

# The Development of a GPS/Pseudolite Positioning System for Vehicle Tracking at BHP Steel, Port Kembla Steelworks

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## BIOGRAPHY

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## ABSTRACT

The Satellite Navigation and Positioning (SNAP) group at The University of New South Wales (UNSW) has been actively conducting research into high precision kinematic GPS, alone and in combination with pseudolites, for the past eight years and two years respectively. This has led to the development of innovative carrier phase single-epoch ambiguity resolution procedures, and software programs that can process GPS and pseudolite data. This paper assesses the

performance of these procedures, as well as pseudolite-only kinematic positioning. Results are presented of trials at BHP Port Kembla Steelworks in Australia, where ultimately the high-precision (cm-level) indoor and outdoor positioning system will be used in the tracking of vehicles.

## INTRODUCTION

The BHP Steel works at Port Kembla in Australia cover an area of approximately 3km<sup>2</sup>. Operations at the works turn iron ore into semi-finished steel products for customers such as the car industry. At the steelworks large steel slabs are manufactured by the continuous casting process, and distributed to the slab handling area via the internal rail network. The steel slabs vary in size from 6 – 12.5m in length, 0.75 – 1.8m in width, and 0.23 – 0.3m in thickness. Slabs are unloaded either by overhead crane and stacked undercover, or using large forklifts and stacked in an outside holding yard. In a single stack there may be up to 12 slabs, with stacks separated by approximately 1 meter. A crane tracking system is used to monitor the indoor slab stacks, and an inventory system based on a Geographic Information System (GIS) has been developed to generate crane 'job instructions' and to automatically manage inventory information without driver data entry. No such tracking is carried out for the forklifts that store and retrieve slabs in the outside holding yard. The maintenance of slab inventories in those areas is therefore by 'pen & paper' and is of lesser accuracy, and potentially hazardous for ground staff. Therefore there is a need for a forklift tracking system to provide forklift operators with clear graphical job instructions, via vehicle VDUs, that include details of other operators in the area and any hazards, thereby reducing the risk of potentially fatal incidents. Rail operations within the Steelworks face similar problems where misinterpretation of, or departure from, verbal safe-working communications could result in potentially dangerous incidents between the fleet of 20 locomotives operating on the plant. The accuracy requirements for the positioning of forklifts and locomotives is better than 10cm horizontally and the carrier phase-based Real-Time-Kinematic (RTK) GPS easily satisfies this.

## SNAP ALGORITHM FOR RTK

Commercial off-the-shelf RTK GPS systems can deliver centimeter-level accuracy in real-time using a pair of GPS receivers; but there are several constraints to their use. The process of carrier phase ambiguity resolution (AR) is essential in order to achieve centimeter-level accuracy. If enough GPS satellites were continuously tracked and cycle slips or satellite signal loss of lock never occurred, carrier phase ambiguities would only need to be determined once at the start of the navigation/survey session. Unfortunately this is seldom the case and satellite signals often become blocked due to buildings. Typically a RTK GPS system must determine carrier phase ambiguities OTF (On-The-Fly) many times during a navigation/survey session for most applications. The time taken to resolve ambiguities is therefore a crucial factor in any RTK system.

During the 1990s several ambiguity search procedures for OTF-AR were proposed, including the FARA, FASF, Cholesky, Hatch, and U-D decomposition methods (Frei & Beutler, 1990; Hatch, 1990; Landau & Euler, 1992; Chen 1993; Abidin, 1993). However, the most optimal procedure uses the LAMBDA transformation in combination with the U-D decomposition search procedure (Teunissen, 1994). When these ambiguity domain search techniques are combined with search procedures in the measurement and coordinate domain, single-epoch OTF-AR is possible (Corbett, 1994; Han, 1997). Of course with single-epoch AR cycle-slips pose no problems. Although single-epoch or instantaneous AR has seen much attention in research institutes, it is only recently that commercial products have been released. Ashtech's Z-Extreme claims 'instant' RTK ('time-to-AR' of 2 seconds, or at the very least a few seconds of data) when tracking six or more GPS satellites (on both the L1 and L2 carriers), with good satellite geometry (PDOP less than 5), and baseline lengths shorter than 7km. For single-epoch AR computing ambiguities is one thing, knowing that they are correct is another. This requires careful attention to issues such as optimal functional and stochastic data modeling, statistical testing, quality assurance (QA), and AR validation procedures. These issues have been considered in the single-epoch AR positioning algorithm developed at UNSW.

The single-epoch AR positioning algorithm has been discussed in previous publications (Han et al., 1999; Dai et al., 2001a). The basic steps of the methodology are outlined here:

1. *Float solution*: Dual-frequency code and carrier phase measurements is used to compute an ambiguity-float solution. The stochastic model used is estimated from the residual series over the previous epochs, when the integer ambiguities are fixed correctly.
2. *Fidelity of models*: The fidelity of the stochastic and functional models is checked using a statistical test against the  $\chi^2$ -distribution. If the test is not accepted

then outlier detection is carried out and satellites are removed.

3. *Ambiguity search*: The LAMBDA procedure is then implemented to search the integer ambiguity set (Teunissen, 1994; Han & Rizos, 1995).
  4. *Ambiguity validation and outlier detection*: The validation criteria test suggested by Han (1997), and the ratio test, is implemented. If both tests are passed, the ambiguity resolution is assumed to be correct. If either test fails outlier detection is performed by removing satellites, starting with the lowest elevation. AR (step 3) is then performed on the reduced satellite set. This continues until all possible combinations of 5 or more satellites are tested.
  5. *Fault detection*: To further ensure that ambiguity resolution is correct, fault detection is conducted. This is based on the fact that Total Electron Content (TEC) of the path through the ionosphere has a very strong correlation in space and time. The double difference TEC sequence ( $\nabla\Delta\text{TEC}$ ) should change smoothly. If  $\nabla\Delta\text{TEC}$  between the current and previous epochs is greater than 5cm the solution is rejected.
- *Previous ambiguities*: If AR fails in steps 3 & 4, or the outlier detection in stage 2 results in less than 5 satellites available, the previous fixed ambiguities (without cycle slips) are introduced. The statistical test in step 2 is then performed using only carrier phase observations, and where necessary outlier detection is performed. If the procedures fail in this step the solution is rejected. In the context of the procedure, AR in this way is called OTF to distinguish it from single-epoch.

From here on the single-epoch AR procedure will be referred to as SNAPK. Assessing the performance of carrier phase kinematic GPS is difficult due to the lack of a 'truth' positioning system with greater positioning accuracy. However, comparisons with existing commercial RTK systems are useful in assessing AR times and validating ambiguities. The NovAtel Millennium-based RT2 GPS system was used as the benchmark RTK system, referred to from here on as RT2. The following kinematic positioning experiments were carried out to assess the performance of the processing strategy.

## PERFORMANCE ANALYSIS OF SNAPK ALGORITHM USING CIRCLE REPEATABILITY

In this test the GPS antenna was made to repeat a circular path and both real-time position data and raw data were collected. This would allow the post-processed (simulated real-time) SNAPK result to be compared against the RT2 real-time result, and the computation of position deviations from a circle.

The test equipment was constructed from an old record turntable and is shown in Figure 1. A box mounted on the turntable housed the RT2 GPS receiver, a radio modem to provide a real-time data link, and a laptop computer to log real-time position and raw GPS data. The GPS antenna was mounted on a pole attached to the top of the box, giving a 70cm circle radius.



Figure 1. Test equipment for circle repeatability test.

The experiment was conducted on the roof the Electrical Engineering (EE) building at The University of New South Wales (UNSW) and the RT2 reference receiver was set up approximately 10 meters from the kinematic rover test area. After ensuring the RT2 had resolved carrier phase ambiguities the kinematic test was started and raw data at both the reference and rover receiver were collected, together with the RT2 real-time positions. The antenna rotated at an approximate velocity of 2.4m/s and was left uninterrupted (clear) for the first 35 minutes of the test. During this period there were 7-8 satellites and PDOP values of 2.8-3.2. Then at every 5 minute epoch interval during the next 30 minutes the rover antenna was covered for approximately 20 seconds whilst still in motion, causing a loss of lock on all satellites being tracked. The RT2 rover receiver would then reacquire satellites and perform OTF-AR. The maximum number of satellites tracked during this period was 8 and the lowest PDOP was 2.9.

### AR PERFORMANCE

The total number of fixed ambiguity solutions for the clear and obstruction test for the RT2 and SNAPK are given in Table 1. For the clear part of the test the RT2 system gave the maximum number (2100) of fixed ambiguity solutions, while the SNAPK gave two less. Of the fixed solutions

99.1% from SNAPK were from single-epoch ambiguity resolution. For the obstruction period SNAPK had 75 more fixed ambiguity solutions than RT2, and 97.5% of these were from single-epoch ambiguity resolution.

Table 1. No. of fixed ambiguity solutions.

Solution type	Total No fixed ambiguity solutions	
	Clear	Obstruction
RT2	2100	1466
SNAPK	2098 (18 OTF)	1541 (39 OTF)

In the obstruction period the time to resolve carrier phase ambiguities is a key issue in dictating the number of fixed solutions. But when do we start the clock? For this analysis the criteria was that at least 5 satellites, with dual-frequency data, were available above 15 degrees elevation, and with a PDOP of less than 5. These are the minimum requirements for the SNAPK algorithm. Using the raw data files and the aforementioned criteria, start times were determined for the 6 intentional satellite obstructions. The time taken to achieve fixed ambiguity solutions for both RT2 and SNAPK was computed and are detailed in Table 2, and represented in Figure 2. In all cases fixed ambiguity solutions were achieved between 6 and 22 seconds quicker using the SNAPK algorithm. SNAPK delivered single-epoch solutions between 2 and 15 seconds after the start criteria had been met. Why the AR times are so variable requires further investigation. One reason might be that the data quality from the receiver is sometimes poorer just after reacquisition.

Table 2. Time to AR.

Obstruction	Time to resolve ambiguities after tracking at least 5 SVs with dual frequency data (sec)		Time diff. RT2 – SNAPK (sec)
	RT2	SNAPK	
1	26	4	22
2	23	5	18
3	16	10	6
4	23	15	8
5	18	2	16
6	21	8	13
Total	127	44	83

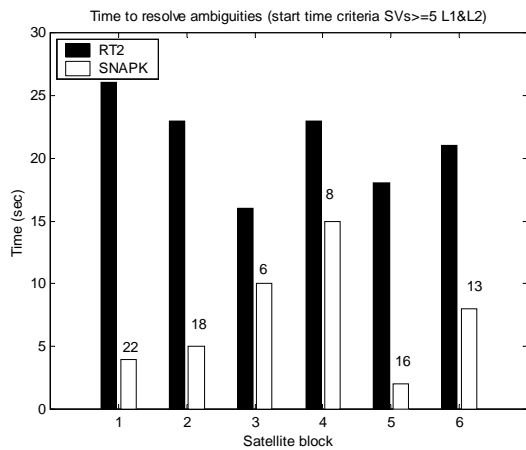


Figure 2. Time to AR (numbers indicate difference).

### QUALITY OF POSITION SOLUTIONS

Fixed ambiguity solutions were extracted for analysis for both the RT2 real-time positions and the SNAPK post-processed results. Differences between the two solutions were computed and are given in terms of ENU in Figure 3.

Overall the position difference time series for the RT2 and SNAPK are acceptable and due to different processing algorithms (functional and stochastic models). The standard deviations in the horizontal component time series are less than 4mm, and 8mm in the vertical. Also there are no significant biases between the two solutions with mean values in the horizontal components of less than 0.1mm, and 4mm in the vertical. To assess how close the SNAPK and RT2 points lie on a circle, a least squares procedure was used to estimate the radius and center of the circle using the easting and northing data. The estimated circle center and radius compared to less than 1mm, and the radius was 2mm different to the measured value. Figures 4 and 5 show the horizontal position results and residuals of the least squares estimation for RT2 and SNAPK respectively. The data gaps in the second half of the residual time series are due to intentional obstruction of GPS satellites as described above. The residual time series both show that for the most part the SNAPK and RT2 positions lie within approximately 1cm of a best-fit circle, and have a standard deviation of 5mm. In some instances, the moment where the antenna is covered spikes occur in the residual time series, and these can also be seen in the horizontal plot. The spikes could be due to a number of factors including: poor measurement quality as the receiver is about to lose lock on satellites, or multipath. The maximum value of the residual is 8cm and so could potentially be due to undetected cycle slips or incorrect ambiguity resolution. However, since they appear in both the RT2 and SNAPK time series this is unlikely.

Overall the experimental results indicate that:

- the precision fixed ambiguity solutions from SNAPK are similar to commercial RTK systems;
- single-epoch SNAPK AR approach has the potential to deliver a greater number of fixed solutions than other OTF techniques, due to the speed of AR;

- no incorrect ambiguity position solutions were obtained, by using the QA procedures for ambiguity validation and fault detection.

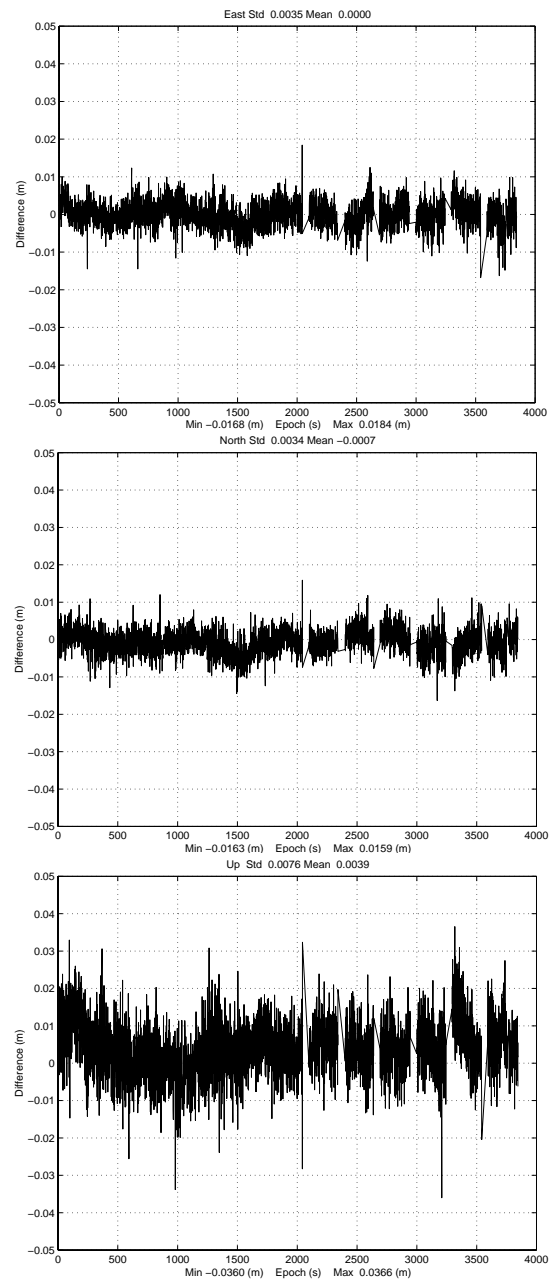


Figure 3. ENU difference in RT2 and SNAPK position.

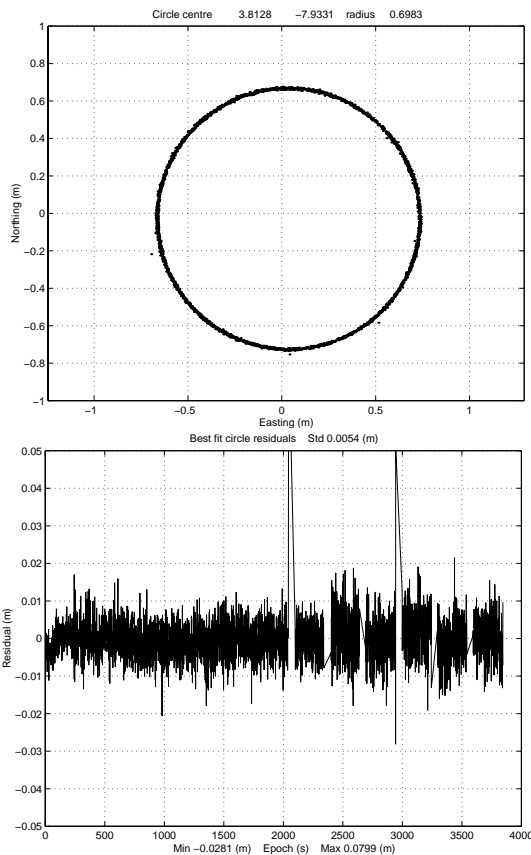


Figure 4. RT2 horizontal position (top) and circle least square residuals (bottom).

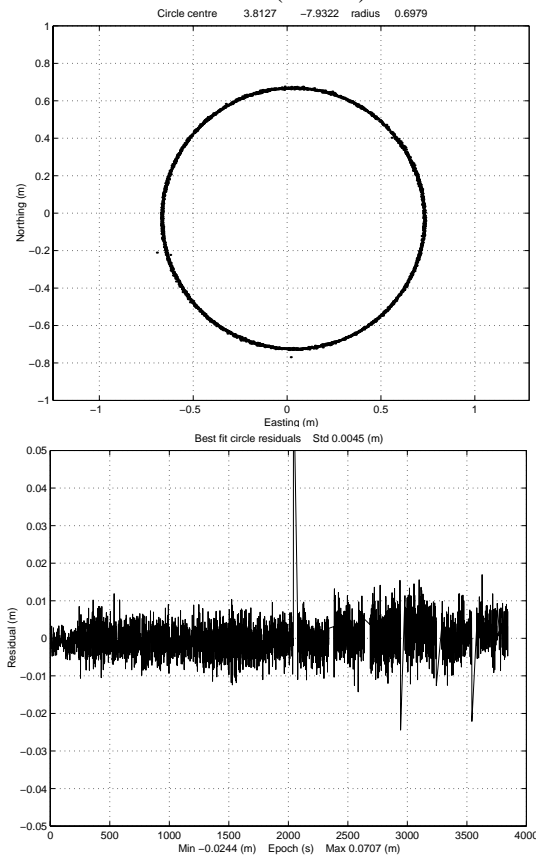


Figure 5. SNAPK horizontal position (top) and circle least square residuals (bottom).

## FORKLIFT TRACKING TRIAL USING SNAPK

A test was conducted at the BHP Steelworks in Port Kembla to assess the ability of the SNAPK algorithm in the harsh steelworks environment. NovAtel RT2 equipment was installed on a forklift that operated in the export slab area. The forklift is responsible for unloading/loading steel slabs from locomotive wagons and stacking them in defined yard locations. Figure 6 shows the forklift in operation stacking slabs of steel, with a GPS antenna mounted on the roof of the cab. The reference GPS station was situated approximately 2km away at Berkley Hill. The trial consisted of six sessions spread over 4 days, and both real-time and raw observation data were collected.



Figure 6. Forklift operating in the export yard at BHP Steel.

The RT2 real-time position solutions were extracted for analysis and the raw data were processed in simulated real-time using SNAPK. Statistics were generated for the number of available satellites, above 15 degrees elevation, during the six trial sessions, and are given in Table 3. For four of the sessions there were less than 4 satellites for between 6 and 10% of the time. This is because large buildings close to the work area can cause satellite signals to be obstructed. As previously discussed for single-epoch AR, the minimum number of satellites required is 5. During the 6 trials there were 5 or more satellites between 68.2 and 99.6% of the time.

Table 3. Availability of GPS satellites for 6 trials.

SVs	Percentage availability of SVs for 6 trials					
	1	2	3	4	5	6
<4	10.15	6.11	3.35	7.51c	0.25e	7.15f
4	16.37	7.74	13.76	24.21	0.13	11.31
5	29.92	42.36	43.93	38.30	2.12	26.50
6	23.74	40.05	28.45	27.90	17.45	25.69
7	14.74	3.55	5.24	2.08	41.85	15.05
8	4.87	0.19	4.37		32.73	12.80
9	0.20		0.91		3.67	1.49
10					1.21	
11					0.59	

The total number of fixed ambiguity solutions for RT2 and SNAPK were calculated and are given in Table 4, and

represented in Figure 7. For all but two sessions SNAPK gave between 4.2 and 6.9% more fixed ambiguity solutions than the RT2 solution. For the other two sessions the RT2 gave 1 and 6.2% more fixed ambiguity solutions. In session 5 the number of fixed ambiguity solutions for both solutions was high (85.3% for RT2 and 92.19% for SNAPK). This was partly due to the fact that the forklift was stationary for much of the session and 99.6% of the time there were 5 or more satellites above 15 degrees. The least number of fixed ambiguity solutions were obtained in session 2, where 44.7 and 52.4% of fixed ambiguity solutions were obtained for RT2 and SNAPK respectively. This was despite the fact that this session had the second highest number of at least 5 satellites available (86.2%). The reason why this session was particularly bad requires further investigation. But there is no doubt that the steelworks environment could potentially be very bad from a multipath point of view.

Table 4. Percentage of time for which there were at least 5 satellites and fixed ambiguity solutions for RT2 and SNAPK.

Trial	Time period hh:mm:ss	≥5 SVs % of time	% Fixed amb. Sol.	
			RT2	SNAPK
1	3:42:10	73.48	53.02	57.21
2	2:45:53	86.15	44.67	52.35
3	3:58:00	82.89	69.87	68.91
4	4:01:02	68.22	57.69	51.54
5	3:59:03	99.62	85.27	92.19
6	3:28:31	81.54	57.44	63.51

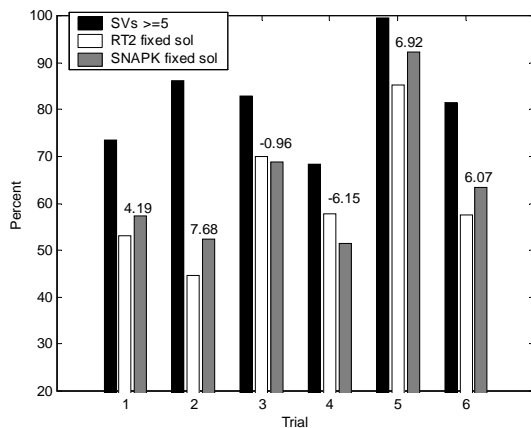


Figure 7. Percentage of time for which there were at least 5 satellites and fixed ambiguity solutions for RT2 and SNAPK (numbers indicate SNAPK minus RT2).

An ESRI-based viewing tool was developed to allow the logged data to be displayed on a digital map of the steelworks. Figure 8 shows a path of the forklift for part of trial 2 yard.

The test has shown that the SNAPK algorithm can operate in the harsh steelworks environment and on four of the 6 trials gave between 4 and 7.5% more fixed ambiguity solutions than a non-single-epoch AR procedure.

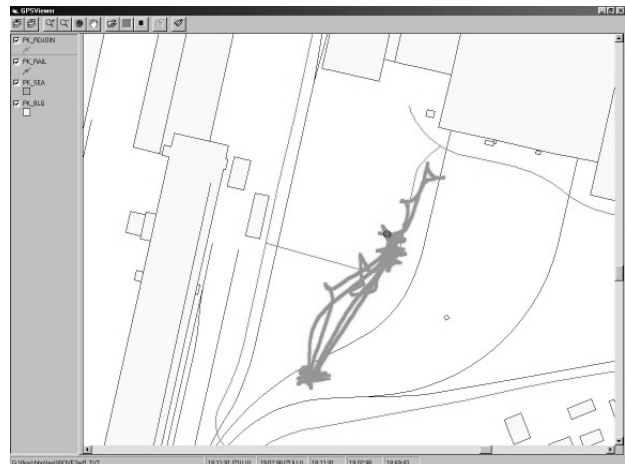


Figure 8. Path of the forklift for part of the trial 2 yard.

The forklift vehicle operations at BHP are not restricted to outdoors, and may operate inside large sheds. Also, during the trials satellite availability was a problem, with four of the six sessions with less than 4 satellites between 6 and 10% of the time. In these situations the inclusion of additional ranging signals transmitted from ground-based "pseudosatellites", also referred to as pseudolites (PLs), could be used to augment or replace GPS entirely.

### PSEUDOLITES

In the 1970s, before the launch of the GPS satellites, pseudolites had been used to test the initial GPS user equipment (Harrington & Dolloff, 1976).

In the last decade pseudolite equipment has been available and been applied to a range of applications, such as aircraft landing (Holden & Morley, 1997; Hein et al., 1997), deformation monitoring (Barnes et al., 2002), Mars exploration (Lemaster & Rock, 1999), precision approach applications, and others (Barltrop et al., 1996; Dai et al., 2001b; Weiser, 1998; Choi et al., 2000; Wang et al., 2000; Stone & Powell, 1999; O'Keefe et al., 1999).

Compared with satellites in space, pseudolites can be optimally located, which can significantly improve the geometric strength of positioning solutions, particularly for the height component. However, due to the comparatively small separation between pseudolites and user receivers, there are some challenging modeling issues such as, non-linearity, pseudolite location errors, tropospheric delays, multipath and noise. In addition, not all GPS receivers can track PL signals and there are near-far signal strength issues. Because of these difficulties PLs are not a mainstream off-the-shelf technology.

SNAP has been actively conducting pseudolite research into the modeling issues associated with pseudolites, and has developed software to process PL data and integrate it with GPS (Dai et al., 2001c).

## KINEMATIC GPS/PSEUDOLITE TEST

An experiment was conducted to examine the performance of a pseudolite-only positioning system that could potentially be used to track forklifts and other vehicles at the BHP works in areas of poor satellite availability, and ultimately indoors. Four pseudolites were available for the test, two IntegriNautics IN200C (IN200) and two Global Simulation Systems GSS4100 (GSS). Canadian Marconi Corp. Allstar (Allstar) GPS receivers were used for reference and rover stations. Allstar GPS receivers allow individual channels to be assigned to track particular PRN codes, and this is an essential requirement when using pseudolites. Also, the Allstar has been shown to have better tracking of PL signals than some other receivers (Tsujii et al., 2002). The circle repeating test equipment described previously was utilised for the test.

In a pseudolite-based positioning system the installation of pseudolites in locations that ensure good geometry is the key to good positional precision. Unfortunately this can often be difficult to achieve logistically. In particular, pseudolite positions at high elevation angles are usually the most problematic. For this reason the walkway outside the EE building (with roof access) was a logical choice for the test area (see Figures 9 & 10). Two GSS pseudolites (assigned PRNs 12 & 32) were setup on permanent poles on the roof of the EE building, approximately 30m above ground level, and connected to two helical antennas of lengths 20 and 15cm. These were directed to beam the pseudolite signals down to the test area on the ground. Additionally, two IN200 pseudolites (assigned PRNs 2 & 4) were setup on tripods at ground level to patch antennas. These were mounted on their side with the antenna pointing in the direction of the test area.

The reference Allstar GPS receiver was setup on a tripod at ground level, approximately 7 meters from the kinematic rover. Table 5 summarizes the approximate elevation angles and distances of the four pseudolites from the rover GPS receiver.

Table 5. Approximate elevation angle and distance to rover.

PL PRN	PL/ Ant.	Elevation (Deg.)	Dist. to Rover (m)
2	IN200/patch	3.8	11.8
4	IN200/patch	0.1	32.8
12	GSS/helical	32.4	40.4
32	GSS/helical	31.2	41.5

Approximately 27 minutes of GPS and pseudolite data were collected at a 1Hz rate, and during this period between five and six GPS satellites were tracked. After the experiment an hour of GPS data were collected using Leica System 500 GPS receivers at the ground-based receiver and pseudolite locations, and at a reference point on the roof of the EE building. On three occasions during the test the Allstar receiver lost lock and had problems tracking PL4 (at ground level).

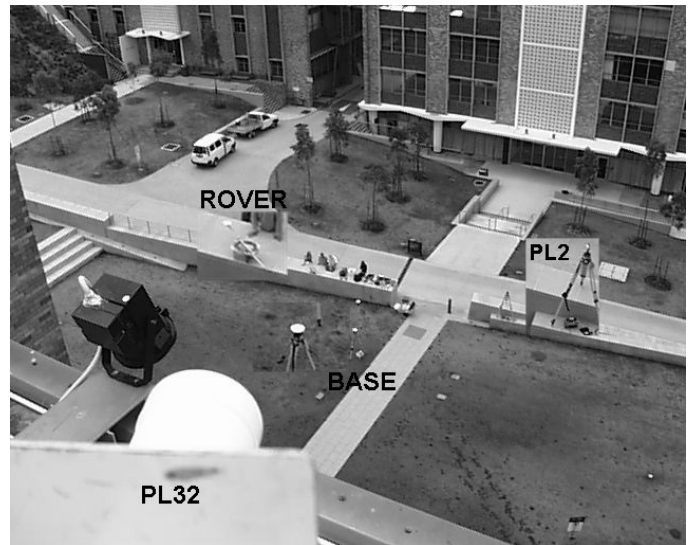


Figure 9. View of test area from EE roof.



Figure 10. View of test area from ground level walkway.

The Leica data was used to determine the precise pseudolite and GPS receiver coordinates. In a static environment it is the usual procedure to compute any multipath biases associated with the PLs (Barnes et al., 2002). However, in kinematic positioning it was expected that these would vary greatly and cannot be calibrated easily.

Single-epoch double-differenced carrier phase solutions were computed for GPS, PL, and GPS/PL combinations. Because the GPS receivers were single-frequency, single-epoch or fast OTF algorithms could not be used and so a static initialisation was carried out to resolve carrier phase ambiguities. Also, when processing the PL data it was apparent that there were many cycle slips from both PLs 2 and 4 at ground level, in addition to the loss of lock on PL4 on three occasions mentioned previously. For this reason the GPS position solution was used to determine the carrier-phase ambiguities for the PL data.

To assess the precision of the three solutions least squares was used to estimate the radius and center of the circle using easting and northing data. Figures 11 to 13 presents the horizontal position series, least square circle residuals and vertical time series (mean subtracted) for GPS, PL and GPS/PL positioning. The standard deviations for the circle residuals and vertical are given in Table 6, together with the HDOP and VDOP values for the three solutions.

For the GPS solution (Figure 11), up to epoch 400, the residual time series has values as large as 5.1cm. During this period the number of satellites was 5 and the HDOP was large (4.8). The poor horizontal geometry during this period is due to the fact that the surrounding tall buildings were obstructing some GPS satellites. With 6 satellites available (after epoch 400) the residuals are all within 2cm. The vertical geometry does not change greatly during the session, and this is reflected in similar residual values (within 3cm) for the entire period. Overall residual standard deviations for the entire period are similar for both horizontal and vertical of about 1cm.

In the PL solution (Figure 12), visually the horizontal plot does not appear circular in places; for example the bottom left quadrant looks flattened. Data gaps due to PL4 tracking problems can be seen in the residual time series. Throughout the time series there are spikes as large as 5cm. The data spikes and misshapen circle suggests that the errors are due to multipath. As expected the precision in the vertical is worse, and this is due to the geometry of the four PLs. If the pseudolites were placed in the optimum configuration (Dai et al., 2001) then better precision could be obtained.

For the integrated GPS and PL the solution (Figure 13) geometry was very high with HDOP and VDOP both less than 1.5. The good geometry is reflected in the standard deviations (approximately 5mm) for both the circle residual and vertical time series. There are data spikes of the order 2cm in the residual time series and probably due to the PL data.

Table 6. HDOP, VDOP. least square circle residuals standard deviation and vertical standard deviation.

L1 single epoch solution type	HDOP	VDOP	Stdev circle residuals (mm)	Vertical stdev (mm)
Pseudolite-only (4 PLs)	3.6	5.5	13.2	16.0
GPS-only (5-6SVs)	4.8-1.7	3.0-3.9	8.9	9.9
GPS-pseudolite (4 PLs & 5-6SVs)	1.4-1.1	1.4-1.3	4.7	5.1

The experiment has shown that in the case of an integrated GPS-PL solution the precision in the vertical component can be improved to a level where it is similar to the horizontal.

Pseudolite-only kinematic positioning has been demonstrated with just 4 PLs, but there were signal tracking problems, and multipath error affected the positioning results. Signal tracking can only be improved through modification of the receiver firmware tracking loops. Additional firmware modifications are also necessary for indoor positioning, because of the time-tag error. This error arises because the pseudolites that are used are not synchronized, unlike GPS satellites. Therefore, in order for the GPS receivers to record measurements at the same time, the receivers must adjust the sample time to the data message of one master pseudolite.

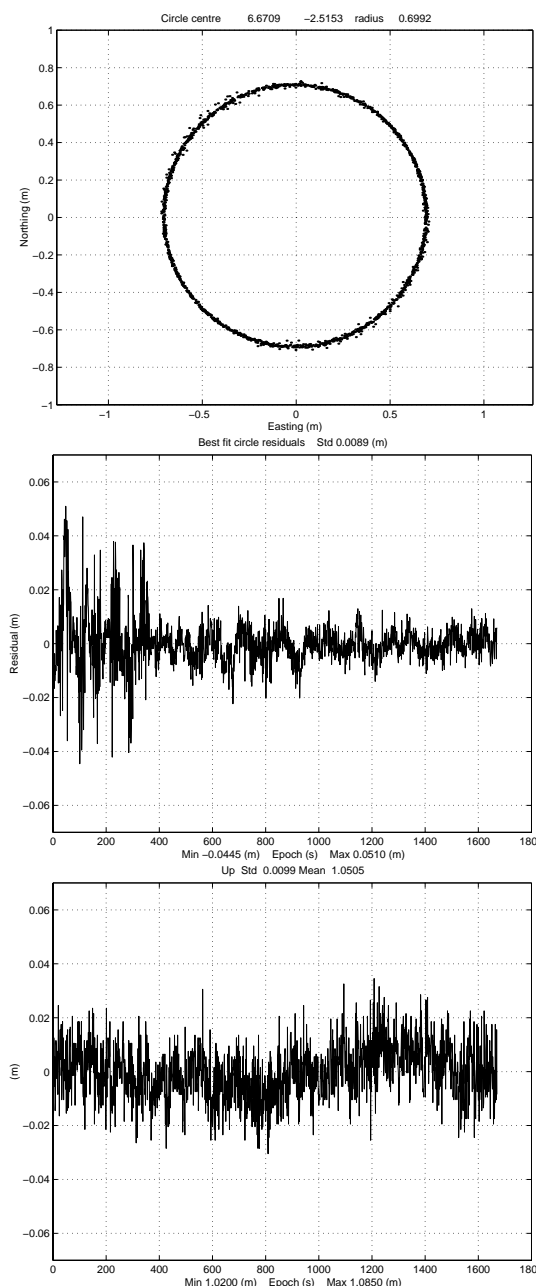


Figure 11. GPS position solution: horizontal (top), circle least square residuals (middle), vertical with mean subtracted (bottom).

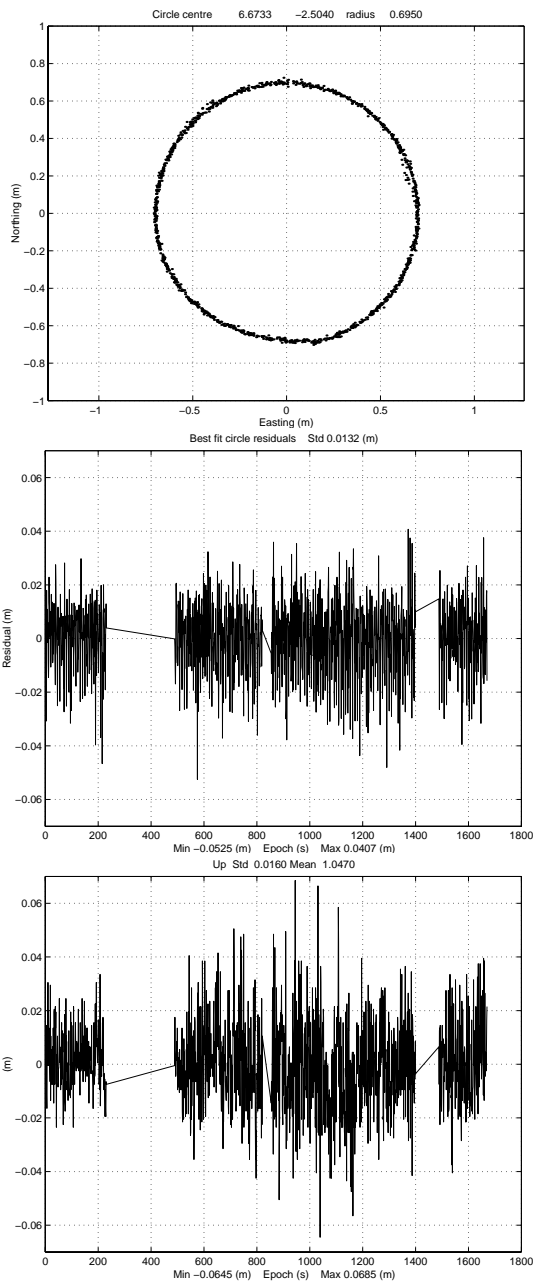


Figure 12. PL position solution: horizontal (top), circle least square residuals (middle), vertical with mean substrated (bottom).

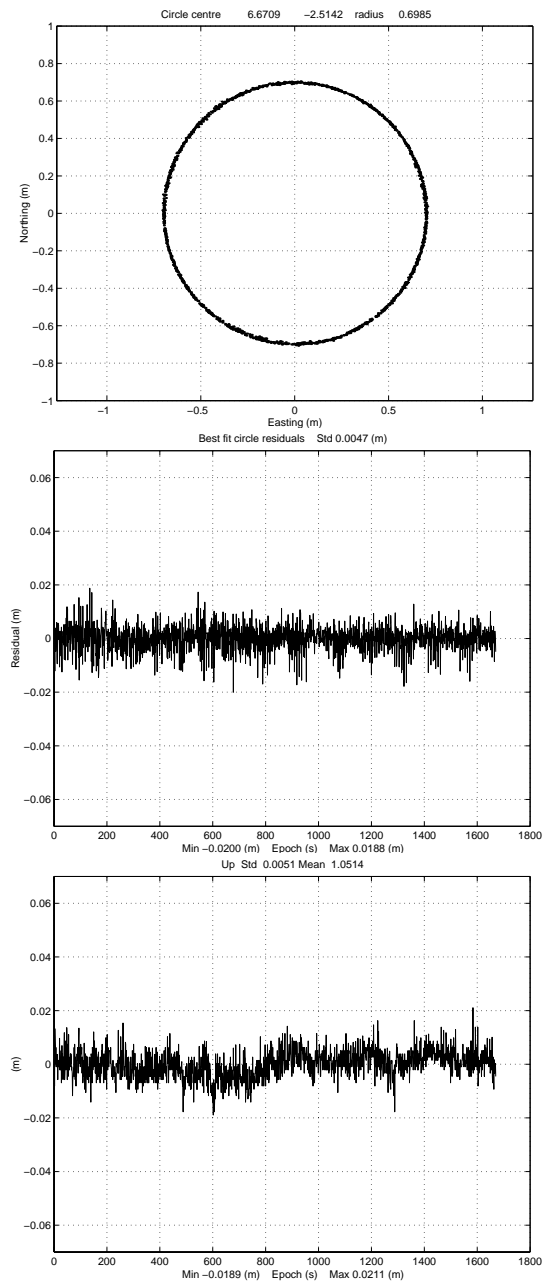


Figure 13. GPS-PL position solution: horizontal (top), circle least square residuals (middle), vertical with mean substrated (bottom).

## CONCLUSIONS

Summarizing the following conclusions can be drawn.

It has been demonstrated that the precision of fixed ambiguity solutions from SNAPK is similar to that of commercially available RTK systems.

Single-epoch SNAPK AR has the potential to deliver a greater number of fixed solutions than other OTF techniques. In a steelworks environment, on four out of 6 trials, there were between 5 and 7.5% more fixed ambiguity solution in comparison to a non-single-epoch RTK.

No incorrect ambiguity position solutions were obtained, by using the QA procedures for ambiguity validation and fault detection.

When using pseudolites in a kinematic environment, reliable signal tracking and the issue of multipath error needs to be addressed. Better signal tracking can only be achieved by modification to the GPS receiver firmware. This is currently being investigated using software development kits from Mitel and Sigtec, and the OpenSource GPS receiver (Kelley et al., 2002).

Finally, a the real-time version of the SNAPK algorithm, that incorportes PL data, is nearing completion and ongoing trials at BHP are continuing.

## ACKNOWLEDGEMENTS

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