Real-Time Carrier Phase Positioning Using the RTCM Standard Message Types 20/21 and 18/19.

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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 14 years, with her recent focus being on carrier phase positioning methods and software.

Keith J. Van Dierendonck received a BA in Mathematics from the University of California, Santa Cruz in 1990 and has attended graduate studies in Geomatics Engineering at the University of Calgary. He has been involved in GPS for 10 years in constellation simulator development, error analysis, receiver system test and carrier phase positioning.

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, and has been active in several areas of software development since switching to the GPS field two years ago.

Tom Ford obtained a B.Math in 1975 and a B.Sc. in 1981 from the Universities of Waterloo and Toronto, respectively. From 1981 to 1989 he designed software for inertial and GPS survey systems for Nortech Surveys Ltd. Since 1989, he has been at NovAtel Inc., and been involved with various areas of core technology development, including signal processing, and carrier based positioning with GPS, pseudolite and Glonass signals, and most recently attitude determination.

ABSTRACT

NovAtel has recently incorporated the use of RTCM SC-104 standard RTK (Real-Time-Kinematic) message types into its real-time carrier phase positioning products. The RTCM RTK messages are implemented either as corrections to the pseudorange and carrier phase (Types 20 and 21), or as raw measurement information (Types 18 and 19).

A comparison is given of the two types of message pairs, and a discussion is presented on the development issues that were faced when incorporating this capability into the existing RTK products.

Results are presented from tests involving the RTCM type 20/21 implementation in the NovAtel RT2 product used with RTCM type 20/21 messages generated from other manufacturers' receivers with third party software. Comparisons are made between the performance using two NovAtel receivers, and that obtained when using a different manufacturer's receiver as the base station.

INTRODUCTION:

Differential GPS positioning methods use the spatial correlation of most GPS errors to greatly increase the obtainable position accuracy. Differential methods are used for both pseudorange and carrier phase positioning. The disadvantage of using differential positioning of either kind in real-time is that in addition to the rover receiver used for the local positioning, a base station receiver is also required, along with a data link which it can use to provide information to the rover receiver. Soon after GPS receivers became readily available to the civil community, the usefulness of infrastructure systems providing differential messages to large numbers of users with various types of receivers became obvious. The

RTCM SC-104 standard format for differential pseudorange corrections took hold fairly quickly and is currently in wide use. Users of Real-Time-Kinematic (RTK) carrier phase positioning systems also have recognized the usefulness of such systems. But because real-time carrier phase positioning systems were developed later than pseudorange systems, carrier phase infrastructure systems are only now coming into widespread use. The RTCM SC-104 has defined a tentative set of messages for carrier phase positioning systems in [1] (Version 2.1), and is now working on a revised version of these messages in RTCM SC-104 recommended standards Version 2.2 [2].

Two pairs of RTK messages are defined in the RTCM SC-104 standard, with the idea (but not the requirement) that each pair of messages would be used together. The message types 18 and 19 contain raw carrier phase and pseudorange measurement information. Message types 20 and 21 contain information based on the same measurements, but formatted as corrections to the carrier phase and pseudorange measurements, in a manner similar to the RTCM Type 1 pseudorange correction message.

OBJECTIVE:

In 1994, NovAtel introduced the RT20 single frequency RTK system [3]. In 1996, with the introduction of the NovAtel MiLLenium dual frequency receiver, the RT2 RTK system was also introduced [4]. The rover positioning algorithms for these two systems exist as one piece of RTK software which acts as an RT2 system when L1 and L2 measurements are available, and as an RT20 system when only L1 measurements are available. At the time of the RT2 introduction, NovAtel RTK products used only NovAtel-proprietary inter-receiver message formats based on the proprietary messages defined in the RTCM SC-104 [1] and RTCA [5] message standards. These proprietary messages provided very efficient data transmission, and allowed for the simultaneous transmission of pseudorange differential corrections, but did not allow for operation with other manufacturers' receivers. The need arose for the ability to use the RTCM SC-104 Version 2.1 type 20 and 21 messages which are now being transmitted by a German government infrastructure system, the AdV [6]. NovAtel also wanted to provide its users with the capability to operate with systems transmitting the RTCM messages 18 and 19, since these will probably be more prevalent than the type 20 and 21 messages. The objective of this project was to incorporate RTCM message type 18/19 and 20/21 capability into the NovAtel RTK products without disturbing the existing RTK software. In the base station software, this was clear cut. New routines to encode the observations in the given formats were laid out and implemented. In the rover receiver software, the goal was to locate all the type 18/19 and 20/21 decoding functions and all functions related to the interoperation with other receivers in a set of pre-processing functions. These functions would then compute base station measurements for the existing RTK positioning software using the previously defined internal software interface. This involved decoding the messages into a format which would be the same as the existing interface to the RTK positioning routines, plus handling any issues of basic differences in receiver functionality (primarily the handling of clock biases). Figure 1 shows a simplified block diagram of the ideal rover software. The message selection and decoding software is in one block which prepares reconstructed base station pseudorange and carrier phase measurements for the position estimation block. The position estimation functions 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 position estimator makes a prediction of the base station measurements at that time epoch, and combines them with the rover measurements to provide position estimates with a typical latency of about 100 ms, regardless of the data link delay. The RMS position error is typically 1 or 2 cm on short baselines (assuming messages can be sent every 1 to 2 seconds, and reasonably good geometry), even under user dynamics. The matched position estimator waits for the base station measurements to arrive for that time epoch, and provides a delayed, but more accurate position estimate. References [3] and [4] provide more detailed descriptions of the NovAtel RTK system architecture.

The first step in the project was to precisely define the desired capability. There are two sets of RTCM RTK message types (18/19 and 20/21), which are intended to be used as pairs. However, there is no requirement in the RTCM SC-104 standard that they be used together. A type 18 (raw carrier phase) message *could* be paired with a type 21(RTK pseudorange correction) message, or even a type 1(pseudorange correction) message. In fact, the standard does not even specify that a pseudorange-based message be sent at all (although this would be a very unlikely way to structure a base station system). Within the defined message pairs, many ways exist to send the messages (order of messages, L1 only or L1/L2, message rates, etc.) To further complicate matters, the RTCM SC-104 is in the process of moving from the current Version 2.1 tentative definition of types 18-21 [1] to a new Version 2.2 standard [2] in which the type 18-21 messages will most likely not be completely compatible with the previous standard. In considering all the many message scenarios which could be received by the rover receiver, the number of possibilities quickly becomes overwhelming. It was decided to use a "phased-in" approach, with the first three phases as follows:

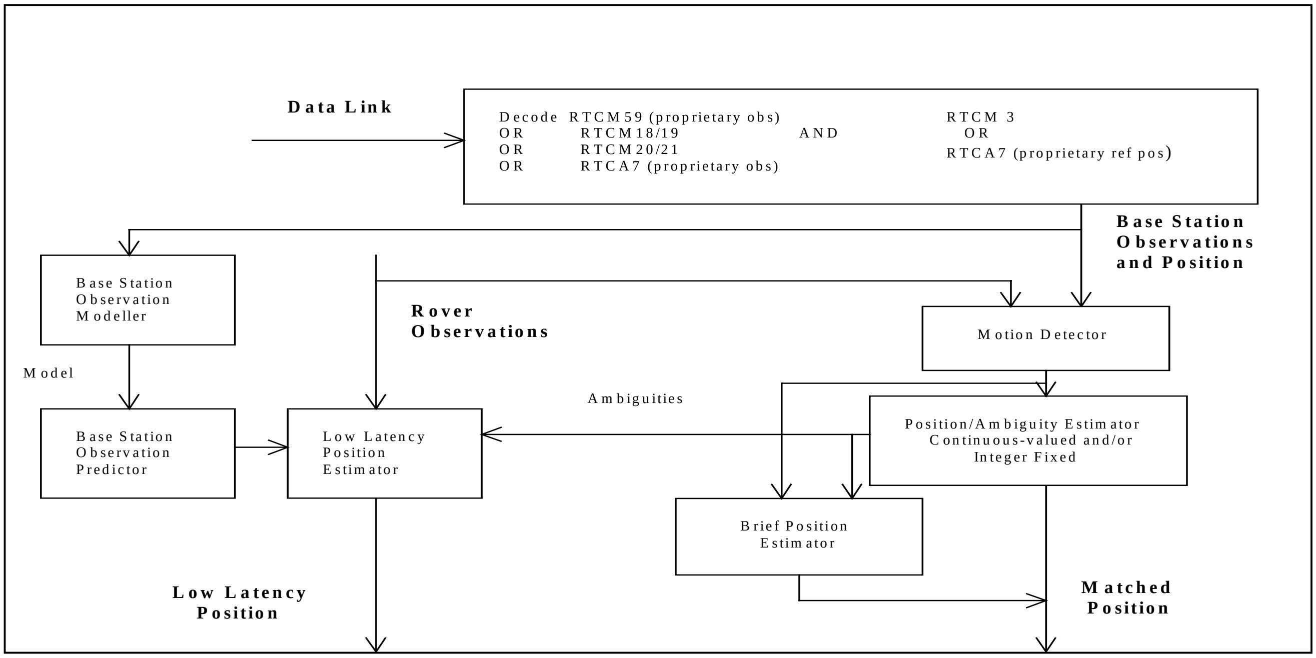

Figure 1. Simplified Block Diagram of NovAtel RTK Rover Software

Basic assumptions:

- Base station position is transmitted.
- Measurement quality similar to NovAtel narrow correlation receivers.
- Full wavelength L2 carrier phase.
- Any unclear points in the Version 2.1 RTCM standard will follow the clarification in RTCM SC-104 Version 2.2.

Phase I (base and rover software):

- RTCM SC-104 Version 2.1 type 20/21s used as a pair, with L1 pseudorange and carrier phase and L2 carrier phase, all transmitted at the same rate. This is the set of messages used by the German AdV system.

Phase II(base and rover software): Phase I, plus

- RTCM SC-104 Version 2.2 type 18/19s, used as a pair.
- L1- only or L1/L2 for type 18/19s
- Processing of the messages at the rover occurring as often as pseudoranges are transmitted.
- Base station co-ordinate accuracy extended with proposed new message type 22.

Phase III: Phase II, plus

- The basic carrier phase positioning portion of the rover RTK system will run whenever a carrier phase message is received (without requiring an accompanying pseudorange message).

Phase I has been implemented at this point, and Phase II is in the final stages of implementation and test. Phase III will require some changes to the existing RTK positioning software, and will be implemented at a later point in time.

USING TYPES 20/21 VS. TYPES 18/19

Uncorrected (raw) carrier phase and pseudorange measurements are transmitted by RTCM RTK messages 18 and 19, respectively. Messages 20 and 21 contain corrections for the carrier phase and pseudorange measurements, respectively. The corrections are defined here just as in [1] and [2]:

$$corr_{\phi} = (r_{exp} - b_{sv} * c + b_{base} * c)/\lambda - \phi - A \quad \text{(type 20)}$$
$$corr_{\rho} = r_{exp} - b_{sv} * c + b_{base} * c - \rho \quad \text{(type 21)}$$

r_{exp} is the computed range in meters at the measurement time from the base station co-ordinates to the satellite.

b_{sv} is the satellite clock offset computed from the downlink satellite clock model, in seconds. It is defined here as the amount by which the satellite clock is ahead of GPS time.

b_{base} is the estimated clock offset of the base station receiver, in seconds. It is defined here as the amount by which the local clock is ahead of GPS time.

c is the speed of light in meters per second.

λ is the appropriate wavelength for L1 or L2 in meters.

ϕ is the carrier phase measurement in cycles, defined to have a sign which increases as the range to the satellite increases.

A is an arbitrary constant integer number of cycles chosen at the start of tracking to keep the size of the correction small.

ρ is the pseudorange measurement in meters.

$corr_{\phi}$ and $corr_{\rho}$ are the corrections transmitted in the type 20 and 21 messages, respectively.

The corrections can be applied directly to the measurements taken at the rover, rather than doing a difference between the base station and rover measurements.

Advantages of Types 20 and 21

Reference [1] gives the following advantages for using the type 20 and 21 correction messages rather than the type 18 and 19 uncorrected measurement messages:

1. Fewer bits are required for a correction than a raw measurement.
2. Corrections are less time sensitive than raw measurements.
3. This method can be more throughput efficient, or can at least offload some computational load from the rover receiver to the base station.
4. The transmitted base station position co-ordinates are not used to compute the rover's output position in a correction-based algorithm.

Further Discussion on Type 20/21 Advantages

Point 1: Once an ephemeris identification tag is included for types 20 and 21, the messages are defined to be the same size as the type 18 and 19 messages. There is information on the correction rate included in the type 21 pseudorange correction message which does not exist in the type 19 raw pseudorange message, so technically the correction messages contain more information than the type 18 and 19 messages, but the rate information is not difficult to compute at the remote receiver. There is also an advantage in the fact that the number of bits allowed for the corrections is large enough so that the entire dynamic range of the correction values can be accommodated without roll-overs. This is not the case in the type 18 uncorrected carrier phase message which does roll-over. The carrier phase roll-over can (and must) be handled by the rover software, but it is inconvenient to implement and increases the potential for software problems. Point 1 does, therefore, provide some advantages, but they are modest, and don't reduce the number of bits transmitted per time epoch.

Point 2: This point refers to the fact that corrections change slowly while the raw measurements change rapidly due to the dynamics of the satellite ranges. This means that an algorithm using the raw measurements needs to account for any differences in measurement time between the base station and rover receivers, while the corrections will be valid for an extended period of time (maybe as long as a few seconds, with SA being the major error). This can simplify the software at the rover, and can decrease the rate of transmission required from the base station. This is a valid consideration, but if the truncation error on the base station co-ordinates can be tolerated, or mitigated with the proposed new message in the Version 2.2 standard, a correction can be derived at the rover from the raw measurements if the base station position and an accurate measurement time are known. Then this becomes primarily an argument concerning the better way to mechanize the rover positioning algorithms. Other methods can also be used to estimate the base station range dynamics so that rapid base station transmissions are not required [3] and [4].

Point 3: When the rover is using a correction-oriented algorithm, some computations can be offloaded from the rover to the base station when using types 20 and 21. This could be helpful in some situations. However, this is only an advantage when that particular implementation is used at the rover. If measurements must be reconstructed from the corrections, as is discussed later, the type 20/21 messages actually increase the throughput requirements at the rover.

Point 4: This is one of the more noteworthy advantages of the type 20/21 format. The base station co-ordinates would ordinarily still be transmitted so that the user could form the appropriate atmospheric models and could choose appropriate methods for ambiguity resolution, but the truncation error in the transmitted base station position does not directly corrupt the rover's position output as it does in a raw-measurement based scheme. (This applies only to the error incurred by quantizing the base station co-ordinates for transmission; any error in the base station co-ordinates being used at the base station to compute the corrections will still corrupt the output rover position). This is a pertinent issue, since the type 3 base station coordinate message which is defined in RTCM SC-104 Version 2.1 is limited to 1 cm resolution, which may not be sufficient for some survey applications. It is shown later that this advantage exists for the type 20/21 messages even when a double-difference algorithm is used at the rover. The proposed RTCM SC-104 Version 2.2 standard contains a new message type 22 which adds to the resolution of the type 3 message, thus eliminating this concern. However, implementing a new message obviously adds to the complexity of the rover and base station software.

Disadvantages of Types 20 and 21

Reference [1] also discusses disadvantages of using the type 20/21 messages. The primary disadvantage is that the base station and the rover receivers must use *exactly* the same satellite position and clock estimates in order to obtain the desired centimeter-level accuracy. This means the same set of ephemeris and clock parameters must be used, and the computations must be exact at both the base station and rover receivers. In a double-difference implementation, or in an implementation where the corrections are computed at the rover, the same ephemeris data and computation algorithms will be used to compute ranges to both receivers. Errors incurred will typically be largely spatially correlated, and will not affect the position solution unless they are very large. A very different situation occurs when splitting the ephemeris computation between the rover and base station, as is done with the type 20/21s. Approximation errors which never would have been noticed before can suddenly become major error sources in the RTK system. The use of different ephemeris data at each site during an ephemeris changeover will produce errors which are intolerable in a carrier phase positioning system. This is a major disadvantage which significantly complicates the matter of achieving a reliable working system, particularly if many different types of GPS receivers are involved. Another disadvantage is that if problems arise with the system, such as with the ephemeris change-over, it will be hard to find whether the problem lies with the base station or the rover software.

Concluding Comments on Message Types

Many RTK manufacturers already have systems in late stages of development or in the field, so from an RTK receiver manufacturer's point of view, the "preferred" message set would be the pair which conforms to the way their RTK algorithms have already been implemented (usually using a manufacturer-proprietary message format). The NovAtel RTK algorithms use a double difference implementation which uses raw measurements, so the natural first choice would be to use type 18 and 19 messages. However, since the need arose to use types 20 and 21, and since both message pairs are defined as part of the standard, both message pairs have now been implemented in the NovAtel RTK software. These messages require a large number of bits (2280/epoch for 9 satellites with L1 and L2 pseudorange and carrier, not including any overhead added by the radio, vs. 968/epoch for the NovAtel proprietary format), so it is highly unlikely that service providers will be transmitting both message pairs, at least in the near future.

DEVELOPMENT ISSUES

Receiver Interoperability

It is very common now for pseudorange differential systems to use different manufacturers' receivers at the base station and rover locations, with few problems. However, this ease of interoperability may not be guaranteed for carrier phase positioning systems. See for example [1], [7] and [8]. This concern is due to the increased accuracy level of carrier phase systems and the need to do some type of carrier phase cycle ambiguity resolution at the rover receiver. Of particular concern are the effects of non-matching antenna phase center locations and patterns as well as small differences in the way the carrier phase is computed. Antenna phase centers and patterns and deterministic carrier phase differences will generally cancel out when using like antennas and receivers, but could cause significant errors when a mixed set of antennas or receivers is used. Many carrier-phase based post-processing programs currently allow RINEX data from different receivers to be used. However, RTK systems usually demand less user input on details such as antenna characteristics, and in a real-time system, there is no "second chance" to reprocess the data if the parameters used turn out not to be optimum. The proposed type 22 message contains some extra antenna information, but many questions still remain, and probably will continue to remain until mixed antenna/receiver systems have been used and analyzed extensively.

Clarification of RTCM SC-104 Version 2.1 Standards

During the implementation of this software, it was discovered that a number of points in the RTCM SC-104 Version 2.1 standard needed clarification. It so happened that the RTCM SC-104 was preparing a new Version 2.2 with new documentation during the time when this software was being developed. Most of the clarification issues seen have been cleared up in the documentation for the proposed RTCM Version 2.2 standard. A few are noted below:

The time tag in the type 18-21 messages was not clearly defined. The draft version of the Version 2.2 standard [2] defines its meaning exactly, along with information on the timing of the measurements. Reference [2] also clearly defines the sign of the carrier phase measurement, which wasn't the case in Version 2.1.

The definition of the carrier phase and pseudorange corrections for types 20/21 in [1] and [2] makes no reference to the satellite clock offset. It can be assumed that it must be included in determining the correction, otherwise the value will not fit into the number of bits allowed in the message. It is not clear from the documentation, however, what should be done with the "tgd" term. This term relates to the delay difference in the L1 and L2 channels on each satellite, and is contained in Subframe 1 of the GPS downlink data with the satellite clock parameters. ICD-GPS-200 [9] states that it shall be applied to the satellite clock model for single frequency receivers but not dual frequency receivers. Thus, it is ambiguous whether or not it should be included in the satellite clock offset used in computing the type 20/21 messages, which are defined for either single or dual frequency receivers. The NovAtel software was formulated to agree with that used by the German AdV system (no use of tgd for either L1 or L2).

When using either pair of messages (18/19 or 20/21), anywhere from 1 to 4 messages will be sent on each time epoch. Unfortunately, in the RTCM Version 2.1 standard, the rover receiver had no way to tell how many messages would be sent at a given time epoch. This produced a problem, since RTK positioning software typically wants to use all the available data for a time epoch at once. The rover can wait until the next epoch's data arrives to process the data, but that produces a large increase in the latency of the position output at the rover, which is very undesirable in a real-time system. This is discussed thoroughly in [7] and a resolution to the problem is included in [2].

Reconstructing Uncorrected Measurements from Type 20/21 Corrections

In order to avoid changing the existing RTK positioning software, it was necessary to take the pseudorange and carrier phase corrections in the type 20 and 21 messages, and reconvert them into the raw pseudorange and carrier phase measurements which the NovAtel RTK rover software expects. This is done by reconstructing the observations from the corrections:

$$\rho = r_{exp} - b_{sv}*c - corr_{\rho} + b_{base}*c$$
$$\phi = (r_{exp} - b_{sv}*c + b_{base}*c)/\lambda - corr_{\phi}$$

Where:

r_{exp} is the computed range in meters at the time tag transmitted in the message from the transmitted base station co-ordinates to the satellite.

b_{sv} ,c, $corr_{\rho}$, $corr_{\phi}$, λ, ρ and ϕ are as defined earlier in this paper.

b_{base} is an estimate of the clock offset of the base station receiver, in seconds. It is defined here as the amount which the local clock is ahead of GPS time. It is not transmitted in the message, and must be derived from the measurement time tag, by assuming that the measurements are taken on integer seconds of the local clock (for a system transmitting once per second).

A different reconstruction could be done by defining r_{exp} to be applicable at the measurement time of the rover. The measurement synchronization referred to later could then be skipped. That was not done in this case because the object was to have the observations derived from 20/21 messages look as much like those from 18/19 and NovAtel proprietary messages as possible. Thus, commonality is maintained in the software and more efficient testing is possible.

It has been noted that the RTCM type 3 base station position message has a resolution of only 1 cm. Since the pseudorange and carrier phase measurements are being reconstructed using this truncated position, this error will be projected onto the reconstructed range. This will cause an error in the computed baseline. Fortunately, when the output position is computed by adding the baseline to the transmitted base station position, the two errors cancel to provide the user with a correct output position. Since the errors introduced on the ranges are consistent with an actual baseline, the carrier phase residuals remain small and the ambiguity selection is not affected. Figures 2 and 3 show this. An experiment was done, collecting zero baseline data with two NovAtel receivers using message types 20 and 21. The base station position was defined to generate a large truncation error of (0.0048,0.0048,0.0048) meters. Figure 2 shows the averaged baseline co-ordinates computed, which do tend toward the above values. Figure 3 shows the north, east and vertical errors in the output position. It can be seen that the errors seen on the baseline do not occur here. Measurement residuals were inspected and seen to be of the usual size for a zero baseline. When using type 18/19s, the computed baseline will be correct, but the output position will show the truncation error in the transmitted base station position. The use of the proposed type 22 message can eliminate this issue entirely.

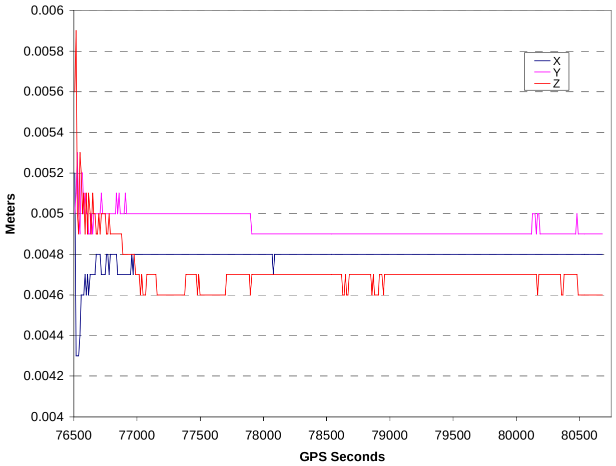

Figure 2. Baseline Values for Zero Baseline Test NovAtel/NovAtel with RTCM 20/21s

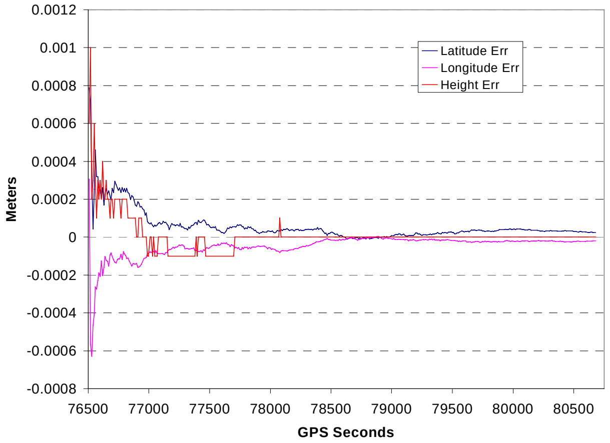

Figure 3. Latitude, Longitude and Height Errors Zero Baseline Test, NovAtel/NovAtel with RTCM 20/21s

Handling a Drifting and Resetting Clock Bias

GPS receivers use a local clock to measure pseudorange and carrier phase. The difference between this local clock and GPS time is referred to as the receiver clock bias or offset. Most GPS receivers used as base stations or rovers will have an internal clock which has a significant drift, or change in clock bias, with respect to GPS time. Typically, manufacturers limit the deviation of the local clock from GPS time so that it will not become too large. Different methods are used to maintain this clock synchronization. NovAtel receivers continually steer the local clock so that it remains close to GPS time. Some other receivers let the clock drift naturally until the clock bias reaches a certain value (typically 1 ms), then reset the local clock so that the clock bias returns to a value close to zero. This was the one area where it was necessary to make a small change to the existing software. The algorithms to synchronize measurements between the base station and rover had to be modified slightly to accommodate the possibility of a resetting clock.

INTER-RECEIVER TEST RESULTS

Tests were performed in order to verify the operation of the system, and to assess potential problems with mixed receiver and antenna systems. The operation of the RT2 system using a NovAtel base station and a NovAtel rover was verified for both the type 20/21 and type 18/19 messages. Several tests were also performed using other manufacturers' receivers as base stations together with a NovAtel rover receiver. Real-time tests used the "GNRT" software from the German company Geo++ to generate the type 20/21 corrections. This is a version of the software used to generate the corrections for the German AdV system. The results from the inter-receiver tests are presented here. No attempt is made to do in-depth analysis on antenna patterns or receiver tracking methods. The intent is simply to provide a general idea of whether the tested receivers and antennas can provide reliable cm-level positions when used together.

Zero Baseline Inter-Receiver Accuracies

In order to analyze the potential problems in interoperating with other receivers, zero baseline data was collected from two NovAtel MiLLenium receivers, one Trimble SSi and one Ashtech Z12. One NovAtel antenna was used for all the receivers. The purpose of this was to eliminate any effects that the antenna might produce, and look only at the effects produced by the receiver tracking itself. The various data files were processed in static mode by an offline version of the RT2 algorithms to produce baseline estimates. Figure 4 shows a plot of the magnitude of the 3 dimensional error for each receiver pair. The data spans 2 hours, with an artificial reset to the RT2 processing after 1 hour. It can be seen that, as one might expect, the NovAtel to NovAtel processing produces the smallest error. However, the errors with the other receiver pairs are still quite small (less than 2.5 mm worst case). This error is well under the size of the typical carrier phase multipath effect, and would not be noticed for most real-time applications. It has not yet been determined whether the offsets come from actual tracking differences, approximations in the handling of clock biases, data formatting, or some other effect.

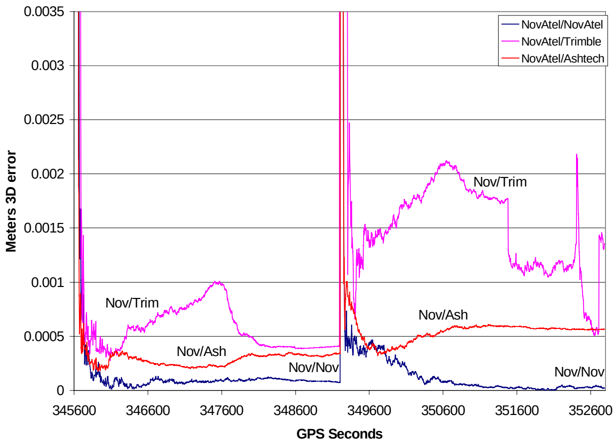

Figure 4. 3D Error on Zero Baseline

Short Baseline Tests using RTCM 20/21 Messages

NovAtel Antenna Tests.

The first short baseline inter-receiver tests were done using NovAtel antennas for both receivers. A Trimble SSi receiver was used as the base station with the GNRT software generating RTCM type 20/21s in real-time. A NovAtel MiLLenium receiver was used as the rover. Figure 5 shows ECEF x,y and z baseline errors for the NovAtel RT2 real-time solution. This data set includes 6 different hours, so it can be seen that ephemeris changeovers are handled without problems. The x,y and z errors converge to values which are a few millimeters off from zero. This is to be expected due to the truncation on the transmitted base station position. As discussed earlier, this error will not be present on the output position.

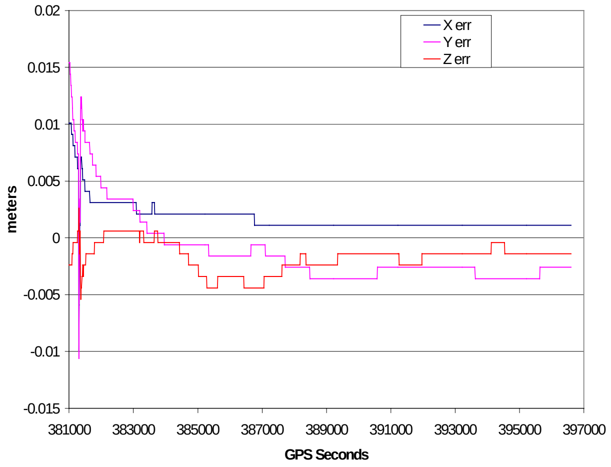

Figure 5. X, Y and Z Baseline Errors
Trimble to NovAtel

Mixed Antenna Real Time Accuracy Tests

Real-time tests were performed between a Trimble SSi receiver and a NovAtel MiLLenium receiver and between an Ashtech Z12 receiver and a NovAtel receiver. Antennas sold with each receiver were located on the NovAtel rooftop and used with the appropriate receivers. The GNRT software was used to generate RTCM 20/21 messages for the real-time tests. As a comparison, data was also post-processed between two NovAtel receivers using the NovAtel proprietary message format. Since the exact locations of the phase centers of the Trimble and Ashtech antennas were not known to us, only consistency tests were possible. These tests still provide very valuable information. Most errors which could occur would be present on the pseudorange or carrier phase measurements. This means that over time, the effect of the error on the baseline will change. Therefore, if the system can compute a consistently repeatable baseline, it can generally be assumed to be performing well. The different phase center locations of the two antennas adds a constant offset to the baseline which could be corrected with knowledge of the antenna characteristics. All low latency data was computed with a 2 second delay between the base station and the remote. In reality, the NovAtel proprietary messages would be received with less delay (due to fewer bits required, and no message computation outside the receivers) which would decrease the base station measurement prediction error, but we wanted to remove this effect from the comparison.

The variation in the low latency rover position output from the real-time test using a Trimble receiver as the base station and a NovAtel MiLLenium receiver as a rover is shown in Figure 6. Although this was a static test, the low latency position does not have any smoothing over time, so any drift in the solution due to measurement errors would be apparent quickly. Figure 7 shows a run post-processed with the RT2 algorithms. It uses two NovAtel receivers and antennas and the NovAtel proprietary message format. Although an exact comparison of accuracy cannot be made since a different base station antenna was used (and hence different multipath existed), it is valid as a rough comparison since all the antennas were located on the same rooftop within a few meters of each other. It can be seen that no significant drift in the position occurs over time for either case, and the accuracy of the Trimble/NovAtel positions is roughly equivalent to the accuracy of the NovAtel/NovAtel positions. The few points with missing data in the Trimble/NovAtel plot were determined to be due to a phase-continuity reset on all satellites at the base station. Figures 8 and 9 show similar graphs for a run done using an Ashtech receiver as the base station. This run suffered from poor satellite coverage and degraded signal quality from all receivers in its latter portion.

However, the Ashtech/NovAtel and NovAtel/NovAtel data show no significant position drift and the two data sets show similar performance with the exception of one unexplained outlier which can be seen in the Ashtech/NovAtel position data.

Mixed Antenna Resolution Time Tests

In order to continue the evaluation of the inter-receiver operation with RTCM type 20/21 messages, the data collected for the above tests was reprocessed offline with artificial RT2 algorithm resets induced so that resolution times could be compared. When post-processing the cross-receiver data sets, the actual type 20/21 message data generated in real-time was used, along with the raw observations recorded by the remote receiver, once again using the RT2 algorithms. As a comparison, NovAtel to NovAtel data sets were also post-processed using the NovAtel proprietary message format. Once again, due to the different antenna locations, exact performance comparisons cannot be made, but data sets from the same time span should show similar performance. Resolution time statistics for the Trimble to NovAtel data set, and the NovAtel to NovAtel set run at the same time are shown in Table 1. Although the 12-13 resolutions done in each data set are not enough to provide precise resolution-time statistics, they give a general idea of the relative performance of the data sets. The data was processed in static mode, and also in "forced kinematic mode" (in forced kinematic mode, the RT2 runs its algorithms as if the receiver were moving, even though it is stationary). It can be seen that the resolution times are similar for both sets. The main difference shows up in the 80 and 100 percent resolved statistics. Since these numbers are based on only a few ambiguity resolutions, the numbers are not statistically significant.

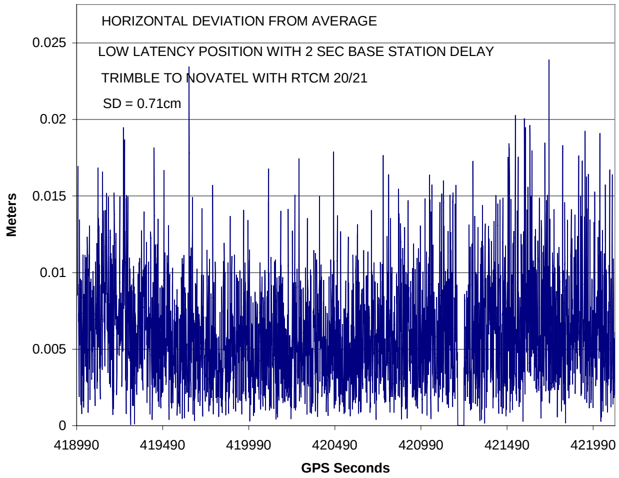

Figure 6. Low Latency Horizontal Position Error
Trimble to NovAtel Real-time Short Baseline
RTCM 20/21s

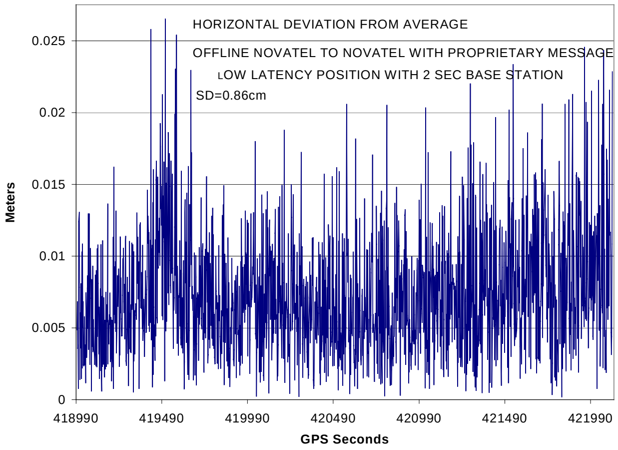

Figure 7. Low Latency Horizontal Position Error
NovAtel to NovAtel Offline Short Baseline
NovAtel Proprietary Messages

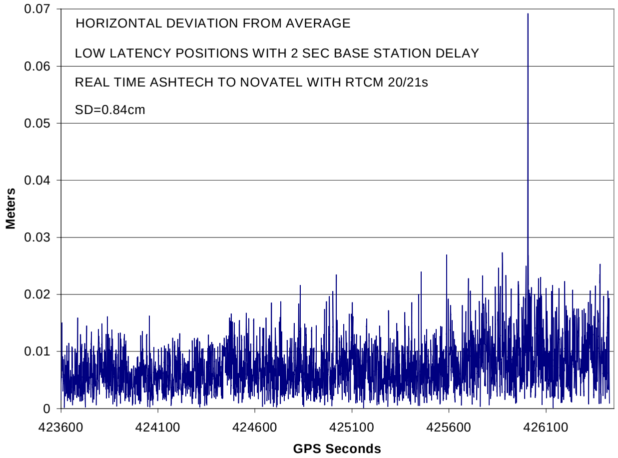

Figure 8. Low Latency Horizontal Position Error
Ashtech to NovAtel Real-time Short Baseline
RTCM 20/21s

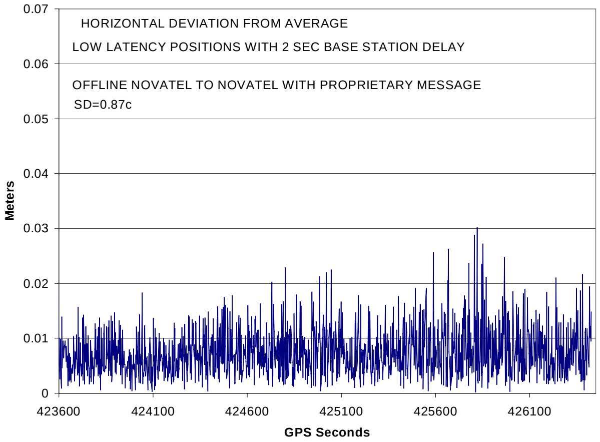

Figure 9. Low Latency Horizontal Position Error
NovAtel to NovAtel Offline Short Baseline
RTCM 20/21s

	Trim / Nov Static	Nov / Nov Static	Trim / Nov Kin	Nov / Nov Kin
Number of resets	13	12	13	13
50% resolved	30 s	31 s	30 s	31 s
80% resolved	58 s	35 s	46 s	62 s
100% resolved	166 s	58 s	> 250 s	107 s
Incorrect lane choices	0	0	0	0

Table 1

AdV Tests

RTCM-capable RT2 systems are currently in a Beta-test phase. This Beta-testing includes units in Germany being used with the AdV system. Preliminary tests on various baseline lengths using the AdV-generated type 20/21s have shown as good or better performance than that provided with two NovAtel RT2 receivers (better performance with AdV could be expected, since a base station which is part of an infrastructure system can use a low-multipath antenna sited in a low-multipath location).

CONCLUSIONS

NovAtel has incorporated the capability to use RTCM SC104 Version 2.1 Type 20/21 and Version 2.2 Type 18/19 messages into its existing RTK product line for both base station and rover receivers. The ability to use the NovAtel proprietary message format is also available in these products. Excellent results have been obtained using two NovAtel receivers with RTCM messages, and also when using a NovAtel rover receiver with RTCM type 20/21 messages generated from other manufacturers' receivers (specifically, Trimble and Ashtech). This is very promising for the use of RTCM RTK messages in current and future carrier-phase positioning infrastructure systems.

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