Beeline RT20 - a Compact, Medium Precision Positioning system with an Attitude.

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BIOGRAPHY

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.

Waldemar Kunysz obtained a Master of Nautical Science Degree from the Merchant Marine Academy of Poland in 1981 and a BSEE from the Technical University of Nova Scotia in 1989. From 1991 to 1995 he specialized in antenna design for Micronav Int. Inc. From 1995 to the present he has been an RF engineer for NovAtel Inc.

Rod Morris obtained a BSEE in 1991 from the University of Calgary. Since joining NovAtel Inc. in 1995 he has specialized in the signal processing area, making contributions to core tracking algorithms involved with GPS, slaved antennas, pseudolites and Glonass.

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.

Jim Rooney obtained a BSCE in 1990 from the University of Alberta. From 1988 to 1990, he was part of a compiler development team for IBM, Canada. He joined NovAtel Inc. in 1990, and worked in the wireless access group until 1993. Since 1993, he has been instrumental in many core development areas for Novatel including the design of software for NovAtel's dual frequency GPS systems.

Theo Smit obtained a BSEE in 1986 and an MSEE in 1989 from the University of Calgary, specializing in digital signal processing systems design, and worked there as a research engineer developing algorithms for the analysis of knee sounds. He joined NovAtel in 1990, and was a key member of the digital cellular terminals and CDPD modem design groups. Since 1995 he has been involved in the software and hardware design of NovAtel's dual frequency GPS systems.

ABSTRACT

Methods that transform phase differences to vehicle orientation are well known in the GPS community. These generally involve some combination of phase measured at multiple antenna/receivers such that the phase data from the various receivers is combined and used to generate attitude in an external processor. Usually these systems generate attitude as their primary function and pseudo range position as a secondary function. NovAtel has developed a system that generates both single axis attitude (measuring azimuth and pitch) and a position solution with medium precision (10 to 20 cm RMS). The integration of these technologies is novel in that all of the measurements are made by a single receiver processing data from 2 different antennas. In order to accomplish this, modifications to the RF and signal processing sections of the receiver were made. These modifications, along with the overall system integration are discussed.

Also described is the attitude determination technique, which uses the fixed baseline length constraint between antennas to help resolve L1 carrier ambiguities. The medium accuracy positioning method combines both pseudo range and L1 carrier measurements taken at both the primary antenna of the local receiver and at a base station receiver.

Test results that illustrate the system performance are presented.

INTRODUCTION

The Beeline RT20 system consists of a pair of NovAtel Inc. 501 or 502 antennas and a single NovAtel Inc. OEM

6 receiver, with associated software. The measurements provided by this receiver include an inter-antenna azimuth and elevation plus the position and velocity of a designated primary antenna. The accuracy of the azimuth measurement is 0.4 degrees of arc for a 1 metre antenna separation. The accuracy of the position varies between normal single point accuracy to the 5 to 20 centimetre level. The purpose of this paper is to describe this system, including its components, their integration and the system test results that demonstrate the specified system accuracy.

In 1992, NovAtel Inc. initiated a program to develop algorithms that used double difference phase and pseudorange observations to generate highly accurate inter-antenna position vectors. Coupled with that project was a system that used observations from two receivers (OEM 1 in this case [1]) whose two antennas were linked by a fixed length baseline to get a vector solution accurate to the centimetre level. This system used the distance constraint between the two antennas to find a set of integer ambiguities in an average time of 80 seconds. The double difference observations were then modified by the ambiguities generated and from these derived observations a centimetre level baseline was generated. The baseline was then rotated from the ECEF to the geographic reference frame and from this, azimuth and elevation angles were computed. This system was tested at sea on the CFAV Endeavour from Oct 11 to 19, 1993. The results of that testing were favorable [2], but the system integration was too cumbersome allow successful introduction to the market.

In 1994, NovAtel Inc. brought a 2nd generation receiver (OEM 2) to market that included a medium precision L1 carrier based positioning system. This system generated floating estimates of double difference ambiguities and maintained quadratic models of the base station measurements to provide low latency positions that were accurate to better than 20 centimetres. This system, called RT20 [3], has been a critical and financial success.

In 1995 and 1996, NovAtel Inc. developed a dual frequency L1/L2 receiver (MiLLenium OEM 3) with 12 L1 and 12 L2 channels. A positioning algorithm that used dual frequency carrier phase measurements to provide centimetre level positioning accuracy was part of the real time software on this receiver. The positions generated by this receiver had the characteristics of having high accuracy and low latency. This system (RT2 [4]) estimates floating and fixed integer ambiguities for various combinations of L1 and L2 carrier measurements. When the RT2 algorithms were developed, they were designed in such a way that they either included or could be easily modified to include the design requirements for a single frequency distance constrained system.

So in 1997, NovAtel Inc. put together a design team to take the various components and build a tightly integrated system that could provide a single axis attitude measurement coupled with a positioning system that would meet the accuracy requirements of many applications.

The tasks that the design team had before it included hardware and software components. The tasks related to hardware included redesign of the radio frequency component to filter two isolated L1 signals instead of one L1 and one L2, a redesign of the power supply to provide power to two L1 antennas instead of one, and a new layout of the OEM 3 board (now OEM 6) to incorporate these changes plus the addition of a second antenna feed. The software tasks include a modification of the tracking subsystem to track two independent L1 signals instead of a pair of L1/L2 signals whose dynamics were identical. It included a redefinition of the acquisition subsystem to track only the highest satellites for the configured number of channels. It included a number of modifications to the RT2 fixed integer ambiguity filter to allow the effective use of L1 only measurements in conjunction with a distance constraint. It involved the installation of a duplicate RT20 filter used to estimate the single frequency ambiguities linking the base station and primary antenna observations so that a position accurate to 20 centimetres or better could be generated. Finally, transformation, logging and command routines had to be designed and implemented to enable the appropriate man to machine interface.

SYSTEM DESCRIPTION

The components of interest include hardware and software sections. A detailed description of the two sets of components and their integration follows.

Hardware Components:

The hardware components of this system include two 501 L1 or 502 L1/L2 antennas and an OEM 3 receiver that has been modified (now OEM 6) to accept and process two sets of L1 measurements. One of the antennas, “Antenna A” is designated as a primary antenna, and any positions generated by the receiver will be associated with this antenna. The other antenna, “Antenna B” will be used only to establish the relative baseline between the two antennas. The following is a description of the modified hardware section.

The GPS receiver employs a single stage down conversion heterodyning architecture that consists of four main sections:

1) RF section (filters and preamplifiers)

2) LO stage (VCO, synthesizer and mixer)
3) IF stage (SAW filters, AGC, IF amplification, A/D)
4) Signal Processing Section (24 digital channels, memory, processor)

The primary functions of the RF section are to set the Noise Figure of the receiver, to reject out-of-band interference and to filter out the image frequency. It also provides DC power to both active GPS antennas.

The LO stage design ensures adequate rejection of mixer harmonics, LO feed-through and unwanted sidebands and images. A 1.0 MHz offset was introduced between two IF channels in order to minimize the inter-channel interference and to avoid the cross-correlation between two identical C/A code signals received on two separate analog channels. Even if full code correlation would occur between two identical signals (same PRN) for an instant, post correlation integration will reduce its effect well below the thermal noise, due to the separation in frequency of interfering codes.

The IF stage provides further filtering of out-of-band noise and interference and amplifies the signal-plus-noise level to the appropriate level required by the 2.5 bit (6 digitization levels) A/D converter. A pre-correlation AGC is implemented to maintain the same signal-plus-noise level at the A/D converter input. The IF filtering is realized with an 18 MHz bandwidth SAW filter centered at the IF frequency of 70 MHz (the other channel has a center IF frequency of 71 MHz). The signal is subsampled with the frequency of 40.0 MHz.

The signal processing section is a hybrid consisting of hardware and software subsets. Its primary functions are to split each analog channel into twelve separate digital channels, acquire and track satellite independently on each digital channel, and demodulate the navigation message.

Software Components:

The software tasks and components are the following:

T1) Signal processing section (acquisition, tracking and demodulation)
T2) Pseudorange filter (pseudorange derived position, clock model, velocity)
T3) Primary RT20 Low Latency Vector and Position Generator (propagates base station model, computes low latency position)
T4) Primary RT20 floating ambiguity filter (carrier/pseudorange filter estimating position difference between base station and rover, velocity, double difference carrier ambiguities)
T5) Beeline/RT2 vector and attitude generator (carrier observations modified by ambiguities and transformed to obtain delta position and single axis attitude)
T6) Beeline/RT20 floating ambiguity filter (carrier/pseudorange filter estimating position difference between Beeline receiver antennas A and B, double difference carrier ambiguities)
T7) Beeline/RT2 fixed ambiguity search engine (carrier filters resolving ambiguities between primary and secondary receiver antennas)

During signal processing the digitized samples are cross-correlated with the internally generated PRN code and the antenna specific doppler is estimated and removed in the MINOS III correlator chip. The 1.0 MHz offset of one analog channel is removed in the digital channels by applying an additional Doppler bias of 1.0 MHz. Throughput concerns imposed a limit on the number of digital channels that the system was capable of processing. The 24 possible hardware channels have been reduced to 16, that is 8 channels dedicated to each of antennas A and B. This became necessary because each member of an L1/L1 channel pair is tracked independently, unlike the L1/L2 system in which L2 loops are aided with L1 loop dynamics to reduce the order of the L2 loops. The satellites are assigned the highest tracking priority based on the elevation angle of the satellite. This does not impose a practical limit on the system performance because there are almost never more than 8 satellites above the ambiguity filters mask angles.

The pseudorange filter uses a least squares process to compute independent (in the sense that there is no state history) position and velocity estimates with associated standard deviations. The cycle time for this filter is either 0.5 seconds or the position’s logging rate, whichever is faster, unless the primary RT20 filter is running. If the RT20 filter is running, the pseudorange filter cycle time is 2 seconds. The pseudorange filter will accept pseudorange differential corrections, and the receiver will accept either RTCM types 1 or 9 or RTCA type 1 messages.

The primary RT20 low latency vector and position generator forms double difference observations from carrier measurements collected at antenna A and at the base station. It modifies these with estimates of the appropriate double difference ambiguities and tropospheric and ionospheric estimates. The modified observations are combined in a 3 state Kalman filter to generate an ECEF position vector linking the base station and antenna A. This uses ambiguities and base station observation models generated in the primary RT20 floating ambiguity filter. This is a low latency task in that it does not have to wait to get a base station measurement to get a solution. It can generate position solutions 4 times per second.

The primary RT20 filter uses observations from the base station and “Antenna A” to estimate the Antenna A position. The observations from the base station can be transmitted using various protocols, namely RTCM types 18/19, 20/21, 59 (NovAtel Inc. proprietary) and RTCA type 7 (NovAtel Inc. proprietary), and all of these will be accepted by this receiver [5]. The RT20 filter generate a set of quadratic models to estimate base station carrier measurements, so that the system can generate low latency positions at a 4 Hz rate without exceeding the 20 centimetre accuracy specification.

The Beeline/RT20 vector and attitude generator uses the carrier measurements from the antenna A and B streams with the best ambiguity set available to generate a delta position between the antennas. It forms double difference observations with the carrier measurements taken at antennas A and B, applies the resolved ambiguities to these, uses these in a three state Kalman filter to generate an ECEF position difference vector, and finally transforms this to the geographic frame. The delta vector in the geographic frame is used to compute azimuth and elevation angles. Typically, this portion of the code has a cycle time of 0.5 seconds, but it can run as fast as 4 times per second.

The Beeline/RT20 floating ambiguity filter generates a delta position and set of up to 7 double difference ambiguity estimates based on observations collected at antennas A and B. The delta position generated here is used to provide a low accuracy (on the order of 10 to 15 degrees) azimuth measurement. Its main function is to provide an initial ambiguity estimate about which the RT2 search engine can start.

The RT2 search engine generates a set of fixed integer double difference ambiguities related to the observations measured at antennas A and B. Initial ambiguity estimates and uncertainties generated in the secondary RT20 filter are used to define a center point and search window for each double difference observation. Double differences are used, rather than single differences because with this design, knowledge of the line bias difference is not required, so no significant startup calibration is necessary. Resolution of ambiguities is possible without an inter-antenna distance constraint, but this type of resolution typically takes 15 to 20 minutes. If a distance constraint is used, the time to resolution is about 70 seconds. In the distance constraint case, the typical observation lane window is between 20 and 30 lanes. With 7 double difference observations, and an assumed lane window of 25 lanes, this means that all but 1 of 6,103,515,625 lanes are eliminated in just over a minute. The method used to resolve ambiguities is based on the Magill adaptive filter [6] (an ensemble of conditional Kalman filters) that is modified to incorporate a distance constraint as an elimination criteria. Once the ambiguity space has been reduced to one candidate, this portion of the system is executed once per 30 seconds to ensure the integrity of the ambiguities.

Integrated System Description:

Conceptually, the total system consists of a base station, a radio link, a pair of antennas on a fixed baseline and the Beeline/RT20 L1L1 receiver. The fixed length baseline between antennas A and B is determined to the centimetre level, and the baseline between antennas A and the base station antenna is determined to the 20-centimetre level. The vector between the base station antenna and antenna A is added to the position transmitted in the RTCM type 3 message to get the ECEF position of antenna A, the primary Beeline antenna. The vector between antennas A and B is rotated to the local geographic frame, then the vector components in this frame are used to compute azimuth, elevation and with the propagated vector covariance, the associated uncertainties.

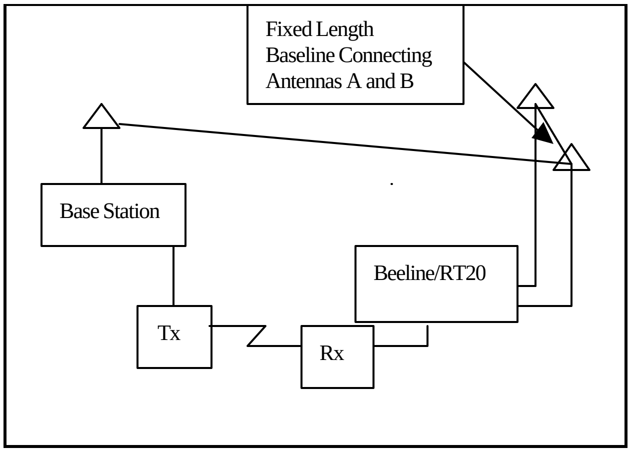

Figure 1: Conceptual Beeline/RT20 System

A high level representation of the Beeline/RT20 hardware is shown in Figure 2.

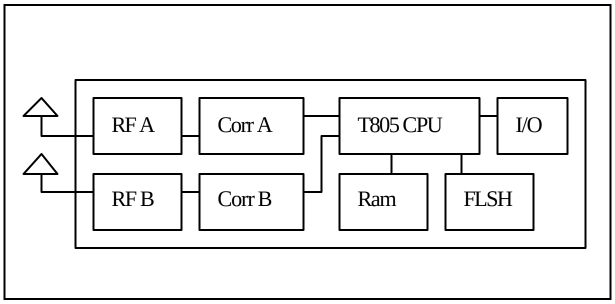

Figure 2: Simplified Beeline/RT20 L1L1 schematic

The Inmos T805 Transputer is the original processor that all of NovAtel Inc. GPSCards use. It runs at 25 MHz, which is relatively slow by today's standards, but this system still provides a reasonable level of performance. The software architecture is the reason for this. The operating system is a multitasking environment, and the key to a consistent level of performance is to ensure that tasks that are time consuming but not time critical, such are the ambiguity estimation (RT20) and ambiguity resolution tasks (RT2 search engine) run in the background, while time critical functions run to completion. The tasks T4, T6 and T7 are background tasks whose main function is to generate ambiguity estimates and (in the T4 case) maintain base station observation models. An overview of the system software architecture is shown in Figure 3.

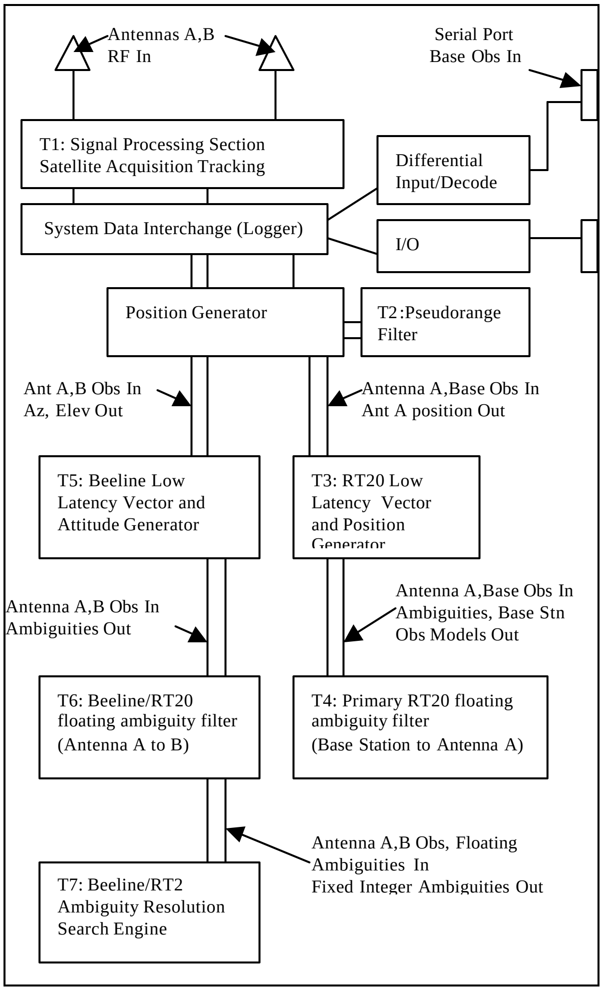

Figure 3: Software System Overview

Particular Problems or System Constraints:

The items in this system which warrant special mention relate to the fixed ambiguity resolution performance and also to the accuracy achievable by this system. A discussion of the achievable accuracy is followed by a description of the resolution processes used.

Accuracy:

The accuracy of GPS systems in general is a function of the geometry and the level of systematic and random errors on the measurements. Whenever anybody specifies accuracy, there is always an associated geometrical qualification, either GDOP or PDOP. When talking about single axis attitude, DOP is relevant, but so is the direction of the baseline, the length of the baseline and the orientation of the baseline with respect to the body axis whose attitude is required. The accuracy of the measurements is also a factor, and this is a function of, in order of importance, the state of the ambiguity resolution, the amount of multipath interference, and the phase noise of the carrier signals.The azimuth and elevation angle standard deviations are generated with the following steps:

$$Cov_{Geo} = J^T Cov_{ECEF} J$$
$$Var_{Ct} = B^T Cov_{Geo2} B$$
$$SD_{Az} = Sqrt(Var_{Ct})/L_{Horiz}$$
$$Var_{Up} = Cov_{Geo33}$$
$$SD_{Elev} = Sqrt(Var_{Up})/L_{Horiz}$$

Where:

L_{Horiz} is the computed horizontal length.

Var_{Up} is the linear variance of the baseline in the vertical direction.

Var_{Ct} is the linear variance of the baseline in the cross-track direction.

J is the gradient matrix of the transformation from the ECEF frame to the geographic frame

B is the gradient vector that rotates north and east errors to crosstrack errors.

Cov_{geo} is a 3 by 3 covariance matrix of the inter-antenna baseline with a geographic reference frame.

Cov_{ECEF} is a 3 by 3 covariance matrix of the inter-antenna baseline with an ECEF reference. It is generated from the Beeline/RT2 vector and attitude generator. In the fixed ambiguity case, this is based on the assumption that the ambiguities are error free but the multipath and phase noise contribution to the measurement error is nominally 0.007 metres. If this assumption is incorrect, the reported Azimuth uncertainty will be wrong. Attitude specifications do not usually include any qualification of the multipath environment, but the multipath level can vary from the nominal used here by a factor of 3 or 4. In order to address this condition, the user is given the option of specifying the multipath environment that the system is in. If the level of multipath is higher, then the resolution time will increase and the achievable accuracy will decrease. The specifications assume a nominal multipath level, and define this to be one that will cause an RMS error of 0.007 metres on a double difference phase observable.

Local environment geometry will also affect single axis attitude accuracy. The azimuth error is inversely proportional to the horizontal antenna separation, so the accuracy increases with the antenna separation, but decreases with the tilt of the axis. Another accuracy concern for a single axis system is the amount of crossover error that is the result of antenna axis misalignment from the body frame axis of interest. The effect of a misalignment angle coupled with a rotation about the axis of interest, will cause an angular error described by the following equation:

$$Az_{Err} = ArcTan[Sin(Rotation) * Tan(Misal)]$$

For example, a vertical misalignment error of 5 degrees of the antenna axis from the body roll axis, coupled with a body frame roll about the roll axis will cause a systematic azimuth error as shown in Figure 4. This kind of error will not be significant if the system axis is aligned with body axis of interest or if the platform undergoes minimal pitch or roll.

Fixed Ambiguity Resolution:

A carrier wave front can be represented by a planar surface passing through space. Once a GPS receiver has acquired satellites, it has the capability of counting carrier wave fronts that pass the receiver antenna. The starting point of the count is arbitrary, and will vary from the counts maintained in other receivers tracking the same satellite signal.

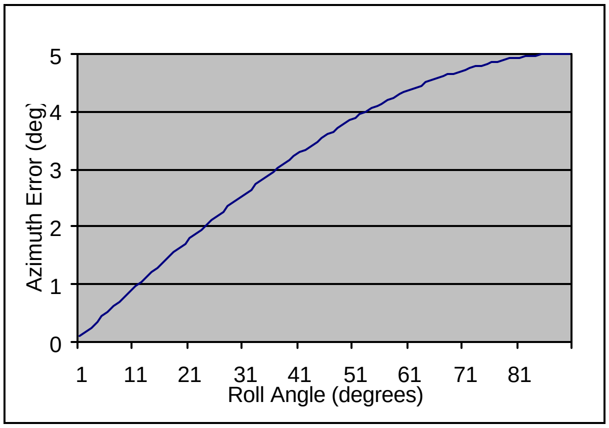

Figure 4: Systematic Azimuth Error resulting from a 5 degree misalignment angle.

The amount of deviation in initial wave front counts between two receivers is the single difference ambiguity, and this quantity cannot be observed directly unless the baseline linking the two antennas, and the clock difference of the two receivers is known precisely. A double difference of two single difference observations can be taken, and then the requirement to know the receiver clock difference disappears. The baseline linking the two antennas is the quantity the user is interested in, so some other method besides using a known baseline must be used to resolve double difference ambiguities.

Resolution of ambiguities can be accomplished with a minimum variance estimation process (as in RT20 [3]) or with adaptive filtering techniques (such as RT2 [4],[6]). The ambiguity resolution method for the Beeline/RT20 system involves both resolution methods. An RT20 estimate initializes the search window (both its center and its size), and an adaptive filter uses residual and length comparisons (with the input constraint) to eliminate the incorrect integer lane choices.

In the implementation of an adaptive filter, a suite of ambiguity sets is maintained as a collection of possible candidates. Each candidate set can, with the carrier observations, generate a baseline and, if there are redundant observations, a set of residuals, and over time, an accumulation of squared residuals. Incorrect lane choices will usually generate baseline components that are incorrect and residuals that are larger than those generated by the correct lane choices. The wrong lane set will generate a baseline whose length is usually incorrect. When the incorrectly generated length is compared to the constraint length, the incorrect candidate ambiguity set can be often, though not always, eliminated.

The resolution method in this system has three distinct stages:

R1) Initialization Stage
  - Floating Ambiguity
  - Short Baseline <2.5 metres

R2) Adaptive Filter Construction Stage

R3) Candidate Race Stage

The initialization stage reduces the search space to approximately 25 lanes per double difference observation in the constrained case. This normally takes from 20 seconds to 2 minutes (when kinematic) or more. By the end of this stage the lane space has some 6 billion possibilities. If the baseline is short enough, the system uses the length of the baseline in cycles centered around a center ambiguity based on a zero baseline to initialize the candidate set. In this case, the initialization process takes about 5 seconds, and the lane space is often an order of magnitude smaller.

The Adaptive Filter Construction Stage reduces the candidate set from something on the order of a billion to something less than 100. The candidate set is constructed sequentially, with lane reductions occurring every time new satellites are added.

Elimination of lane sets is possible if a distance constraint and at least 4 satellites are available. In this case, lane sets are eliminated if the difference between the baseline length of the associated baseline and the constraint length exceeds a Length Difference Threshold (LDT). The LDT is computed by the following formula:

$$Var_{At} = R^{T} Cov_{ECEF} R$$

$$LDT = (Multipath\ Factor) * Sqrt(Var_{At})$$

R is the gradient vector that propagates the ECEF covariance matrix to the along track direction. In order to do this, a reasonable direction estimate has to be obtained from the Floating Ambiguity filter.

Var_{At} is the variance in the along track direction of the conditional baseline associated with the particular ambiguity set.

In a nominal multipath environment with a reasonable geometry (PDOP<3.0), the LDT is around 0.04 metres.

When doing this, the process selects the order of the satellite inclusion into the adaptive filter by selecting first the 4 satellites that together generate the minimum PDOP. This criteria usually ensures that the computed LDT will be a minimum for the first four satellites as well. The Adaptive Construction Stage normally takes about 20 seconds, but can be less if the baseline is shorter, or more if the geometry is poor or the specified multipath level is high.

The Candidate Race Stage uses sums of squares of residuals and distance comparisons in the constrained case to eliminate the last few (usually 100 or less) candidate sets. In a static environment, this will normally take 10 to 20 seconds, but on occasion will last as long as 10 minutes. In a kinematic environment in which there is significant system rotation, this stage lasts less than 5 seconds. The reason for this is explained with reference to Figure 5. Notice that the orientation of the lane induced error vector does not change when the baseline vector rotates. So a candidate set satisfying the constraint length criteria in one orientation, will have a different length after the antenna pair is rotated.

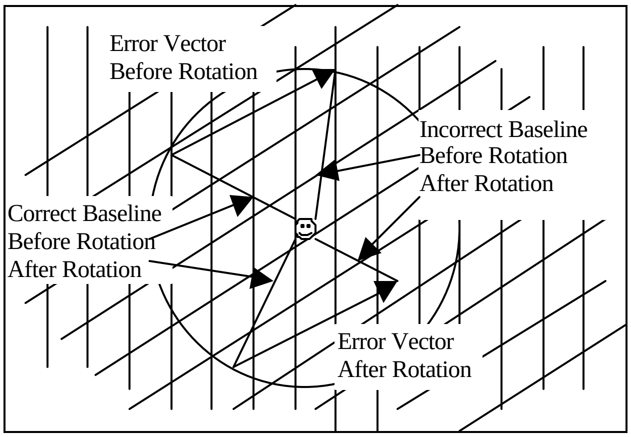

Figure 5: Conceptual Candidate Elimination

The Beeline/RT20 system resolves differently depending on whether there is a known length constraint or not. It also resolves differently depending on whether the system is moving or not and whether the baseline constraint is short (less than 2.5 metres) or not. There are six different combinations of conditions that have expected resolution times between 20 seconds and ½ hour. The times expected for each resolution task are summarized in Table 1.

Mode	R1	R2	R3	Total
NC S	200	20	400	620
NC K	700	20	1080	1800
C S SB	5	20	30	50
C S LB	15	25	30	70
C K SB	5	5	10	20
C K LB	65	25	10	100

Table 1: Resolution Performance
C = Length Constraint, NC = No Constraint
S = Static, K = Kinematic
SB = Short Baseline (less then 2.5 metres)
LB = Long Baseline (more then 2.5 metres)

TEST PROCEDURES AND RESULTS:

The primary objectives of the tests were to quantify the performance of the Beeline system and to ensure that the RT20 system functioned on the same hardware platform. A secondary objective of qualifying the consistency of the RT20 data was addressed concurrently with the Beeline testing. RT20 testing had less emphasis because the RT20 subsystem has proven reliability. Testing Beeline had to measure its performance in four areas. The areas we wanted to know about were the accuracy, precision, and reliability of the system, as well as the time it took to resolve ambiguities in various environments. The tests were carried out in static and kinematic environments, but the lack of control in the kinematic tests allowed answers only to questions of reliability and time to resolution in that mode.

Static Testing:

The static mode testing took place on the NovAtel Inc. rooftop. Two 502 antennas, whose baseline had been established with both RT2 and by a conventional survey based on City of Calgary control points, were linked to a Beeline/RT20 system. The antenna separation distance was 4.588 metres, and the baseline azimuth was 114.46 degrees. The level of accuracy of the system was established by differencing the mean azimuth derived with the system from the azimuth established from GPS and conventional control. The precision of the system was established by computing the sample standard deviation of the differences between the measured azimuth values and the mean of the sample. The reliability of the system is largely a function of the success rate of the resolution process, so a resolution experiment designed to establish this statistic was implemented. Data from this test could also be used to determine the expected time that the resolution process takes. The resolution experiment involved a software modification in which the system monitored itself to see when it had resolved ambiguities. When it had, it would wait 5 seconds and initiate a system reset. This cycle of resolve, wait and reset executed on the system during two tests initiated on Sept 7th and 9th that took 15 and 42 hours respectively. The results from the two tests were very similar. The mean time to resolution was 66 seconds and the resolution success rate was 99.66%. The maximum time to resolution was 627 seconds, and the minimum time was 25 seconds. The two tests had 722 and 2181 resolution attempts respectively with 10 failures proportioned between the two. The mean values of the azimuth and elevation angles measured were 114.41 degrees and –0.56 degrees. These values were unbiased within the accuracy of the external control. The normalized sample standard deviations of the azimuth and elevation angles were 0.25 degrees and 0.67 degrees respectively. The actual standard deviations were smaller by a factor of 4.588 (the baseline length), but the deviations have been normalized to reflect the expected precision for a 1 metre baseline. The largest azimuth deviation from the mean was 0.2 degrees, normalized to 0.92 degrees.

The tests indicated two noteworthy points. Analysis of the test data indicated that the reliability can be improved somewhat. Although there were only 10 failed resolutions over a 57 hour observation period, two pairs of these failures occurred very close together, indicating the possibility that the system could have a systematic problem with some geometries. Also, the variation in resolution is significant. The 627 second resolution did not occur when the system was resolving erroneously, although faulty resolutions often take longer than correct ones. On occasion, there is not enough information (this only happens in a non-rotating system) to quickly pass through the “candidate race stage” of the resolution process. The system will limp along like Hamlet with a few (usually two) candidates that satisfy the length condition and have residual statistics that are similar. As mentioned, this happens only if the system orientation is static.

During these tests, RT20 was running continuously on the same hardware platform, and the steady state (the reset signal affected only the Beeline processes) performance of this subsystem was well within the RT20 specification. The mean steady state height error for the logged position was 0.006 metres, and the sample standard deviation was 0.05 metres.

Kinematic Testing:

The accuracy and precision of the system had been established through static testing, so the main purpose of this experiment was to characterize the resolution capabilities of the system in kinematic mode, in particular, to find resolution success rate and to find the expected time to resolution. The testing took place on the road and in a parking lot close to NovAtel Inc. headquarters. The control for this test consisted of the curb on the road and a parking stall marker in the parking lot. They were used as marks to reestablish the orientation of the test van. The antenna separation on the van was derived by the system, and verified by independent measurement to be 1.17 metres, qualifying this as a short baseline system. The method used in the kinematic experiment consisted of driving the van with the Beeline/RT20 system installed to a test location (say REPO A) such that orientation of the van could be reproduced on subsequent trips to a precision of less than 2 degrees. Then the operator would leave REPO A, immediately reset the Beeline subsystem and drive until a resolution occurred. When the system indicated it had resolved, the driver returned the van to REPO A and collected data for 20 seconds.

The cycle just described, drive, reset, resolve, return, collect data, was repeated for 3 hours, during which the system went through 147 resolutions. The resolution was labeled a success if its derived azimuth and elevation angles agreed with the mean of the sample to a tolerance of +/- 2 degrees. Of those 147 resolutions, 142 were deemed to be successful for a resolution success rate of 96.6%. The mean resolution time for each resolution in this test was 17.5 seconds. The maximum time taken to resolve was 60 seconds, and the minimum time taken was 8 seconds.

The resolution success rate of 96.6% for the short baseline kinematic system is somewhat lower than that of the static long baseline system, but the resolution time is much less. The difference in the resolution time for the two systems occurs because the first and second stages of the resolution process (initialization and Adaptive Filter Construction stages) are faster for a short baseline system, and because the final candidates race stage of the process is much more effective in a kinematic than in a static system. The long baseline static system has a higher resolution success rate than the kinematic system because the uncertainty in the direction of the antenna axis in the short baseline system makes computing a precise length difference rejection threshold more difficult.

Test Results Summary:

The results of the static and kinematic tests are summarized in Table 2.

Date	Mode	Trys	Fail	Res Tm
Sept 7	C S LB	722	4	69 s
Sept 9	C S LB	2181	6	64 s
Sept 11	C K SB	147	5	17.5 s

Table 2: Resolution Test Results

CONCLUSIONS

NovAtel Inc. has successfully developed a Beeline/RT20 system that combines a single frequency RTK process (RT20) with a single axis attitude system (Beeline) on a single hardware platform.

In the Beeline/RT20 system, ambiguity resolution is often significantly faster in a kinematic environment than it is when it is stationary.

The following is a performance summary for the Beeline/RT20 system:

- RT20 position accuracy: 20 cm after 3 minutes static, 10 minutes kinematic
- The system will accept differential corrections encoded using RTCM type 1, 59 *, 18/19, 20/21 or RTCA type 1 or 7 *. (* NovAtel Inc. prop)
- Beeline accuracy (after resolution, 1 metre baseline):
  Azimuth: 0.4 degrees
  Elevation: 1.0 degrees
- Beeline time to resolve
  Static: 70 seconds
  Kinematic: 20 seconds
- Output Rate: 2 Hz

The Beeline/RT20 system performance meets or exceeds design expectations in all areas.

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