Test Results from a New 2 cm Real Time Kinematic GPS Positioning System

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BIOGRAPHIES

Janet Brown Neumann obtained a BSEE from the University of Kansas in 1978 and an MSEE from Iowa State University in 1981. She has been active in GPS software and algorithm development for 13 years, with her recent focus being on carrier phase positioning methods and software.

Allan Manz obtained an B.Sc.(86), P.G.D.(89), and M.Sc.(93) in Mech. Eng. from the University of Saskatchewan. He was active in the area of real time collision avoidance for autonomous vehicles for six years before switching to the GPS field during the previous year.

Tom Ford graduated from the University of Waterloo in 1975 with a B.Math and from the University of Toronto in 1981 with a BSc. Until 1989 he designed software for inertial, doppler and GPS survey systems for Nortech Surveys Ltd. From 1989 to the present he has been part of the Novatel GPS design team, and has made contributions to various areas including signal processing, pseudorange and carrier based navigation, attitude determination and most recently pseudolite integration.

Orest Mulyk is student in the Computer Engineering Department at the University of Alberta, Edmonton, Alberta He has been working at NovAtel as part of a co-operative education program.

ABSTRACT

This paper presents test results from the new RT2 real-time carrier phase positioning system developed by NovAtel. The single frequency carrier phase positioning technology introduced in 1994 as RT20 has now been expanded to take advantage of the dual frequency capability recently introduced. The objective in developing this system was to add to the technology used in RT20, retaining its advantages while adding dual-frequency algorithms to speed initialization time, improve short baseline accuracy by using fixed integer ambiguity estimates, and extend the range of usable baseline lengths with ionospheric corrections.

This paper fust provides a brief description of the measurement processing used for various baseline lengths. Testing methods are then described and results are presented describing integer resolution speed, positioning accuracy and performance during poor radio coverage.

INTRODUCTION

The RT20 real-time kinematic (RTK) carrier phase positioning system was introduced in 1994 by NovAtel [1]. It uses an Ll-only receiver, and performs a continuous-valued estimation of carrier phase ambiguities with a Kalman Filter to obtain a nominal accuracy of 20 cm on short baselines. The emphasis is on producing robust low-latency position estimates at up to 5Hz rates, with modest data link requirements. Emphasis is also placed on ease of use by automatically detecting motion, not requiring user-entered parameters and smoothly accommodating varying baseline lengths.

A new RTK system has now been developed to take advantage of the dual frequency capability recently introduced by NovAtel. The objective in developing this system was to add to the technology used in RT20, retaining its advantages (robustness, high output position rate, modest data link requirements, and ease of use), while adding dual-frequency algorithms to speed initialization time, improve accuracy and extend the range of usable baseline lengths. In the new RT2 system, Ll/L2 observations are used to determine fixed-integer ambiguities on shorter baselines, and to reduce ionospheric effects on longer baselines. All processing is done on the base station and receiver boards. Initialization is done either while moving or stationary. In order to maintain the robustness, ease of use, and variable baseline length capability, RT2 uses several different estimators and measurement types, depending upon the state of resolution and the baseline length. An efficient and robust format is implemented for dual-frequency base station broadcasting, and the RT20 base station observation prediction and motion detection algorithms are expanded to include the L2 observations. Together these features allow the production of 4 Hz centimeter-level positions, still using a modest data link. The nominal measurement accuracy is better than 2 cm, and base station observation prediction allows low-latency position updates at higher rates than the base station message transmission rate, with little accuracy degradation. Transitions to longer baseline lengths are graceful, with convergence time gradually increasing, and accuracy gradually decreasing.

The system has been designed to be easy to use. Once his data link to the base station has been set up, the rover receiver user simply types one command, and the receiver automatically drops into RT2 mode. He will receive the low latency RT2 positions in the NovAtel position logs, with standard deviation values indicating the current positioning accuracy. He may stop and go as he pleases, without entering any further commands. The various modes and estimation methods described below will all be transparent to him. The more interested user can also: choose static or kinematic mode, choose to receive matched positions rather than low latency positions, turn off the integer ambiguitiy fixing function, or initialize from a known baseline. However, these capabilities are completely optional.

SYSTEM DESCRIPTION

Overview:

An RT2 system consists of a base station receiver and a rover receiver. The base station receiver packages its observations into an RTCA "type 7" proprietary message (specific to NovAtel) and transmits them to the rover receiver. The message format uses the redundancy in the various observations to tit Ll and L2 pseudorange and carrier phase observations into one message which contains 140 + 92N bits, where N is the number of satellites being tracked. The user can limit the number of satellites used if he so wishes, and they will then be chosen by elevation angle. The message also contains 12 + 8N spare bits, which can be used for future flexibility. The remainder of the processing occurs at the rover receiver.

The users of this system are expected to be quite varied. Position output latency will be the big consideration for some: for others accuracy may dominate their concerns. Some may be working only at very short baselines, others may want to extend the baselines to tens of kilometers, or even farther. For this reason, the system contains several baseline and ambiguity estimators. Figure 1 shows a very simple block diagram of the positioning system at the rover. The estimators can be divided into two "streams", the "low-latency'* stream, and the "matched measurement" stream. Whenever a measurement set is taken at the rover receiver, the low-latency estimator makes a prediction of the base station observations at that time epoch, and combines them with the rover observations to provide position estimates which have a typical latency of about 100 ms, regardless of the baud rate of the data link. The RMS position error is typically 1 or 2 cm on short baselines (assuming messages can be sent every 1 to 2 seconds, and assuming reasonably good geometry), even under user dynamics. The matched estimators wait for the base station observations to arrive for that time epoch, and provide a delayed, but more accurate position estimate. The matched and low latency estimators run in two separate tasks, so as not to delay the low latency position output.

Low Latency Position Processing:

The low-latency baselines are estimated using a simple 3-state (ECEF XYZ) Kalman Filter. Rather than modelling velocity, the filter is reinitialized with each baseline estimate. No smoothing is done on the position. The primary inputs are the satellite positions, the predicted base station observations, the current rover observations, and a set of ambiguities which have been estimated in the matched stream. These ambiguities are the "best" available at that time, and may be either continuous values or fixed integers.

The observations are predicted using a set of 3-state Kalman Filters which mode1 the Ll carrier phase observation and its velocity and acceleration [l]. These states are used to predict the base station observations at future time epochs. The Ll states are also used in the prediction of L2. A filter is maintained for each satellite tracked at the base station. Residuals are calculated, and used in the baseline estimator to choose tbe double difference reference satellite, to weight different observations according to their accuracy, and to output accurate standard deviation values.

Matched Observation Processing:

The processing done in the "matched" stream performs a number of functions. The major functions are 1) perform motion detection, 2) estimate ambiguities, 3) estimate a position, 4) perform integrity monitoring.

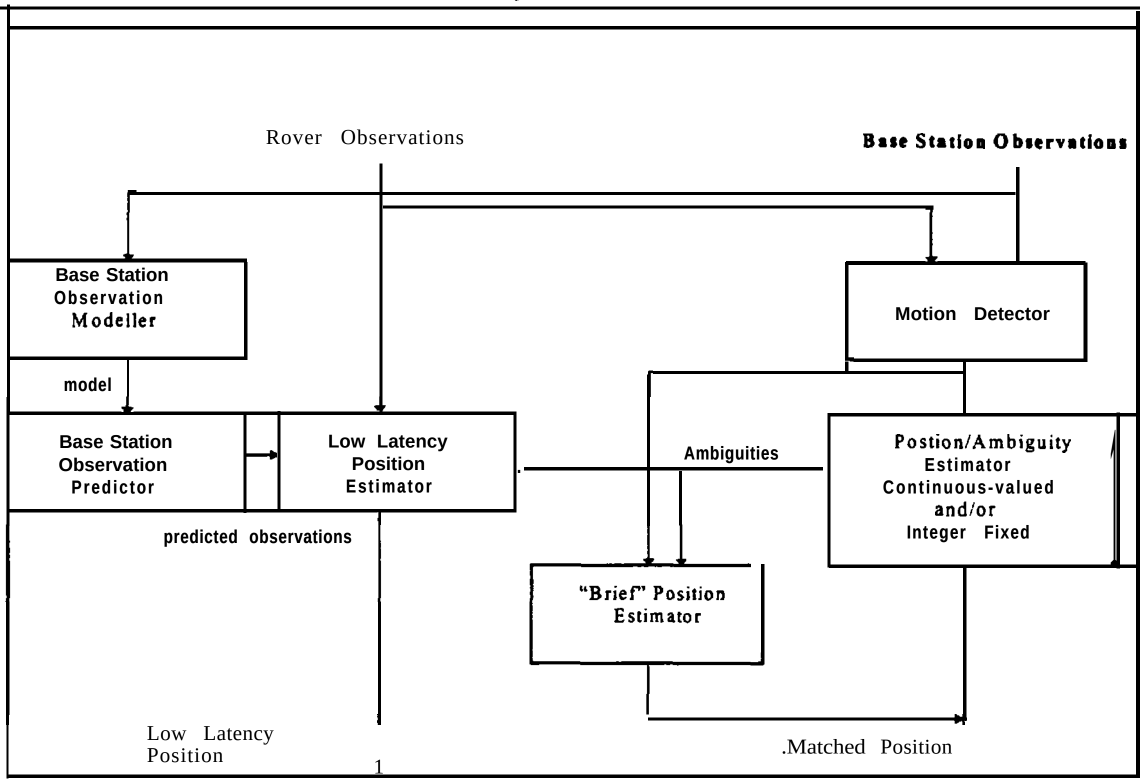

Figure 1. RT2 Rover Positioning Block Diagram

The advantage of using the carrier phase observation for positioning lies in the fact that it can be measured much more accurately than the pseudorange can be measured. Unfortunately, it is an ambiguous measurement; the number of whole carrier phase cycles between the user and the satellite at the start of tracking is not known, and must be estimated. This estimation can be in the form of a continuous value (as in the RT20 system), or can be obtained by estimating the best set of integer ambiguity values. The latter is known as an "integer ambiguity resolution". This can be done with either single frequency (Ll only) or dual frequency (L l/L2) data, but the extra information in the second frequency greatly increases the speed and reliability of resolution.

The continuous-valued ambiguity/baseline estimator used in RT20 has been expanded to use L2 observations in addition to the Ll observations. This estimator models both baseline components and ambiguity values as states in a Kalman Filter. It is described in [l] and is based on concepts presented in [3]. (The rover position estimate is derived directly from the base station position and the baseline estimate.) This estimator is used to provide position estimates prior to integer ambiguity resolution, to initialize the ambiguity search space, to monitor fixed integer baseline estimates, and to produce position estimates at longer baselines using iono-free observations. A fixed-integer ambigutiy and baseline estimator is used as the primary position estimator for short and medium baseline lengths. A "brief' baseline estimator also runs to provide matched positions in kinematic mode between the nominal updates which take place at 4 second intervals. It uses the latest 'best ambiguity" set and the current observations to estimate the three baseline components. The matched stream of estimators also includes a motion detector so that the best use may be made of static occupations, without burdening the user with the need to enter "stop" and "go" commands to the receiver. The motion detector runs whenever a base station observation set is received. It can detect motion of about 2 cm per second or greater. Under normal operating conditions, it produces false alarms only under poor coverage or geometry conditions. The user can also manually specify static or kinematic mode to the system, if he prefers. All the baseline estimators use a double difference mechanization of the observations. See [5] or [8] for a description of the double differencing operation.

Use **of** Ll and L2:

When both Ll and L2 are available, the observations can be used in a number of ways. They can be used separately, with separately resolved ambiguities (continuous-valued or integer), or they can be formed into a linear combination with one combined ambiguity defined.

Some common linear combinations used with Ll and L2 observations are wide-lane, narrow-lane and iono-free A quick summary is provided here, [4], [5], and [9] provide more details on the subject.

Wide-lane:

$\Phi_{WL} = \Phi_{L1} - \Phi_{L2}$

The error due to noise and multipath is:

$\varepsilon_{L1} - \varepsilon_{L2}$ in wide-lane cycles, with a variance of $\sigma_{L1}^2 + \sigma_{L2}^2$ in wide-lane cycles'.

where:

Φ_{L1} and Φ_{L2} are the Ll and L2 carrier phase observations, ε_{L1} and ε_{L2} are the errors on the Ll and L2 carrier phase observations due to noise and multipath, and σ_{L1} and σ_{L2} are the standard deviations of those errors.

If σ_{L1} and σ_{L2} are 0.05 cycle (about 0.85 and 1.2 cm, respectively), σ_{WL} will be 0.0707 wide-lane wavelengths(86 cm), or about 6 cm., when used as a range measurement.

Integer wide-lane values are about 86 cm apart. The wide spacing eases the search process, but the amplification of the error degrades the accuracy of the wide-lane positions.

Narrow-lane:

$\Phi_{NL} = \Phi_{L1} + \Phi_{L2}$

The error due to noise and multipath is:

$\varepsilon_{L1} + \varepsilon_{L2}$ in narrow-lane cycles, with a variance of $\sigma_{L1}^2 + \sigma_{L2}^2$ in narrow-lane cycles'

If σ_{L1} and σ_{L2} are 0.05 cycle, σ_{NL} will be .0707 narrow-lane cycles(11 cm), or about .78 cm.

Integer narrow-lane values are about 11 cm apart. This makes them difficult to search for, but they produce accurate positions once determined.

Iono-free:

$\Phi_{iono\text{-}free} = 2.546\Phi_{L1} - 1.984\Phi_{L2}$

The error due to noise and multipath is:

$2.546\varepsilon_{L1} - 1.984\varepsilon_{L2}$ in iono-free cycles.

It's variance is:

$(2.546)^2\sigma_{L1}^2 + (1.984)^2\sigma_{L2}^2$ in iono-free cycles^2.

If σ_{L1} and σ_{L2} are 0.05 cycle (about 0.85 and I.2 cm, respectively), σ_{WL} will be 0.161 iono-free cycles, or about 3.07 cm.

This combination produces an observation free of ionospheric corruption, but with increased error due to noise and multipath. Due to the increased error, this combination is used only for longer baselines.

Double differences can be formed with any of the various L l/L2 combinations.

In the RT2 system, on baseline lengths of IO km or less, a wide-lane integer ambiguity resolution is done first using a fixed integer searching technique. The searcher is based on the concepts presented in [3], modified somewhat for practicality. A handoff from wide to narrow-lane ambiguities happens as soon as it can be done reliably. The narrow-lane position solution is then used as the primary output to the user. An Ll only integer ambiguity estimate is also maintained, to be used if the L2 signal is dropped while the Ll signal is still tracking. (When the wide-lane and narrow-lane ambiguities are known, the individual Ll and L2 ambiguities can be computed directly).

INTEGER RESOLUTION SPEED

The amount of time required to obtain integer ambiguity estimates is always of interest in a fixed integer ambiguity system. It has been noted a number of times (e.g. [6] and [7]) that specifying the resolution speed means very little, if a corresponding reliability level is not indicated. It is also useful to make a general description of the operating conditions needed for that speed and reliabilty level (e.g. multipath environment and baseline length), as these can greatly affect both the resolution speed and reliability.

The data used to verify the integer resolution speed was collected from the NovAtel rooftop with one antenna using a "choke ring" for low multipath and the other antenna in a fairly typical rooftop environment. We feel this represents a typical user environment. The base station would normally be sited under fairly low multipath conditions, but the user of the rover receiver generally has less control over his environment. At the elvation angles used for RT2 (above 11 degrees), the carrier phase double difference residuals (primarilly due to multipath) are typically 0.05 cycles or less on Ll and L2, but can sometimes reach 0. l cycles or slightly more. The baseline length is about 4 meters, with less than one meter of vertical difference.

Observation data was collected for 39 hours from the rooftop environment noted above, and stored. The data was then processed offline using the RT2 algorithms, in both static and kinematic modes, with algorithm resets forced every 5 minutes. In these runs, and also in several other runs done with slightly different reset periods, no erroneous integer ambiguity decisions were made. Figure

2 shows a histogram of narrow-lane integer resolution times for the kinematic mode. Figure 3 shows cumulative narrow-lane integer resolution time statistics for both modes. (Note that for a given number of available satellites, an actual kinematic resolution would generally be a bit faster since the multipath is broken up when the user is moving). Although in most short baseline cases, there is little difference in the resolution times for "static" and "kinematic" modes, in Figure 3, statistics are presented for both modes, since in difficult cases, knowing itself to be static does help the system. The RT2 motion detector makes this decision is transparent to the user. Figures 2 and 3 represent statistics for a "typical mix" of satellite constellations with 6 or more satellites above the 11 degree mask angle. The system will also resolve in either mode with 5 satellites, but it is slower, and the times less consistent. Also, since there are few time periods with only 5 satellites above the mask, the statistics are less meaningful For this data set, median narrow-lane integer resolution times with 5 satellites in static and kinematic modes were about 1.8 and 3.6 minutes, respectively.

Various other sites for the rover receiver were also tested, and the system was found to make erroneous choices only when the multipath became quite excessive. Resolution times were found to be fairly consistent up to baseline lengths of 5 km, then increasing slightly as the baseline increases to 10 km (longer baselines are discussed in the next section). Accuracy on short baselines was consistant with that found on the rooftop.

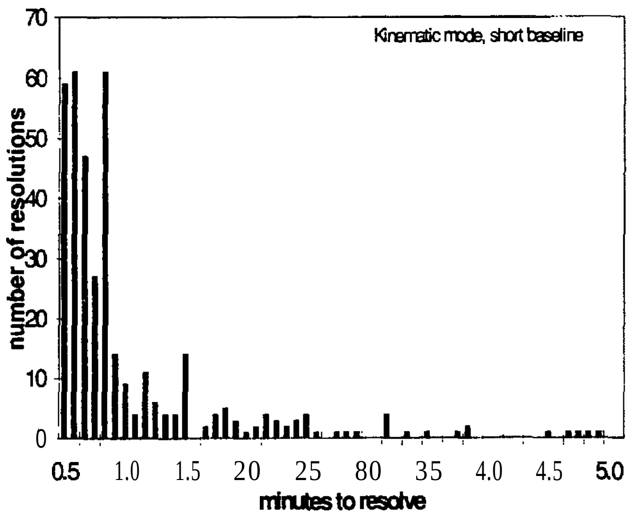

Figure 2. Histogram of RT2 Narrow-lane Resolution Times

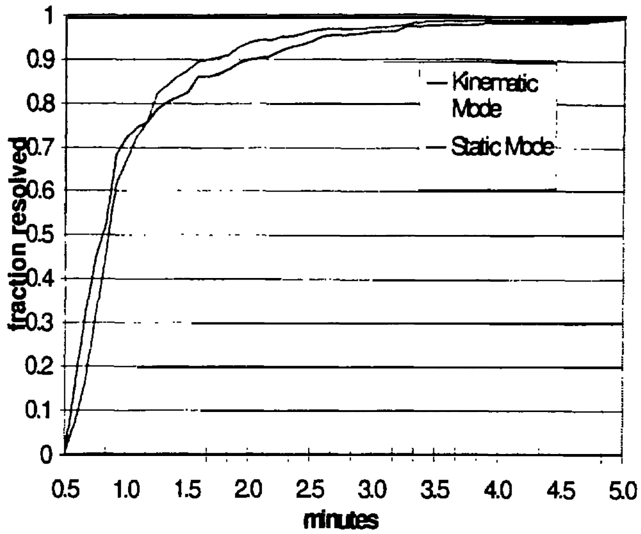

Figure 3. Cumulative Narrow-lane Resolution Tune Statistics

LONGER BASELINE LENGTHS

For baseline lengths between 10 and 30 km, the system does not attempt to do the hand-off from the wide-lane to the narrow-lane integer ambiguity estimate. The user is provided with an averaged wide-lane position in static mode. Ln kinematic mode, a continuous-valued ambiguity solution using the wide-lane information is provided. (This allows smoothing to be done on the error inherent in the wide-lane position). An independent continuous-valued ambiguity solution is also maintained to be used for integrity monitoring purposes.

Data collected from two 16 km baselines during daytime hours was processed off-line with the RT2 algorithms. The data processed totaled 10 hours. Algorithm resets were forced every 15 minutes. The resolution time and repeatability results are summarized in Tables 1 and 2. Table I(resolution time) represents results from all runs with more than 5 satellites over the mask angle (about 13 degrees) during the majority of the resolution process. Table 2 (repeatability) presents the rms errors of the matched positions at 600 seconds past reset for all runs which had an integer resolution at that point. "True" baselines were determined by processing each data set off-line in forced static mode without resets. These "true" baselines are believed to be good to around 2 cm each in the horizontal and vertical directions. No erroneous integer ambiguity selections were made during this processing.

At first glance, it appears that the kinematic mode is more accurate than the static mode. This is somewhat misleading, however. Statistics were only computed when the system had an integer resolution at 600 seconds. The resolution speed is highly dependent on the observation biases. In several cases where the biases were large, the kinematic mode had not resolved at 600 seconds, whereas the static mode had. Therefore, the static mode statistics contain more cases with large observation errors.

Mode	50% resolved	66% resolved	80% resolved
Static	2.5 min	3.5 min	4.5 mm
Kinematic	6.25 min	7.0 min	9.75 min

Table 1. 16 km Resolution Time Results

Mode	Horizontal rms error @600 sec since reset	Vertical rms error @600 sec since reset
Static	4.8 cm	5.2 cm
Kinematic	3.3 cm	5.0cm

Table 2. 16 km Matched Position Repeatability Results (with integer resolution)

At baseline lengths longer than 30 km, the solution from the continuous-valued ambiguity Kalman filter is supplied. It uses an iono-free observation combination at this baseline length

KINEMATIC MODE ACCURACY

Data was collected to determine the accuracy of the positions in kinematic mode. The data was collected after integer resolution, from antennas on the NovAtel rooftop (the same antennas used to compute the statistics shown in Figures 2 and 3). The rover receiver was forced to operate in kinematic mode so that the accuracies would reflect those from an actual moving scenario. The "true" baseline was computed by off-line processing many hours of data. Figure 4 shows the low-latency horizontal position error for 35 minutes of data computed with base station observations sent once per second. Position data was collected once per second and a data link (a direct connection with an RS232 serial cable) with a baud rate of 2400 was used. 7 satellites were used in this solution. The rms of the horizontal error is 1.25 cm. Figure 5 shows a similar plot for data collected with the base station observations sent at once per 2 seconds, using a 1200 baud data link. Low latency positions were once again collected once per second, and matched positions with each base station update. The low latency horizontal rms is 1.2 cm. Figure 6 shows the horizontal error in the "matched" output positions for the same data set as shown in Figure 5. The rms error for this case was 0.53 cm. Data was also collected from the above two setups for longer periods of time, with low latency positions collected every 5 seconds, and matched positions collected every 8 seconds. The results of these tests are SUMMARIZED in Tables 3 and 4.

Base Station Update Rate	Baud Rate	Hours of Data Used	Low latency Rms Error	Matched Rms Error
1/SEC	2400	17	1.34 cm	1.15 cm
1/2 SEC	1200	16	1.43 cm	0.74 cm

Table 3. Short Baseline Horizontal Accuracy Results

Base Station Update Rate	Baud Rate	Hours of Data Used	Low latency Rms Error	Matched Rms Error
1/sec	2400	17	1.58 cm	1.22 cm
1/2 sec	1200	16	1.96 cm	1.06 cm

Table 4. Short Baseline Vertical Accuracy Results

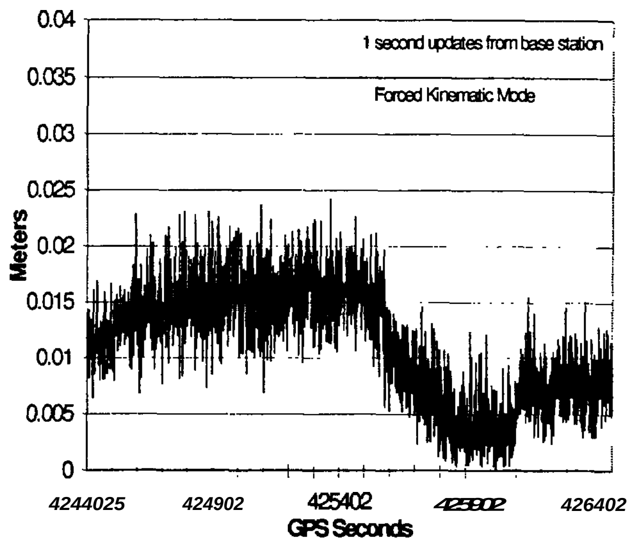

Figure 4. RT2 Low Latency Horizontal Position Error with 1 Second Base Station Updates.

KINEMATIC TESTS

Theoretical accuracy of the positions in kinematic mode was verified using rooftop data as described above. The user's dynamics should not add any discernible error using our estimation techniques. The effect of user dynamics was verified with a number of off-line

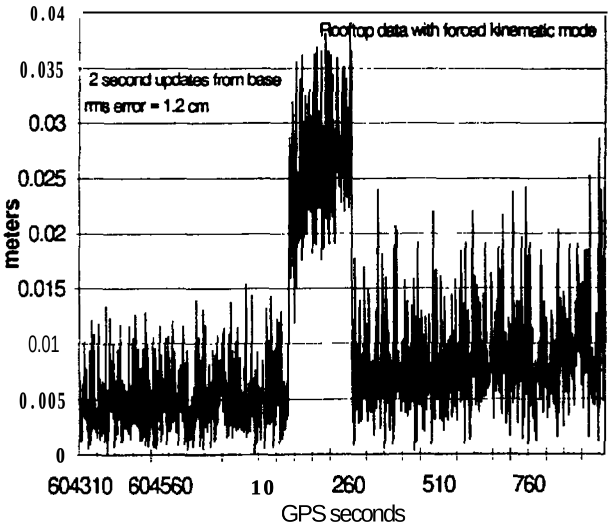

Figure 5. RT2 Low Latency Horizontal Position Error with 2 Second Base Station Updates.

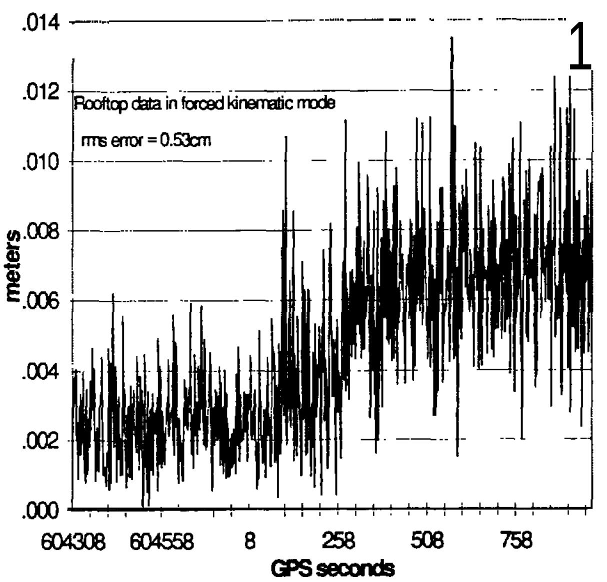

Figure 6. RT2 Horizontal Matched Position Error. (Kinematic Mode).

simulations using the RT2 algorithms. Nevertheless, it was seen as very desirable to do a significant amount of testing in an actual dynamic environment. This section presents some sample data from two of the many kinematic runs which have been done in our test van.

This van was outfitted with an antenna and a receiver, and the data taken while driving around in the vicinity of the NovAtel building. The choke ring antenna used for collecting the rooftop data was used with the base station receiver, and the van used an antenna withouta choke ring mounted on a pole on the side of the van. The distance from the base station to the van was generally 1 km or less. A major difficulty in analyzing data of this type lies in obtaining truth data for comparison. It is very difficult to obtain independent truth data which is good to the centimeter level. Since the primary interest was in verifying our own RT2 positioning algorithms, a GPS carrier phase post-processing package using Ll only (SemiKin from the University of Calgary [8]) was used as a comparison. This does not provide a complete test, since any error in the Ll carrier phase will show up in both positions. However, the actual kinematic accuracy of the positions has been computed using known baselines on the NovAtel rooftop. The goals of the kinematic testing were to: 1) show that actual motion is handled correctly in the RT2 position estimators, 2) confirm that the low latency positions do not suffer from user dynamics, and 3) verify the operation of the motion detector. The comparison to post-processed data is quite useful for these purposes. Figure 7 shows the difference in horizontal position between post-processed positions obtained with matched Ll measurements, and RT2 positions obtained with low-latency Ll/L2 combined measurements. Measurements were recorded 1/sec The error has an rms value of 1.05 cm, indicating that indeed, the kinematic positioning filter is working well. It can also be seen that no extra error can be observed due to the user's dynamics. Figure 8 shows the horizontal and vertical displacement during the run. Due to the use of the current rover observations, there is no "extrapolation overshoot" in the RT2 measurements. For this run, base station messages were sent once per second. The typical difference between the time of the base station and the low latency position output was 2 seconds, with a few cases of 3,4, and 5 seconds (due to poor radio coverage). Figure 9 shows a comparison of the low latency RT2 and the post-processed Semikin measurements during another run in which the RT2 algorithm was forced to reset every 200 seconds. The van was constantly in motion during this time, and the base station messages were sent once per 2 seconds. Figure 10 shows the number of satellites available to the searcher, and the delay between the latest base station message, and the low latency position output. The jumps in base station message delay are caused by missed messages due to poor radio coverage. It can be seen that even though the conditions are somewhat stressful (6 satellites not always available, and frequent missed base station messages), the RT2 system is resolving for integer ambiguities in 1.5 to 2 minutes.

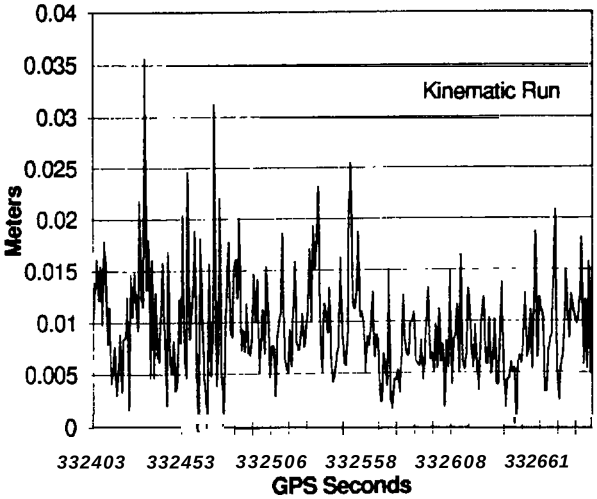

Figure 7. Horizontal Position Difference -- Low Latency vs. Post Processed Positions.

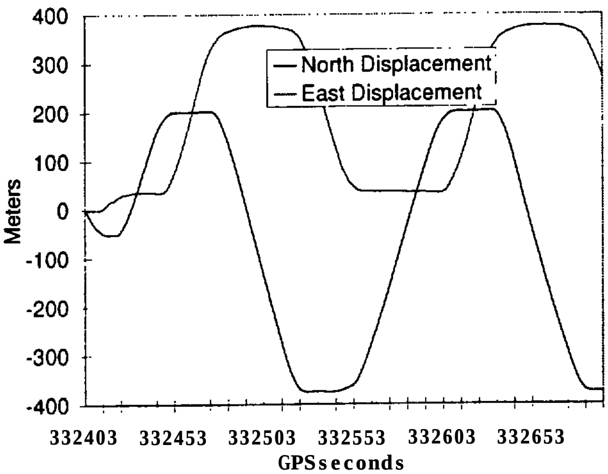

Figure 8. North and East Displacements for Kinematic Test Runs without Resets.

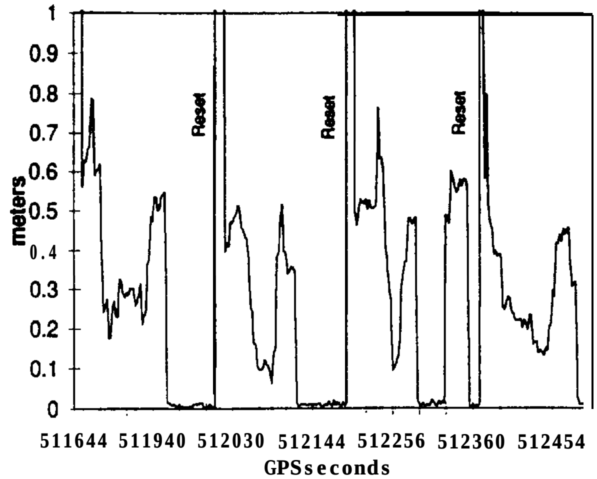

Figure 9. Horizontal Position Difference -- Low Latency vs. Post-processed Positions. Kinematic Run with Forced Algorithm Resets.

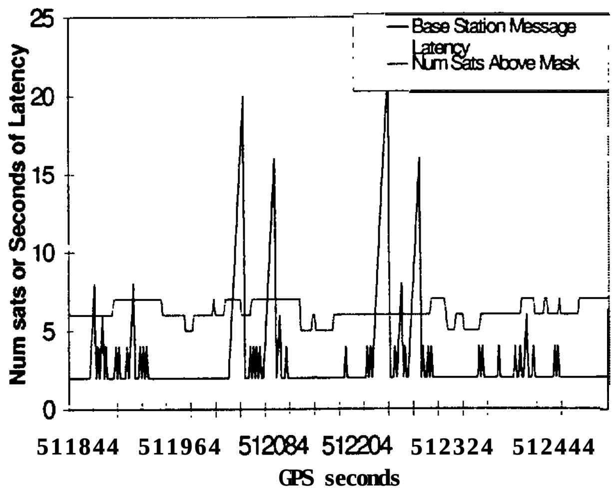

Figure 10. Number of Sats above Mask and Base Station Latency for Kinematic Run with Resets.

STATIC POSITIONING

When the rover receiver is in static mode (either through a motion detector decision, or a user command), the computed position is averaged in time. The accuracy slowly converges from 1 or 2 cm to a few millimeters or less. Figures 11 and 12 show plots of horizontal and vertical error for several 1 hour static convergence periods.

SUB-OPTIMAL CONDITIONS

A real-time differential GPS positioning system (either pseudorange or carrier phase) is sometimes forced to operate in less than optimal conditions. The design of the system should seek to minimize the effect of these poor operating conditions. Some of the problems which may be encountered are loss of the base station to rover radio link, excessive multipath, and shading of GPS satellites.

If the radio link to the base station is lost, the RT2 base station observation predictor continues to operate, with gradually degrading accuracy. The output standard deviations will provide an indication of the degradation. The delay since the last base station message is also provided in the low latency output log. If the outage is

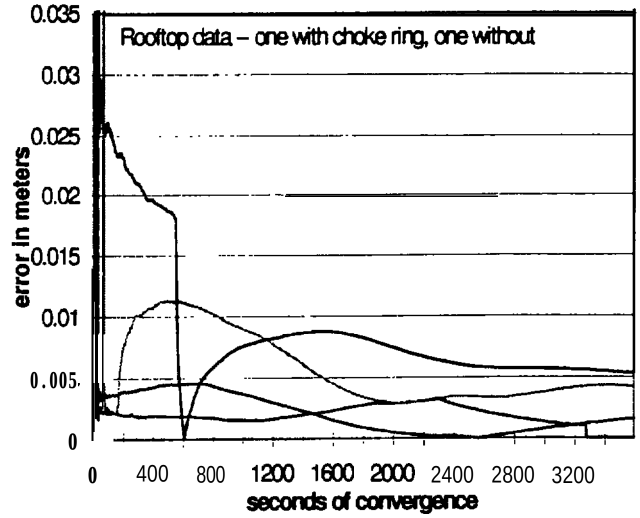

Figure 11. RT2 Horizontal Error from Sample Static Convergence Runs.

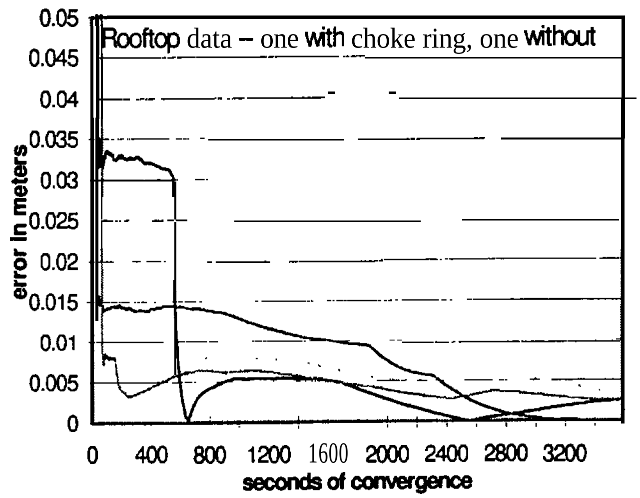

Figure 12. RT2 Vertical Error from Sample Static Convergence Runs.

greater than 30 seconds, the receiver will return to single point positioning, and RT2 will reinitialize when the link returns. After 30 seconds without communication, the RT2 system can no longer recognize whether the base station receiver has undergone cycle slips, and in order to maintain its integrity, it must reset. Figure 13 shows the horizontal position error and the output standard deviations in the low latency measurements in a kinematic run with several breaks in the radio link. The graph is a composite of several time segments, so the horizontal axis is not continuous. The standard deviations (the larger numbers in the graph) do rise appropriately with the radio outage error. As in the kinematic data section above, the error is computed as the difference between the low latency position output, and the position computed by an L1 only post-processing program. The message latency is shown in Figure 14.

Excessive multipath conditions can cause problems for fixed-integer positioning systems primarily in two ways. 1) The very large pseudorange errors can cause a problem in initializing the integer ambiguity search-space. 2) Large carrier-phase multipath values can "confuse" the ambiguity searcher, making a "wrong" combination of integer ambiguities look right. The RT2 system has been designed to accommodate typical to moderately large multipath levels, without making erroneous lane choices. In the face of very large multipath (well over double the pseudorange multipath seen in our "typical" rooftop environment), occasional erroneous lane selections can occur. The RT2 system contains solution integrity monitoring in order to handle this situation. Residuals of the wide-lane solution, the Ll only solution, and the L2 only solution, and the difference between the fixed integer solution and the position output of the continuous-valued ambiguity Kalman Filter are all monitored. Our experience has been that most errors are caught and corrected within a few minutes.

GPS users frequently must contend with shading of the satellites. This can be a problem with carrier phase positioning systems since they generally must use a higher mask angle than pseudorange systems. The continuous-valued ambiguity Kalman Filter in this system uses all satellites down to a 2 degree mask angle, but deweights those under 11 degrees quite heavily in the solution. This allows the user to continue to receive a position (albeit degraded) even when the coverage at higher elevation angles is poor. It also allows the motion detector to continue to function (although its false alarm rate will increase). The RT2 system requires at least 5 satellites over 11 degrees with Ll and L2 present in order to make an integer resolution. However, once the integers are resolved, the L2 signal is not required, and 4 satellites above 11 degrees are enough to maintain kinematic positioning at fixed integer accuracy. As long as the continuous-valued Kalman Filter continues to run (4 or more satellites above 2 degrees), any known integer ambiguities will be remembered, in order to speed the re-resolution process, and position averaging continues if in static mode. If less than 4 satellites are available above 2 degrees, the entire system resets.

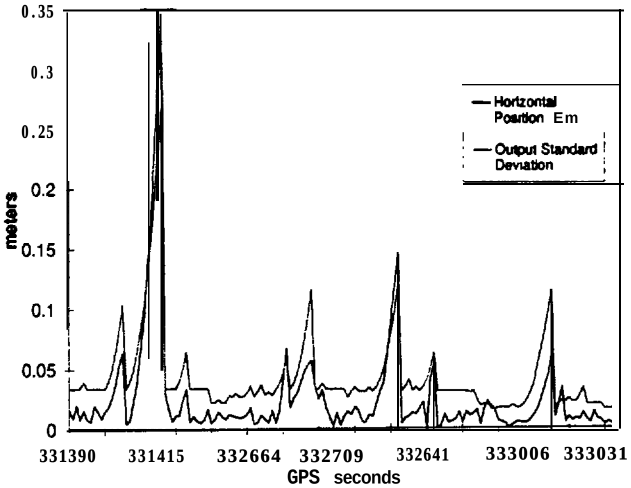

Figure 13. RT2 Performance During Radio Outages

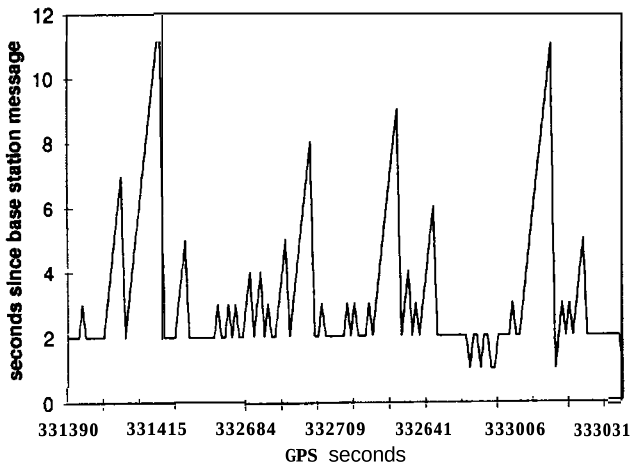

Figure 14. Length of Radio Outage

CONCLUSIONS

Test results from the NovAtel RT2 real-time-kinematic carrier phase positioning program have been presented here. These results show typical integer resolution times of about 1 minute on short baselines, and typical low latency horizontal position accuracies of 1 to 3 cm with a direct RS232 data link baud rate of 1200 to 2400 (about twice the message bit rate). An example of the extension to longer baseline lengths has also been shown, with gradually degraded accuracy and integer resolution time. The results indicate that the goal of producing a system which is reliable, accurate, easy to use, flexible in baseline length and which needs only modest data link requirements has been successfully met.

ACKNOWLEDGMENTS

The authors would like to thank Jim Rooney, Kip Fyfe and Pat Fenton for their help in collecting data for this project. The authors would also like to thank R. Grover Brown for his helpful suggestions concerning this paper.

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