PRECISE REAL-TIME KINEMATIC DIFFERENTIAL GPS USING A CELLULAR RADIO MODEM

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ABSTRACT

A series of tests, involving NovAtel's GPS sensor and a NovAtel CRM (Cellular Radio Module) in various differential static and kinematic settings, was conducted in early 1992 to assess the accuracy of differential GPS positioning. NovAtel is a cellular systems and subscriber equipment manufacturer located in Calgary and has recently developed a new GPS receiver. This receiver, available initially in a PC card format, has ten dedicated channels and is capable of extremely accurate and high rate measurements of both the C/A code and the Ll carrier phase of the GPS system.

After a brief overview of the technology used in the main GPS differential system, details and some of the design advantages and capabilities of the various components are given. This is followed by an overview of the various experiments performed and presentation of the results. Data collection and post mission data processing tasks, used for verification of the real-time results, were performed by NovAtel and The University of Calgary's Department of Surveying Engineering.

INTRODUCTION

The results from differential positioning experiments obtained using GPS are the subject of this paper. The main goal of these experiments was to evaluate the effectiveness of using precise C/A (10 cm)[1] code measurements and a cellular modem data link to position consistently and accurately. To assess the performance of the positioning system, various techniques were used. These include using commercially available GPS post processing software (Semikin and C³NAV)[2] and previously surveyed baseline calibration pillars. After a brief description of the equipment used, the testing methodology is reviewed. Various results are then presented which demonstrate the effectiveness of the NovAtel GPSCard™ receiver.

DATA COLLECTION SYSTEM

Overview

The differential GPS positioning system used for this test involved the integration of a portable PC and a cellular modem (cf. Figure 1). An expansion chassis on the PC had the required 8 bit ISA connector for the GPS receiver card. A standard DB9 cable was used to connect the serial port of the PC to an external CRM modem. Magnetic adapters were used on both the cellular and GPS antennas for vehicle mounting. Coaxial cables were required for each of the antennas. Power for the entire system was provided from the test vehicle's 12 volt DC source.

Real-time software used on the PC was developed by NovAtel and consisted of a group of six display screens used to interface with the GPS receiver. The software also was required to: download the firmware to the GPSCardTM, initiate and store

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raw and computed data to the PC's hard disk, and provide an operator interface for the cellular modem. Differential data from the monitor station was broadcast over a ceIlular link. This data was subsequently received at the remote station and passed from the PC serial port, through the program, directly to the GPSCardtm through the ISA bus.

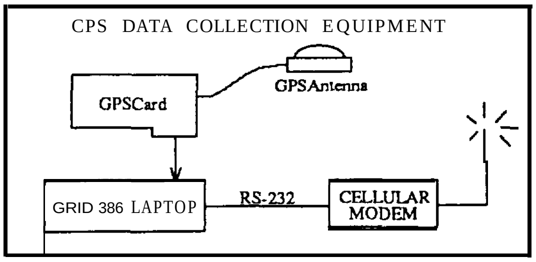

Figure l-Field Data Collection System

GPS Receiver

The NovAtel GPSCardTM receiver1 is a high-performance 10 channel receiver capable of independently tracking the CIA code and carrier phase of all the GPS satellites in view. A wide bandwidth RF front end, combined with high rate multibit sampling, narrow code correlator spacing, and digital signal processing features, yields substantially higher code phase tracking accuracy (10 cm RMS) and high multipath rejection[3]. The high performance onboard 32 bit CPU (INMOS T805), permits rapid raw data recording (100 msec) and high position update rates (200 msec). The dual serial data/command ports and assorted input/output strobes provide support for integration with external systems, real-time differential positioning, remote receiver control, data logging, and time transfer.

GPS Antenna

The NovAtel GPSAntenna™ is a custom microstrip GPS Ll antenna with integrated LNA (low noise amplifier). The internal element design provides signal reception and other advantages of a microstrip antenna (i.e. narrow bandwidth, low cost, and ease of assembly), without suffering some of the inherent disadvantages such as cross polarization signal reception and poor low elevation angle gain. The substrate material used in the antenna element is low loss, with very consistent dielectric properties and excellent high temperature stability. It has a measured phase center variation of 2.66" RMS (1.4 mm at an Ll frequency of 1575.42 MHz). In order to minimize the effects of multipath, a specially designed aluminum choke ring ground plane was used during some of the tests.

Cellular Modem

The Cellular Radio Module (CRM) is a NovAtel designed miniature cellular telephone with built in modem and fax support. This unit allows portable data and voice communications through a cellular radio link. This product is designed to be included within the IBM PC-Radio, an industrial notebook computer. The CRM unit measures 21.5x8x2 cm, requires 5 volts input voltage, draws 9 Watts of power when transmitting, and operates from -10°C to +60°C. Some special features which the CRM supports are: dual output power (0.6 and 1.2 watts), uploadable modem firmware, 32 digit dialing, and dual system registration.

For the CRM to operate, the user must be registered with a cellular system provider. All specialized cellular and modem functions are accessible using Hayes extended protocol commands[4]. The CRM is compatible with standard modems and the higher rate transmit capabilities (9600 baud) are facilitated by various data error correction and compression standards (i.e. CCITT V.32, V.42, V.42BIS, and MNP-4, MNP-5). The CBM also supports Group III Facsimile, and comes in both EAMPS (North American) and ETACS (British) formats. The CRM unit, which was used in a stand alone configuration for this test, was controlled by software on the field testing computer using a built in PC serial communications port.

Portable Test Computer

Two GRID 1535 EXP 386 portables were used for the test. An expansion chassis, capable of taking two full length ISA cards (8 and 16 bit), provided a slot for the GPSCard™ receiver. The computer features include a 12.5 MHz 386D with math coprocessor, **a** 40 MB hard disk drive and a VGA LCD screen. The GRID 1535 is powered using 12 volts DC. The computer and the GPSCard™ required a total of 28 Watts of power during testing operations.

TESTING **METHODOLOGY**

Data c o ˙ -

In order to access accuracies of the differential positioning capabilities of the GPSCard™ Model 1001 card, a series observation sets where taken. Data was collected over a zero baseline (i.e. using two receivers and one antenna) at NovAtel's corporate head office in Calgary. Data was subsequently recorded on various short base lines west of Calgary. The 4 km and 8 km GPS data sets were measured on an Electronic Distance Measurement (EDM) calibration baseline in the Springbank area. The absolute GPS position for these pillars were obtained directly from the Canadian Government's Geodetic Survey Division. Additionally, data was collected over a 12.5 km baseline in the Bearspaw area with absolute coordinates which have been confirmed using other GPS receivers. The semi-kinematic survey was also conducted using the Springbank EDM calibration pillars. A vehicle was used to transport the antenna from pillar to pillar over a maximum distance of 1.3 km. No antenna ground plane was used on the moving remote during this phase of the testing.

All data collected during the various tests was logged in ASCII format. The recorded data fields included: raw range, satellite ephemeris and almanac messages, position, velocity, receiver clock offset, satellite elevation and azimuth, and DOPS (dilution of precision values). Most logs, with the exception of ephemeris, almanac, and DOPS data, were logged at a rate of once per second. At the monitor station, the transmitted differential corrections were logged.

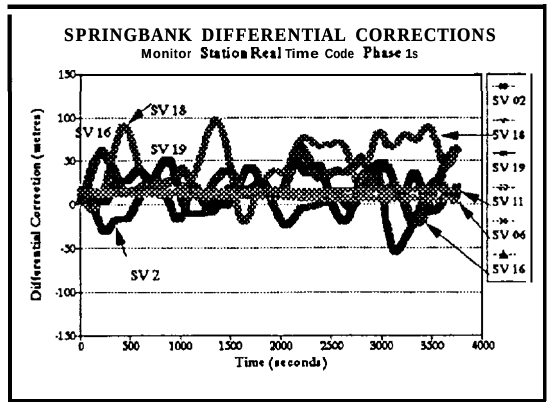

Figure 2-GPS Differential Corrections

The NovAtel receiver specific short form ASCII differential corrections log included: time, satellite prn, differential corrections and their associated rates, and IODE (issue of data of the ephemeris). These correction values were satellite specific (cf. Figure 2) and derived using a fixed position entered by the operator. Carrier phase data was used in the post processing to help assess the accuracy of the real-time differential results derived from code phase.

RESULTS

Evaluation of Results

Evaluation of the results from this test was accomplished using a variety of methods, Zero baseline results were used to assess measurement noise in the absence of atmospheric and multipath effects. Fixed baselines over various distances, derived using independent methods, were then used to assess static positioning real-time accuracies.

Results derived from carrier phase using a fixed ambiguity double difference solution, were used for comparison purposes for both kinematic and static observing conditions. This analysis was performed using the software package, Semikin[5], developed at the University of Calgary. Finally, in order to compare real-time with post-processed results using either pure code or carrier smoothed code, the C^3NAV software program[2] (also developed at the University of Calgary) was used.

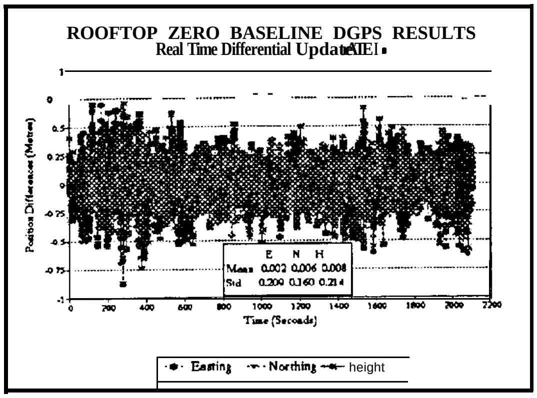

Figure 3-Zero Baseline Differential Results

Zero Baseline GPS Results

In order to the assess the accuracy of the GPSCard™ and the cellular modem, GPS data was collected over a zero length baseline. This configuration removes all common site specific mutipath errors and atmospheric errors. Examination of Figure 3 reveals the code phase measurement noise translates into approximately 20 cm. This is consistent with 10 cm RMS range accuracy and a GDOP of 2. The zero baseline data was collected at a rate of 1 second from the roof of NovAtel's head office in Calgary on March 4, 1992.

Static Baseline GPS Results

A series of tests were conducted to collect GPS differential data over fixed baselines of 4, 8 and 12.5 km. The results from these tests are summarized in Tables 1 to 3 below. The Springbank data was collected on February 17 and the Bearspaw data was collected on March 10, 1992.

The basis for the true values used in the comparison were derived from both previous GPS surveys using other manufacturer's equipment and from Semikin pure phase, fixed ambiguity, double difference data.

Springbank 4 km Static Baseline			
	R/T	P/P C3	P/P C3
Coord	Code	Code	Carrier
Means (m)			
Lat	-0.69	-0.08	-0.05
Lon	-0.17	0.00	-0.02
Hgt	0.31	0.02	-0.01
Standard Deviations (m)			
Lat	0.57	0.32	0.17
Lon	0.24	0.17	0.10
Hgt	0.77	0.75	0.38

Table l-Static Differential Results 4 km

Generally C^3NAV post processed (P/P) code phase only results are slightly better than real-time (R/T) results. This was as expected since there are differential rate errors in real-time which disappear in post processing. The large rates exhibited by the differential corrections in Figure 2 are largely due to S/A effects. This is verified by Block 1 satellites (PRNS 6 and 11) which have no second order trends.

Springbank 8 km Static Baseline			
	R/T	P/P C3	P/P C3
Coord	Code	Code	Carrier
Means (m)			
Lat	0.08	-0.00	-0.01
Lon	-0.13	0.06	-0.06
Hgt	0.19	0.01	-0.01
Standard Deviations (m)			
Lat	0.31	0.33	0.20
Lon	0.80	0.19	0.11
Hgt	1.29	0.39	0.26

Table S-Static Differential Results 8 km

These rate error effects are of course more pronounced if there are any delays in modem transmission due to high noise cellular reception problems. This is an unfortunate by-product of using error detection and compression techniques to transmit data at a higher rate (i.e. 9600 baud). During some of the field testing, delays of up to 30 seconds resulted in differential range correction errors which are magnified by the current satellite geometry into position errors of a few metres.

Bears [redacted] *aseline*

Mea[redacted]			
Lat	-0.10	-0.14	-0.15
Lon	-0.44	-0.42	-0.41
Hgt	-0.12	-0.22	-0.27
Standard Deviations (m)			
Lat	0.60	0.59	0.26
Lon	0.35	0.32	0.13
Hgt	1.01	0.97	0.43

Table S-Static Differential Results 12.5 km

C[3]NAV code and carrier phase combined results are generally better than pure code. This is as expected since the noise level on the ranges are reduced. Standard deviations from the mean, however, are not as low as might be expected. This is due to the small remaining biases in the carrier phase smoothed pseudo range observations (cf. Figure 7).

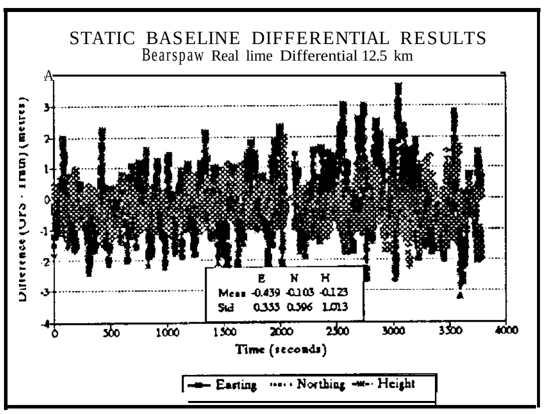

Figure 4-Real-Time Static Differential Positioning Results

Semi-kinematic GPS Results

A semi-kinematic test was performed on March 17, 1992 using a series of pillars at the Springbank EDM calibration baseline. The raw data was later post-processed, as in the previous experiments, to generate post-processed code and code/carrier position differences. The baseline distance for this experiment ranged from 700 metres to 2.3 km.

Semikin software also generates intermediate positions between the pillars using a Kalman filter and previous knowledge of the integer ambiguities. If a cycle slip occurs on only one satellite, its integer ambiguity can easily be recovered. It is therefore important to collect data when six or more GPS satellites are visible.

The Semikin kinematic data was used to derive code generated real-time and C[3]NAV kinematic position differences, since it is accurate to within a few centimetres. This is of course assuming that continuous phase data without cycle slips is available.

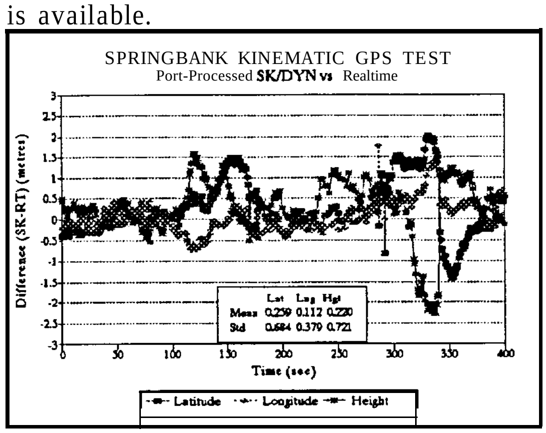

Figure 5-Semikin Dynamic Positions vs Real-Time Positions

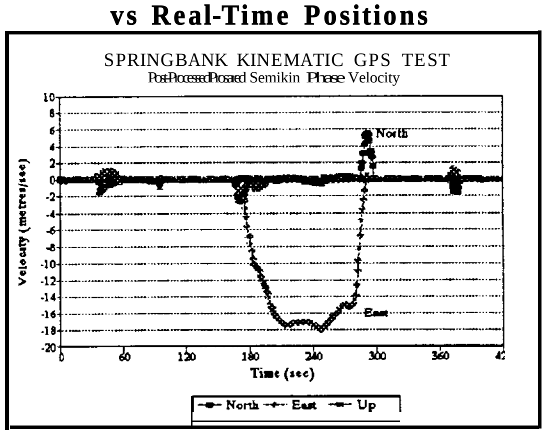

Figure 6-Semikin Phase Derived Velocity

Figure 5 illustrates positions collected when moving the antenna off of a pillar, attaching it to the roof of a vehicle, and driving 2 km to the next pillar. Maximum velocities reached while transporting the antenna were 18 m/s (40 mph) as illustrated in Fi,gure 6. The pillar sites are not totally free from multipath due to local obstruction: (e.g. trees, fences, and power lines) which may explain some of the high level of code errors illustrated in Figure 5. Note that these errors also closely match the periods when the antenna was on the vehicle before leaving for the next pillar.

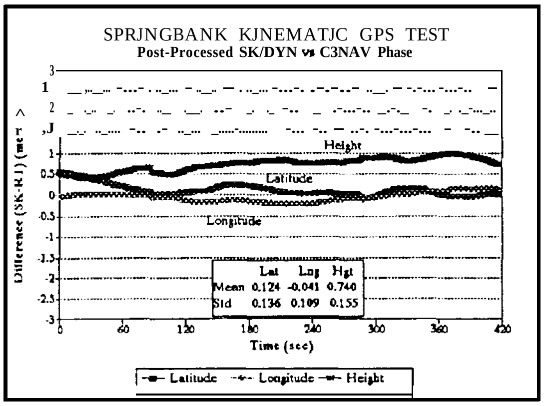

Figure 'I-Semikin Dynamic Positions vs C^{3}NAV Code/Phase Positions

To verify that Semikin and C^{3}NAV results were consistent, a final graph was generated to illustrate the difference between pure phase and phase smoothed code results (Figure 7). Note that minor discontinuities at 90 and 290 seconds are due to the C^{3}NAV switching from one smoothing filter to another to dissipate any biases. Again, as we saw in previous static results, the standard deviations indicate a small amount of biasing (10-20 cm) still occurs.

Several runs were made between the pillars on the Springbank EDM baseline and the results are summarized in Table 4. Kinematic data periods ranged from 300 to 400 seconds and Semikin phase derived results were used for comparison. A majority of the data used in this paper was collected during periods of 5 and 6 satellite coverage with GDOP values ranging from 2 to 5.

Springbank Kinematic Results			
Run No.	Lat.	Lng.	Hgt.
	Means (metres)		
1	0.259	0.112	0.220
2	0.030	0.003	0.545
3	-0.599	-0.497	0.836
4	-0.655	-0.572	0.684
5	-0.765	-0.636	0.356
6	-0.696	-0.729	0.143
	Standard Deviations (m)		
1	0.684	0.379	0.721
2	0.477	0.395	0.605
3	0.357	0.236	0.882
4	0.371	0.287	0.943
5	0.527	0.231	0.632
6	0.523	0.323	0.834

Table 4-Real-Time Kinematic Positioning Results

CONCLUSIONS

The equipment used to collect real-time differential GPS positions was overviewed. The two central components of this positioning system, the NovAtel GPSCardTM 10 channel receiver and the NovAtel CRM modem, were discussed. This GPS field portable system used for data collection will no doubt evolve into a single product and in the future prove economical for various applications in areas of cellular coverage.

Positioning accuracies using code phase based differential corrections were found to range from 20 cm, in an ideal zero length baseline scenario, and up to 1 metre over longer static baselines of 12.5 km. Kinematic results over baselines of less than 3 km were found to exhibit the same errors as static data, with means ranging from 30 to 70 cm and standard deviations from 40 to 90 cm.

Exploitation of accurate code data to resolve integer ambiguities, and in effect achieve real-time cm level double difference positioning accuracies is almost a reality.6 The future of these and other techniques to enhance positioning accuracies, will no doubt be found embedded in the high end application equipment. There will, however, be increased computation and data transmission demands which will require further advances in software and hardware and more research and development.

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Thanks to Rob Miller from the CRM development team at NovAtel who helped get the cellular modems programmed for cellular system authorization and set all those complicated protocol defaults. Last but not least an acknowledgment for the dedication of Henk Kroon from the GPS Products Group at NovAtel for his patience in developing a software interface for real-time.

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