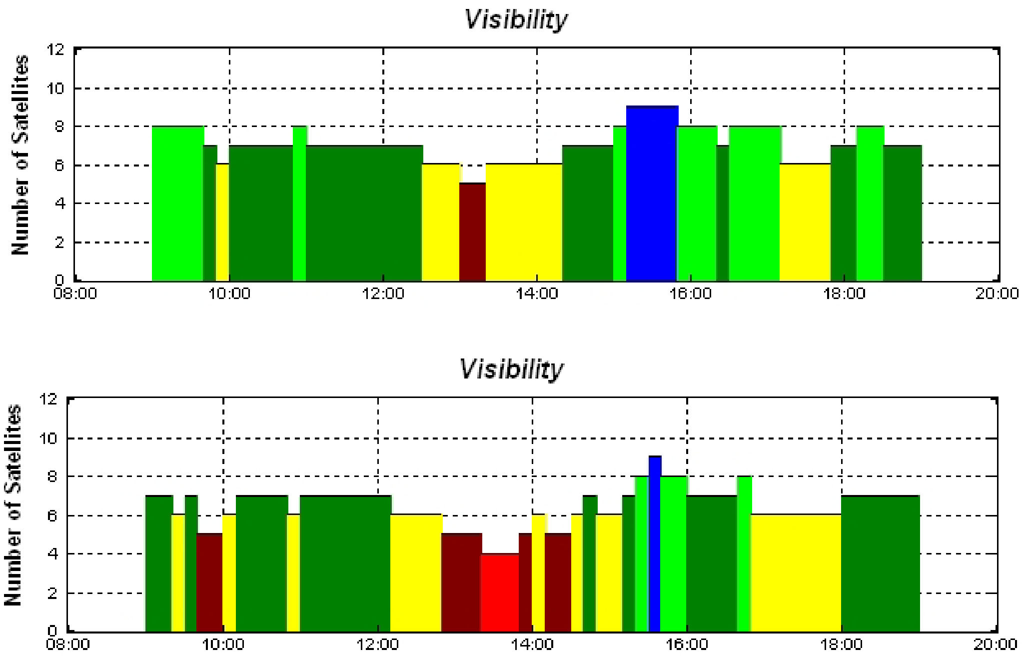

Figure 2 – Number of satellites visible in Melbourne on 14 Sept 2005 from 9:00am until 5:00 pm for cut-off angles of 15° (upper) and 20° (lower).

The European Union GNSS system "Galileo" is scheduled to be operational in 2008. It is anticipated that surveyors will be able to purchase equipment that will seamlessly track the three G's: GPS, GLONASS and Galileo offering an 80 satellite constellation. Under these conditions, survey planning may indeed become obsolete.

1.4 High Productivity Surveying

Once successful initialisation has been achieved, the rover antenna becomes a high precision coordinate generator that does not require line of sight, unlike total station techniques. However, the surveyor must be sure that the AR procedure computed the correct number of wavelengths. In the early days of RTK GPS, this was a significant concern. Nowadays, with better hardware producing cleaner observations coupled with more sophisticated algorithms and tighter quality control, AR is said to be correct 99.9% in ideal conditions. To take a negative approach, 1 in 1000 positions is therefore wrong. Initialisation depends on the number of satellites, good PDOP, the observation span, low multipath and the baseline length. Bad initialisation could mean an incorrect position of a decimetre or more! With experience the GPS surveyor will consider all these issues when deciding if a position is acceptable or not.

The rover receiver includes some interface to give the GPS surveyor up-to-date information about the quality of the positions being computed. Often the status of the solution such as RTK-fixed (usually meaning L1-fixed) is displayed with RMS or standard deviation values. The GPS surveyor needs to be aware that these values refer to the internal precision of the solution inside the GPS receiver rather than the positional accuracy in the field. Often these numbers are over optimistic and manufacturers apply a scale factor such that the number on the screen appears more realistic (ie like a positional error). However if there is an incorrect initialisation, the surveyor will not know.

The professional surveyor must therefore ensure the survey includes sufficient redundancy to catch any possible incorrect initialisations. Some methods may include the following:

- Traverse closure checks
- Reoccupy observed points
  - Wait at least 20 minutes for the satellite geometry to change for an independent check
- Re-initialisation at a known point
  - Observe a point. Re-initialise and check position is the same. Change antenna height and re-initialise.
- Occupy known control during survey
- Combinations of these techniques

1.5 Local Transformations

The native coordinate system of GPS is the geocentric, cartesian World Geodetic System (WGS84). Increasingly the cadastral surveyor is required to connect to MGA control from a deposited plan. Modern RTK systems allow computation of the transformation parameters between the WGS84 system and MGA or local coordinates in real-time in the field. At least three points are required with a fourth providing redundancy and residuals showing the quality of the computed transformation parameters. These residuals can be very useful to identify a control mark with either a bad coordinate or that has moved. Many surveyors begin all RTK surveys by computing local transformation parameters first and regard this as good survey practice.

Two transformations are possible: a full seven parameter transformation using three rotations, three translations and a scale factor or by simply fitting a plane through the control. In both cases the control should surround the job with good geometry and for larger jobs plane fitting should be avoided.

2 PRACTICAL ISSUES FOR THE CADASTRAL SURVEYOR

GPS surveying techniques are being adopted by cadastral surveyors. GPS is by no means a replacement for traditional techniques but rather an enhancement suitable for certain conditions. Some practical considerations are listed below.

2.1 Base station location

When performing a GPS survey often the base station receiver is setup and left to operate autonomously whilst the surveyor operates the roving receiver. Perhaps the most important consideration therefore is the security of the base station: if it is stolen all work stops! From a technical point of view, the base station should be located with an open sky view to maximise the number of satellites it receives. Remember, double differencing works on the principle of simultaneous observations to the same constellation of satellites. If the base station is located such that only six satellites are visible and the rover has nine visible satellites, then only six satellites can be used for differential positioning.

Another consideration for RTK GPS is the range of the radio link between the base and rover. It is wise to place the base station on high ground with line-of-sight across the whole job if possible to maximise the radio reception at the rover – particularly in difficult terrain. Some radios double as radio repeaters. These can be configured to extend the radio range for larger jobs. However the surveyor must be clear that just because a radio range of 15 kms maybe possible with radio repeaters, the major limiting factor remains the ability of the system to initialise. As the baseline length increases, the systematic biases that limit initialisation (primarily ionosphere) also increase. Without correct initialisation, high precision, real time positioning is not possible regardless of radio range.

The base station should also be located in a multipath free environment away from potentially reflective materials such as fences, buildings, metal objects on the ground or water. Note that parking a car near the base station can cause multipath! Also avoid large microwave transmission towers which can completely block out the weak GPS signals.

The location of the base station is therefore a compromise between:

- Security,
- Clear skyview,
- Radio range, and a
- Multipath free environment.

For a cadastral survey it would seem obvious to place the base station on a control mark with known MGA coordinates, however considering the above factors, it is usually better to place the base station at an optimal location (often in the middle of the job) with no coordinates and compute local transformation parameters across the job.

2.2 Working under trees

Modern GPS systems have improved satellite tracking technology such that weaker signals can be observed under trees with moderate foliage. (Note that dense foliage will still cause cycle slips). Despite this advanced tracking capability, the signals are noisier, weaker and therefore more likely to be subject to multipath and diffraction. The surveyor should be aware that positions may not be accurate despite quality indicators showing good solutions.

To overcome this cadastral surveyors can place two or three marks in clearer locations, coordinate them using RTK GPS techniques and then radiate or intersect the cadastral detail required using a total station or theodolite.

2.3 Coordinating marks

The precision of modern RTK GPS positioning in the horizontal direction is quoted by most manufacturers as ±10mm+1ppm. The roving receiver is equipped with a pole which is often two metres in height. Whilst RTK GPS may achieve at worst 20mm, holding a two metre pole straight for a few minutes will introduce more error. Cadastral surveyors therefore use tripods for important points but still log RTK data. For extra rigor, the position could be measured, then switched off and re-initialised. However for a more independent result it is best to wait 20 minutes for the constellation to change geometry. If this procedure is economically unfeasible, the surveyor should devise a schedule to re-observe such marks later in the day. Alternatively, the tripod could be disturbed and setup again at a different antenna height (preferably more than one L1 wavelength different ie 19 cm) and re-initialised.

RTK GPS produces final computed positions only. Therefore there is no check as to how these positions were computed. Surveyors therefore can set both the base and the rover to produce RTK positions and log the raw GPS data for post-processing. The NSW Surveyor General's Directions (2004), No. 9 GPS for Cadastral Surveys recommend that the raw data is archived and that these measurements must be checked as part of a closed figure.

2.4 Antenna Phase Centre Variation (APCV)

The GPS signals received at the antenna are measured at the electrical phase centre of the antenna. This is not the mechanical centre of the antenna namely the point plumbed directly above the survey mark around which the centre of the antenna rotates. The APCV has two components: an offset in easting, northing and height and an elevation dependent component which changes as a satellite rises or sets. Two identical antennas will have the same APCV characteristics, so if the antennas are oriented in the same direction (north) then the APCV effects will cancel. In early GPS antennas APCV was at the few cm level. Modern RTK antenna pairs (ie the base and rover) boast sub-mm APCV. When mixing antennas between manufacturers the effects may become significant (several cms for some older antennas). APCV tables quantify the amount of variation. This is why it is important to input the actual antenna used in the field during post-processing so the software can apply the correct APCV table for a particular antenna. The careful cadastral surveyor should still orient base and rover antennas to the north when mixing antennas however this practice is less crucial in the more common situation using a base and rover from the one manufacturer.

2.5 Elevation Mask Angle

The NSW Surveyor General's Directions (2004), No. 9 GPS for Cadastral Surveys recommend the GPS surveyor uses an elevation mask angle of no less than 15°. The reason for this recommendation is to reduce the effects of systematic errors in GPS surveying namely tropospheric delay, ionospheric delay and multipath. From figure 3 it can be seen that the signals from lower elevation satellites pass through more atmosphere causing the one-way carrier phase observations to be noisier which affects initialisation.

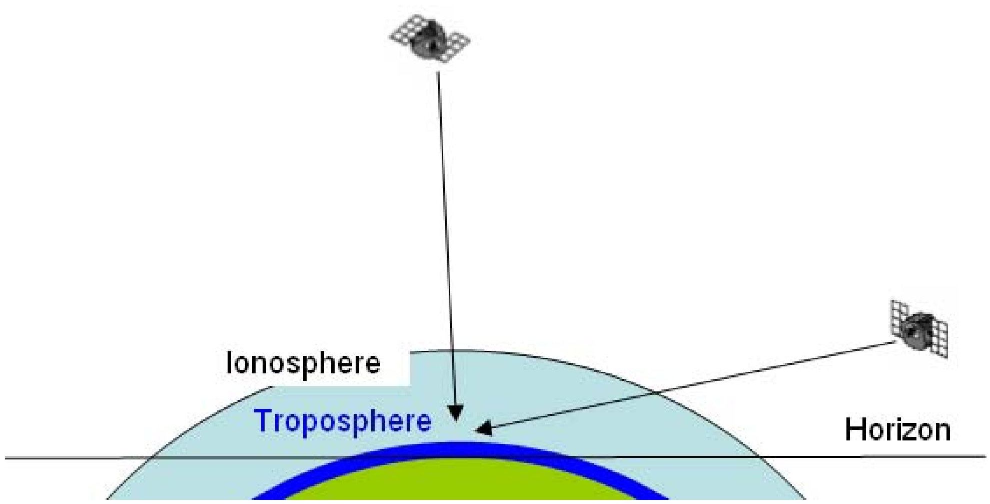

Figure 3 – Elevation mask angle

Low elevation GPS signals also tend to cause multipath. Multipath occurs when the signals bounce off the ground or some other reflector and back to the antenna. The effective path length of the signal is therefore longer than it should be. For carrier phase positioning this can cause errors of up to ¼ of a wavelength (~6 cm). The effects of multipath average out across a session during post-processing however for RTK, multipath can be serious. Setting a higher mask angle can mitigate multipath but is a compromise between reducing the number of visible satellites and measuring clean data. Note, manufacturers boasting multipath resistant antennas refer to pseudo range multipath only which can cause metre level errors. Eliminating pseudo range multipath assists initialisation but carrier phase multipath still persists.

2.6 Atmospheric Biases

For cadastral surveying, distances are usually under 10 kms. Tropospheric models used for RTK GPS will easily account for these effects. Ionospheric delay is however the largest systematic limiting factor for successful initialisation. For RTK GPS initialisation, the algorithm assumes the ionosphere path delay at the rover and base is identical and therefore ignores this effect. As the baseline length increases, this assumption breaks down as the uneven delay at the base and rover can disrupt successful initialisation. Using dual frequency data, the ionosphere free linear combination can be used during the double differencing procedure to overcome this problem and initialise over larger distances. This combination is less precise than the L1-fixed solution. It is not clear from manufacturer literature if this approach is used for longer range firmware upgrades.

The ionosphere is usually most active in the two-hour period between noon and 2pm. It is also more active in equatorial and polar regions and follows an 11 year solar cycle. At present the solar cycle is approaching a minimum. For Australian users located in the mid-latitudes, only the diurnal ionospheric activity around noon is a consideration.

2.7 Scale Factor

Deposited plans (DPs) in NSW are required to show MGA orientation to at least two permanent marks (Surveying Regulation 2001). All other dimensions on the DP are ground distances. Traditionally cadastral surveyors have always worked on ground distances by adopting a common scale factor from the centroid of a job and applying this across the whole area. This is suitable for cadastral surveys which rarely extend further than a few kilometres in either direction. In NSW, cadastral surveyors have previously used the Integrated Survey Grid of NSW with a significantly smaller scale factor than the new MGA system (ISG central meridian is 0.99994 → 60mm/1000m vs MGA central meridian of 0.9996 → 40mm/100m) however the principle is identical. Surveyors from other Australian states and territories have suffered no such change with the implementation of MGA coordinates nationally.

Just as traditional techniques worked on ground distances, the GPS system can be configured to also work on local ground coordinates. A local coordinate system could originate at one permanent mark at an extremity of the job. This coordinate could be a MGA coordinate truncated to use only the 1000s terms (ie E 336 262.876 becomes 262.876). MGA azimuth should be preserved. The combined scale factor can be obtained from SCIMS or computed using a simple Excel spreadsheet available from the Land Victoria website [Land Victoria, 2005]. The survey should be pre-calculated such that local coordinates are adopted at all permanent marks in the field.

Alternatively, a local transformation can be performed in the field such that local coordinates are produced by the RTK GPS system in real-time. This is very useful for field checking with GPS and finding marks. If an EDM is required for distance checks (as prescribed in the NSW Surveyor General's Direction No. 9) these can be made directly on ground distances.

2.8 AUSPOS

In remote areas sometimes there is no suitable or nearby MGA control. In this case the AUSPOS processing engine can be used. Here the base station is configured such that it broadcasts carrier phase data for RTK surveying *and* it logs this raw data at the base station. This logged data is then converted into the Receiver INdependent EXchange format (RINEX) and sent to the online AUSPOS processing engine [AUSPOS, 2005]. Geoscience Australia recommends 6 hours of dual frequency data will guarantee an absolute MGA position to 2cm accuracy. The results are emailed back to the user in (at best) 15 minutes. AUSGEOID98 can also be used if GPS heighting is required however this is not covered in this paper.

2.9 Regulations

The regulations regarding GPS surveying have lagged the technology however this issue is being addressed in most states and territories in Australia. Note that the regulations differ considerably between the states. In all cases the regulations do not discourage the use of GPS surveying and indeed RTK GPS techniques however some traditional requirements inhibit the use of GPS techniques. An example of this in NSW arises from Reg 27 of Survey Practice Regs NSW (2001) which prescribes length requirements such that:

> "When making a survey, a surveyor must measure all lengths to an accuracy of 6mm + 30ppm or better at a confidence of 95%."

This requirement therefore gives rise to the NSW Surveyor Generals direction to check all RTK GPS derived distances under 120m using EDM. (6mm + 30ppm @ 120m = 0.096m → manufacturer standard error for RTK GPS).

All state regulations refer to the Intergovernmental Committee on Surveying and Mapping (ICSM) document, Standards and Practices for Control Surveys (SP1), ver. 1.5, May 2002. The issue of legal traceability now refers to chapter 11 of the Verifying Authorities Handbook [NMI, 2005] produced by the National Measurement Institute (NMI). The primary standard for measurement of position in Australia is the Australian Fiducial network (AFN). So called "Regulation 13" points are properly connected to the AFN and considered legally traceable. A surveyor need only connect a survey to a Regulation 13 mark to claim legal traceability. Interestingly, in New Zealand and many other countries, GPS measurement does not require legal traceability of measurement [Hook, 2005].

2.10 Other comments

RTK GPS surveying offers a number of other benefits for the cadastral surveyor. RTK is very useful for finding survey marks [Veersema, 2004]. Positions can be measured in the field in real-time and distances derived to compare with plan distances. In difficult terrain where traversing techniques would require many setups with short lines to overcome hills or heavy tree cover, GPS techniques can be used to brace a traverse. This can significantly improve loop closure accuracy as the number of setups and short lines is reduced. However the cadastral surveyor should still walk the boundary to ensure evidence of the original boundary is not missed. RTK is no substitute for good survey practice.

3 Concluding remarks

This paper has attempted to give an overview of the pertinent GPS theory to support the practical considerations presented when using GPS for cadastral surveying. GPS surveying always uses high precision carrier phase measurements. The GPS surveyor may choose to use techniques ranging from post processed single frequency measurements up to high productivity dual frequency RTK procedures. It is hoped that the reader will appreciate that GPS is just another measurement tool and that GPS techniques will rarely be used in isolation on a cadastral survey. There will almost always be the need to connect to a mark or feature under a tree using a total station and hence there will always be a hybridisation of techniques. Many cadastral surveyors are increasingly using GPS techniques to strengthen traverse closures, locate marks in the field, eliminate unnecessary setups in difficult terrain and connect to existing MGA control over distances considered unfeasible using traversing techniques.

New GPS systems are constantly being developed to reduce cables, increase battery life, track new signals, interface more seamlessly with total stations and receive data from continuously operating reference station (CORS) infrastructure via mobile phone. CORS networks are also developing in Australia with examples such as GPSnet across the whole of Victoria [Millner et al, 2004], SunPoz which encompasses Brisbane [Higgins, 2002] and SydNet across the Sydney basin [Rizos et al 2004]. CORS infrastructure will eliminate the need for surveyors to use their own base station which will not only improve efficiency but also the heartache of worrying about the security of their base station. Communications issues, reliability of service and coverage are issues that are currently being addressed at all these CORS networks, however the SunPoz network is already being used to support the cadastre in Brisbane.

Surveyors are high precision users of GPS equipment and therefore must understand the system more fully than other GPS users. It is hoped that this paper will encourage more surveyors to utilise GPS surveying techniques in their daily practice and prosper.

Acknowledgements

The author would like to thank his colleague Dr David Silcock from RMIT University and previous students Steven Ferraro (RMIT) and Adam Veersema (UNSW) for their efforts investigating this topic. Also thanks go out to the many highly professional surveyors from both Victoria and NSW who have attended my GPS workshops and shared their experiences. Your contributions are truly valuable.

References

AUSPOS (2005) [online] http://www.ga.gov.au/nmd/geodesy/sgc/wwwgps/, Web site accessed May 24, 2005

Han, S. (1997) **Carrier Phase-based Long-Range GPS Kinematic Positioning**, UNISURV S49, pp185

Higgins, M. (2002) Australia's changing surveying infrastructure from marks in the ground to virtual reference stations, **FIG XXII International Congress**, Washington, 19-26 April, TS5.6.

Hofmann-Wellenhof, B., Lichtenegger, H., Collins, J. (2001), **Global Positioning System: theory and practice**, Springer-Verlag, 5th Rev. Ed., 382 pages.

Hook, J. (2005) Hawkins, Hook & Co, personal communication.

Interfax (2004) Interfax-Military News Agency newswire, July 14.

Inter-Governmental Committee on Surveying and Mapping (2002), **Standards and Practices for Control Surveys (SP1)**, ver. 1.5, [online]. http://www.icsm.gov.au/icsm/publications/index.html, Web site accessed May 24, 2005

Land Victoria (2005) **Map Grid of Australia 1994: A simplified computational model**, [online] www.lands.vic.gov.au, Web site accessed May 24, 2005

Millner, J., Hale, M., Standen, P., Talbot, N. (2004) The development and enhancement of GNSS/GPS infrastructure to support Location Based Services Positioning Systems in Victoria, **International Symposium of GNSS/GPS**, Sydney, 6-8 Dec.

National Measurement Institute (2005) **Verifying Authorities Handbook**, Third edition, [online] www.nsc.gov.au, Web site accessed Aug 2, 2005

Rizos, C. (1997) **Principles and Practice of GPS Surveying**, Monograph 17, School of Surveying and Spatial Information Systems, The University of New South Wales, Sydney, Australia, 560pp.

Rizos, C., Yan, T., Kinlyside, D. (2004) Development of SydNet permanent real-time GPS network, **International Symposium of GNSS/GPS**, Sydney, 6-8 Dec.

Surveyor General's Directions (2004) **No. 3 Control for Cadastral Surveys**, [online]. http://www.lands.nsw.gov.au/Guidelines/SurveyorGeneralDirections/, Web site accessed May 24, 2005

Surveyor General's Directions (2004) **No. 9 GPS for Cadastral Surveys**, [online]. http://www.lands.nsw.gov.au/Guidelines/SurveyorGeneralDirections/, Web site accessed May 24, 2005

Surveyors Act 2002 no 83, [online]. www.legislation.nsw.gov.au, Web site accessed May 24, 2005

Surveying Regulation 2001, [online]. www.legislation.nsw.gov.au, Web site accessed May 24, 2005

Veersema, A. (2004) RTK-GPS for cadastral boundary surveying in NSW, **Final year Thesis project**, School of Surveying and Spatial Information Systems, University of New South Wales.