Reliable Single Frequency Dual Antenna Processing System for Marine Dredging Applications

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BIOGRAPHY

Darren Cosandier is a co-founder of Waypoint Consulting Inc., and obtained a B.Sc from The University of Calgary, Department of Geomatics Engineering in 1990. He is currently near completion of his Ph.D. at the same institution in the area of Photogrammetry/Navigation. Mr. Cosandier has ten years experience in the area of GPS and photogrammetry software development

Koji Kittaka graduated from Kinki University in 1972. In 1981, he founded KITTAKA ENGINEERING LABORATORY CO., LTD. In 1989, Mr. Kittaka developed a position fixing system for dredging vessels using an automatic-tracking light wave distance measurement system. In 1995, he developed a positioning system for dredging vessel using a GPS Real Time Kinematic Positioning system.

Kiyoaki Soen joined Furuno Electric Company after graduating from The University of Osaka Prefecture in 1970. He is specialized in the development of digital circuits and gate arrays as well as system design for GPS receivers. In 1995, he joined KITTAKA ENGINEERING LABORATORY CO., LTD.

ABSTRACT

GPS real-time kinematic (RTK) has been utilized for harbor dredging applications for a number of years. Such applications require both accurate position and heading in order to obtain the location of the dredging vessel implements. The method described here involves mounting two remote GPS antennae on the vessel, denoted R1 and R2. Their distance separation is pre-calibrated and will remain constant with vessel dynamics. A base station (M) is also employed on shore. The vessel's position is obtained by solving for the vector M-R1 or M-R2, while vessel azimuth is computed from R1-R2. Optimal accuracies are obtained using on-the-fly (OTF) techniques.

Traditionally, single frequency RTK can require long initialization times to obtain reliable results—especially for base to vessel distances longer than 5 km. Times of 10 to 25 minutes are common. Nonetheless, the initialization time can be reduced significantly if the R1-R2 distance is considered. This requires specialized RTK software that solves for both M-R1 and M-R2 in a combined OTF solution. The constraints employed to achieve faster base-to-vessel initialization times include the R1-R2 distance constraint and the M-R1, M-R2 and R1-R2 ambiguity constraint. In addition, processing between R1-R2 directly allows for more accurate azimuth determination since such processing is not affected by atmospheric errors associated with a distant base.

Results are presented for two field trials in Japan, including shipborne results on a dredging vessel and car based results using a much shorter antenna separation. The various modes of processing are compared along with their initialization times. For the shipborne results, on average, the distance constrained dual antenna solutions initialized in 7.8 minutes using a minimum time of 5 minutes. Of 28 tests, 27 had correct solutions. When compared to a methodology not applying the distance constraints, times were slower by 60% with one failure as well. In the car tests, the average time drops to 5.7 minutes using a minimum time of 3 minutes. The initialization time for the car results was significantly better than for the shipborne results mostly due to better satellite geometry, but a 1.0 m separation (as opposed to 12 m for the shipborne) may also play a factor.

INTRODUCTION

The process of positioning and orienting a dredge or compaction barge is not a new application. There are many such systems in place today which perform this task on a day-to-day basis. Many dredge navigation systems often use either DGPS or real-time kinematic (RTK) for position determination combined with a gyrocompass for azimuth. The azimuth is required to transfer the position from the GPS antenna to the implement *or grab.* Positioning accuracy requirements for such applications can vary.

In Japan, accuracy requirements are very stringent, where 10 cm are required vertically, while horizontal accuracies are more relaxed at 30 cm. Given that a vessel can be as large as 50 m, the azimuth accuracies must be ½ degree.

In the mid-1990s, Kittaka Engineering Laboratory Co., Ltd. developed a single frequency based system, called NAV-LAH. It employed two GPS receivers and antennae on the vessel. This allowed for both position and azimuth determination and avoided the need for expensive gyrocompasses. NAV-LAH employs on-the-fly (OTF) RTK for position determination. This process is performed independently for each antenna, and computations are performed by Waypoint Consulting Inc.'s DOS RTK processing software (GPS_EMB). NovAtel 3151 single frequency GPS receivers are employed as well. Although fix times are longer than dual frequency, the system cost is considerably less, while accuracies are comparable. The longer single frequency fix times are not an impediment in positioning such vessels because a considerable amount of time is needed to bring the vessel on-line anyway. Nevertheless, faster initialization times are always desirable, and one of the major focuses of this paper is to improve such times without compromising reliability.

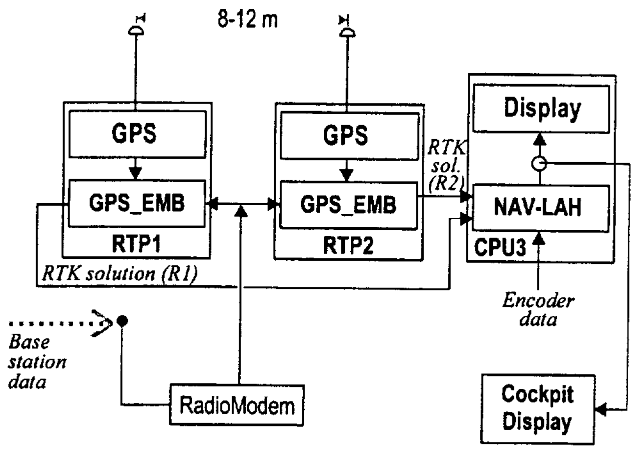


Figure 1: The NAV-LAH system implementation

The existing NAV-LAH system is shown in Figure 1. Encoders measure the trim/heel, rotation and jib angles, which are shown in Figure 2. These values combined with the vessels heading can be used to transfer the position from the GPS antennae to the implement (i.e. the grab). In order to obtain acceptable heading/azimuth accuracies, the remote antennae (denoted R1 and R2) are separated by ~10 m. This often requires that steel towers be installed on the vessel in order to mount the antenna in unobstructed locations. Such towers are expensive and significantly add to the system cost. The NAV-LAH is DOS based and employs three CPUs (see Figure 1). One is required for each RTK processor, while a third combines the information and displays the implement position and depth on a mapping screen using VGA graphics. Currently, there are 65 NAV-LAH systems installed in Japan.

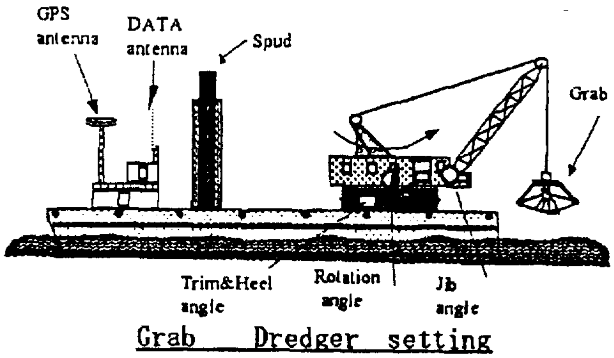


Figure 2: Components of a dredging vessel

In 1998, Kittaka set out to redesign the NAV-LAH system. The result is a second-generation system called the GPS Position and Azimuth Determination *system* (GPAD). GPAD is to improve upon the following aspects over the NAV-LAH:

a) By placing the two GPS antennae much closer together, there will be no need for the second tower, thereby considerably reducing the overall cost. Azimuth accuracies must, therefore, be improved upon over existing levels in order to compensate for smaller baseline lengths. This is achieved by processing the data from R1-R2 directly, which avoids contamination from tropospheric and ionospheric errors.
b) Faster initialization times are desired by using the known distance between the antennae as a constraint. This aspect is given much emphasis in this paper.
c) Windows NT should replace the DOS operating system. The current NAV-LAH system employs a special version of NEC DOS, which is difficult to obtain hardware for. Windows will also facilitate an easier-to-use graphical interface that also allows for multi-tasking.
d) The three CPUs should be replaced by one, thereby further reducing system costs.
e) Single frequency GPS equipment should still primarily be used.

Simultaneously, Waypoint developed a Windows 95/NT version of its DOS RTK software. It would have the capability of processing multiple remote vehicles, attitude *or* azimuth determination and moving baseline processing. This software is called RtEngine.

RTK PROCESSING SOFTWARE

The RtEngine software and its corresponding processing library (i.e. RtDLL) are Waypoint's multi-remote RTK processing package. This package runs under the Windows 95, 98 and NT operating systems and supports both single and dual GPS frequencies. Single frequency will be the primary focus of this paper as this makes the GPAD system much more cost-effective.

RTENGINE

RtEngine is a console program that reads the GPS raw data directly from the computer's serial ports. Five raw GPS data formats are currently supported including Ashtech, Canadian Marconi, Garmin 25/35, NovAtel, Rockwell Jupiter and RTCM 3/18/19. Output is available on an additional serial port using NMEA style messages. A windowed variant of RtEngine will be available in early fall 1999.

Typical applications of RtEngine are:

- Precise multi-remote inverse processing—Up to 20 remotes can be simultaneously processed in this manner (see Figure 3).
- Attitude and azimuth determination—With three or four antennae roll, pitch and heading can be computed, while with two antennae, azimuth is available.
- Moving baseline processing—Such a methodology allows the base station to be non-stationary and can result in much better relative position accuracies *versus a stationary base* if shorter baselines can be maintained. An example of such an application is tracking buoys with respect to an ocean vessel.
- Conventional RTK—Most users use the algorithms present at chip level in the GPS receiver for such processing. However, there are some specialized applications where using RtEngine (or RtDLL) is practical. For example, some GPS receivers can form measurements at a very high data rate, but RTK computations might not be possible at that rate if the GPS's on-board CPU is not fast enough. Therefore, the user can implement the RtEngine algorithms on an off-board CPU that will keep up.
- Specialized applications such as this one, rocket positioning, robot tracking/navigation etc...

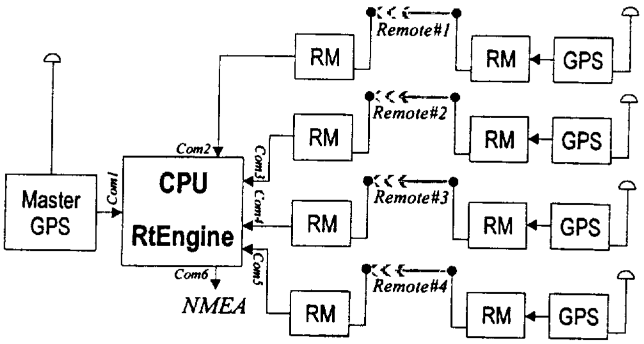


Figure 3: Multi-remote implementation of RtEngine

RTDLL

RtDLL is a Windows Dynamic Link Library (DLL) that contains the RTK processing algorithms used by RtEngine. RtDLL is based upon a (6 + NumSats-1) Kalman filter utilizing double differenced code, carrier and doppler measurements (Martell *et al*, 1993). It is the user's task to collect the data from the serial port *or other input port such as Ethernet* and pass them to RtDLL. RtDLL can buffer the GPS data over a user-specified number of epochs and then attempts to line the data up. Once all of the data has arrived, an epoch may be processed. There are three criteria for considering when enough data is present in the memory buffers in order to process, and the data is deemed lined-up:

a) Once the master and <u>all</u> remote data have arrived (a remote or master dropout will cause the entire epoch to not be processed); or
b) Once the master and all remotes within a specified number of milliseconds have arrived (late remotes will be ignored); or
c) Once all remotes have arrived within a number of milliseconds and the master data is extrapolated forward to minimize latency. This mode causes two solutions to be computed for each epoch. The first solution is based upon least squares and uses the extrapolated master data. A Kalman filtered solution is available when the master data arrives. OTF is executed using the later data as well in order to avoid contamination by the extrapolation. In addition to minimizing latency, this mode will also bridge master dropouts of 20 seconds *or less*.

A very typical single threaded implementation of RtDLL is shown in Figure 4, and it shows the manner in which RtEngine employs RtDLL. However, having one thread in a windowed application is not practical, and the GPS data decoding and RTK processing are often split into separate threads. In such a case, it is important that both do not enter the DLL simultaneously.

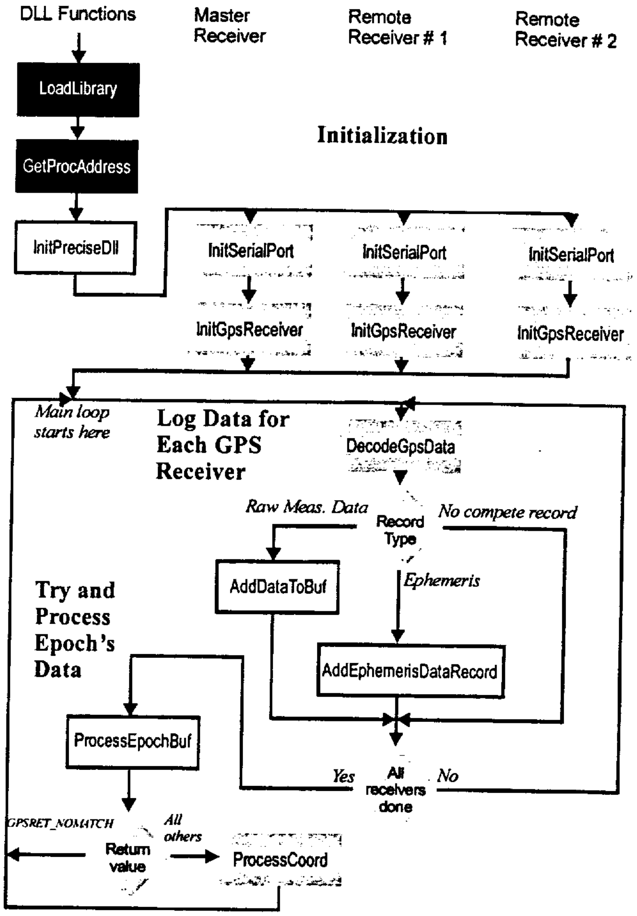


Figure 4: Single threaded implementation of RtDLL

Kittaka chose to use RtDLL for its GPAD system, as this allowed for a more complete control over the program development than RtEngine. Since the vessel movement is very slow, master data extrapolation is not required. In addition, the remote GPS receivers are connected via a direct cable connection to the processing computer and no remote dropouts are to be expected. For these two reasons, method (a) is used for lining up the data. In the future, method (c) may be used to better compensate for master dropouts.

KINEMATIC AMBIGUITY RESOLUTION

Kinematic Ambiguity Resolution (KAR) is Waypoint's adaptation of an on-the-fly (OTF) algorithm, where it was developed in-house. KAR has been steadily improved upon by Waypoint since its initial development in 1993. KAR uses a variance factor intersection testing methodology, which is supplemented with an extensive set of empirical rejection criteria in order to maximize reliabilities.

Intersections are initially obtained using a minimal satellite configuration (i.e. five satellites). Using this initial list of positions/ambiguities, all of the satellites are employed to further remove erroneous intersections. This second list of intersections is then tested back to the loss of lock and as long as 5 satellites is maintained. This last stage is especially important for single frequency because 5 or more minutes of data are necessary to reliably obtain a solution.

KAR has three primary measures reported to the user. Most importantly, the RMS fit of the intersection is computed and expressed in L1 cycles. The reliability is the ratio between the second best and best RMS values. Reliabilities greater than 1.5 generally indicate a correct solution, while values greater than 2.5 are almost always correct. Finally, the average number of satellites used in the solution is also computed.

DISTANCE CONSTRAINT MODEL

One of the major purposes of this implementation is to reduce KAR initialization times by using the known distance between R1 and R2 as a constraint. In its generic implementation, RtDLL processed the baselines M-R1 and M-R2 independently. The distance constraint model merges these two KAR computations into a single solution. This is accomplished by applying a number of additional constraints on top of the KAR intersection lists of M-R1 and M-R2, which, for single frequency, are outlined as follows:

a) The most obvious check is the distance between the candidate intersections of M-R1 vs. M-R2. They should match the fixed distance to a specified tolerance (i.e. 2-3 cm). Using this distance, all of the possible intersection combinations between the M-R1 and M-R2 lists are extracted. Over short distances, such as 1 metre, this check is more effective since there are only a few combinations that pass tests. For longer distances like 10 metres, it only helps to reject intersections along the axis parallel to the vector joining the two antennae.

b) Another constraint applied is the ambiguity constraint, which is depicted in Figure 5. The ambiguity constraint uses the following formula for each double differenced satellite:

$$N_2 - N_1 = N_3 \qquad (1)$$

However, the true ambiguity N_3 is not solved for because the baseline R1-R2 is not part of this Kalman filter. Therefore, the constraint checks for how close N_3 is to the closest same integer value, which remains constant over the test data. The ambiguity constraint is applied on all satellites visible over the period since the loss of lock or when KAR was engaged. The residual RMS of Equation 1 must be below a certain tolerance (i.e. 0.06 cycles), while the reliability computed from two (or more) intersections must also be greater than 1.5.

c) The RMS values from M-R1 and M-R2 are combined into a single RMS, for which the reliability is tested as well.

d) If both baselines M-R1 and M-R2 pass RMS and reliability tests individually and the distance between optimum intersections passes the distance check, then only these two intersections are tested. This can speed up fix time without hampering reliability.

e) If the roll or pitch angle between R1 and R2 remains fairly stable, then this angle can also be applied as an additional constraint, which also helps to improve fix times and reliability.

For dual frequency, the distance constraint is applied only as a check because the individual baselines should not need any help in resolving. Such an implementation showed to be more effective than the above set of constraints, which caused dual frequency to be less reliable. If the KAR intersections for M-R1 and M-R2 do not pass the distance check, then KAR is prevented from engaging the current solution and the search continues. This increases the reliability of dual frequency KAR above existing levels.

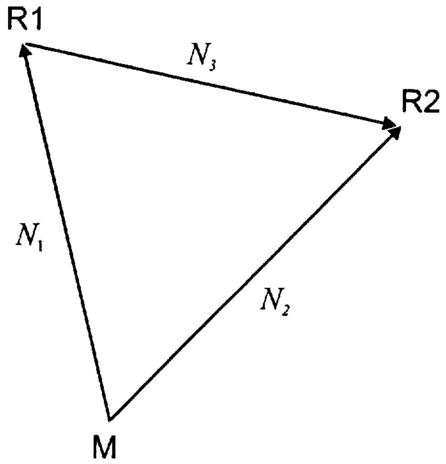


Figure 5: Ambiguity constraint closure (for each satellite)

PROBLEMS AND PITFALLS

Initially, the distance constraint model was found to significantly improve resolution times. Times went from 10-25 to 1-10 minutes. However, this came with a reduction in reliability caused by erroneous intersection selection. Since, in most marine applications, reliability is paramount, this was an undesirable effect. The problem is threefold. Firstly, single frequency KAR works best with small search region sizes (i.e. 1-1.2 m). At 1-3 minutes after the loss of lock, the float solution is often outside of the search area. This combined with very little data to test, results in an erroneous solution passing rejection criteria. Secondly, the atmospheric induced errors tend to be very correlated between the M-R1 and M-R2 solutions. This is especially the case for ionosphere errors, which are heavily systematic and causes the incorrect intersection to appear overly favorable. Finally, errors of the same number of lanes on each of the satellites for M-R1 and M-R2 will result in a passed ambiguity constraint test. Only the RMS test and sufficient data will catch this error.

In order to circumvent these problems, the minimum time used for solving a solution is increased from 1-2 to 5-8 minutes, which helped significantly. This extra time bestows KAR with more data and allows the float solution more time to converge. A number of extra checks are also added. For instance, most of the problems happened when there were only 5 satellites and when only one intersection combination passed distance tests. For this particular case, the minimum time is expanded significantly. In addition, if the best RMS is high in combination with only one intersection passing distance tests, then more time is required as well. Using these additional measures, the distance constraint reliability was improved significantly.

AZIMUTH DETERMINATION

One of the byproducts of the distance constraint model is azimuth. Unfortunately, a precise azimuth is not available until the distance constraint passes all tests, which can anywhere from 5 to 25 minutes. This azimuth is also partially contaminated by the base to remote errors. A more accurate solution is to process between R1 and R2 directly using the moving baseline mode. Initially, it was planned to perform this as part of the M-R1 and M-R2 Kalman filter. However, this increased the complexity dramatically. A simpler and more effective approach is to execute another instance of RtDLL that is configured for azimuth determination mode. In this case, R1 is the *moving* base, while R2 is the remote. Their separation is known and should be stable.

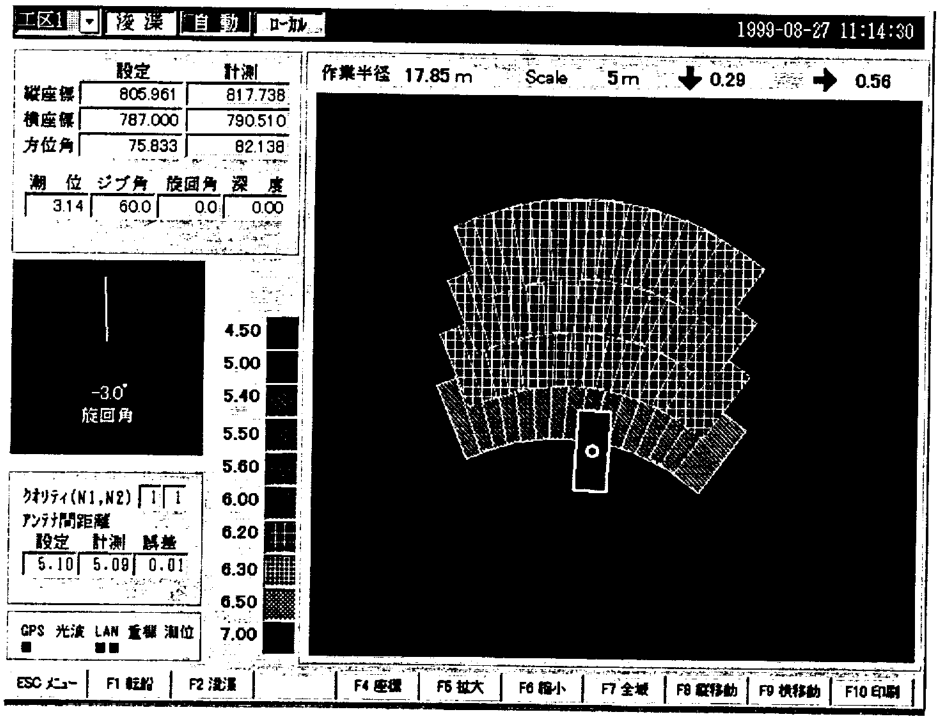
The additional instance of RtDLL is very easy to implement (on the calling application side) and results in an independent solution for azimuth. Since the R1-R2 baseline is not contaminated by atmospheric errors, this azimuth solution should be more accurate and should initialize faster than for the distance constraint derived model. This is especially the case for shorter R1-R2 baseline lengths such as 1 metre, as this reduces the size of the theoretical search. Another advantage to a separate azimuth determination is that it can be used as a check against the distance constraint azimuth. If they are significantly different, then a restart can be issued to one or both RtDLL.

The azimuth determination works in a similar manner to the distance constraint model in that it uses the known distance between R1 and R2 to aid the KAR algorithm. The azimuth determination module also continually checks this distance after a fix is performed. If it deviates significantly from the known value (i.e. 5 cm), then KAR is re-engaged.

THE NEW SYSTEM (GPAD)

The Windows GPAD graphical interface shows the depth and location dredged in the manner shown in Figure 6. This interface is similar to NAV-LAH, but offers additional diagnostic features about the radio and GPS receiver statuses. The main purpose of the GPAD display is to indicate to the operator when a specified depth has been reached. This maximizes efficiency while still maintaining quality control.

GPAD implements two instances of RtDLL configured for distance constraint and azimuth determination modes, respectively. Figure 7 shows a flow diagram of this implementation, where it can be seen that the GPS data from R1 and R2 are passed to both DLLs. R1 is the master for the AzDeterm RtDLL, while R2 is the remote. For the distance constraint, R1 and R2 are remotes, while the base data comes via the radio link.



1999-08-27 11:14:30

	設定	計測
縦座標	805.961	817.738
横座標	787.000	790.510
方位角	75.833	82.138

潮位	ジブ角	旋回角	深度
3.14	60.0	0.0	0.00

-3.0° 旋回角

クオリティ(N1,N2) 1 1

アンテナ間距離

設定	計測	誤差
5.10	5.09	0.01

作業半径 17.85 m Scale 5 m ↓ 0.29 → 0.56

Figure 6: GPAD Graphical User Interface

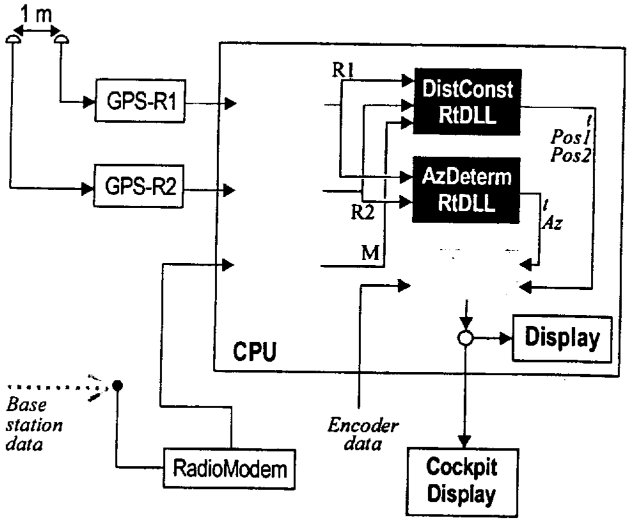


Figure 7: GPAD + RtDLL implementation flow chart

TESTING AND RESULTS

In order to evaluate the software's performance, two test data sets are used. One data set is shipborne with a 12 m R1-R2 separation, and it is useful to evaluate system under operating conditions. The second data set is car-borne and has a 1.0 m separation. These second data are investigated to gauge RtDLL+GPAD system using a much shorter baseline, which will be more indicative of later installations. Currently, all GPAD systems are upgrades to NAV-LAH systems, which employ twin towers and, therefore, have 8-12 m antenna separations.

Of most interest in this analysis is the speed and reliability of the KAR fixes. Single frequency RTK position accuracy is well known from the NAV-LAH system (Soen *et al*, 1996) and investigations by numerous others. In terms of azimuth, the accuracy is linearly dependent on the baseline length. In-house testing at Kittaka has shown that the azimuth accuracy (once a fix is obtained) from RtDLL is comparable to that computed by NovAtel's Beeline when using the same data. Beeline accuracies are presented by Ford *et al* (1997, 1998) and RMS accuracies are estimated to be ~0.4 degrees on a 1.0 m baseline.

SHIPBORNE RESULTS

Testing for this data was performed on the dredging vessel Showa No. 18 of the SHOWA GENECON Co., Ltd., which is shown in Figure 8. Data was logged over ~7 hours continuously on March 19th, 1998 and for more than one hour on the 18th. The system was powered down and up again six times during data collection to simulate fresh starts.

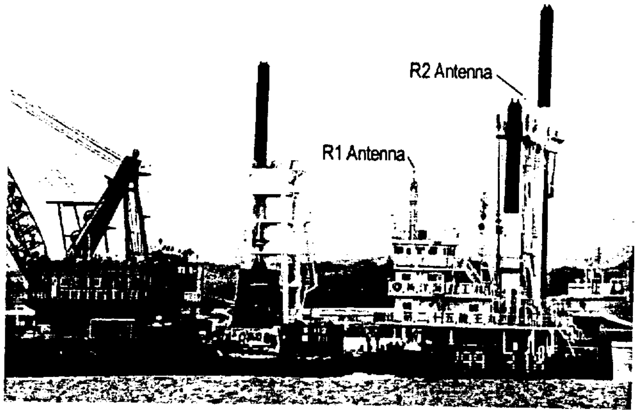


Figure 8: Dredging vessel used for testing

The base station transmitted raw data in Waypoint's propriety format and was located less than four kilometres away. Such short baselines are very typical in Japanese environments, as the allowed radio transmission power is very low at 0.01 watts. The conditions on the ship are less than ideal. Due to the large pillars (known as spuds) emanating from the dredge, there is a considerable amount of signal blockage. These pillars are used to anchor the dredge to the sea floor. Figure 8 shows the location of the R1 and R2 antennae.

Multipath is less of a concern. NovAtel data normally has a C/A code RMS, which is very indicative of multipath, of 1.0 m *or less*. For this data, M-R1 has an RMS of 1.57 m, while M-R2 is 1.44 m. As mentioned previously, satellite blockages cause the most difficulties. Figures 9 and 10 show the PDOP for the two baselines for the 7 hour data period (i.e. second day), while Figures 11 and 12 show the number of satellites for the same two baselines, respectively. There are many periods where the PDOP is over 2.0 and some periods where the PDOP is over 4.0. The RtDLL algorithms will normally not perform a search if the PDOP is over 3.0, as reliability under these conditions is suspect. Figure 13 shows the number of satellites when processing between R1 and R2. There are noticeably fewer satellites due to the blockages of different parts of the sky for R1 and R2 due to the pillars. This indicates that the external azimuth determination might not work as well for this particular data set. Such poorer geometries should not be observed in the production GPAD system since the two antennae will be very close (i.e. 1-2 m apart).

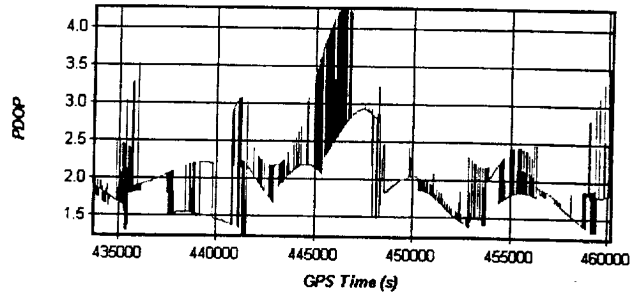


Figure 9: PDOP for M-R1 baseline

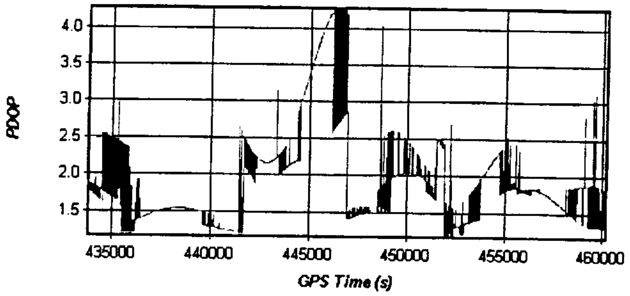


Figure 10: PDOP for M-R2 baseline

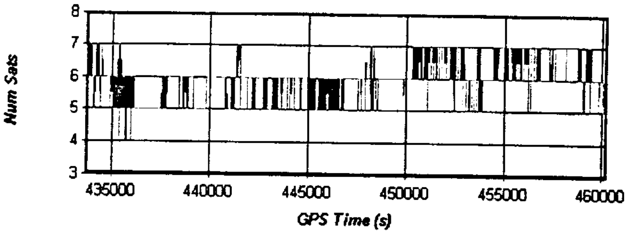


Figure 11: Number of satellites for M-R1

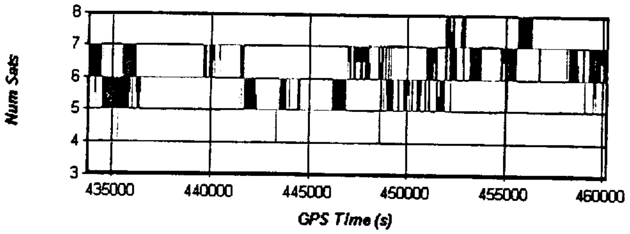


Figure 12: Number of satellites for M-R2

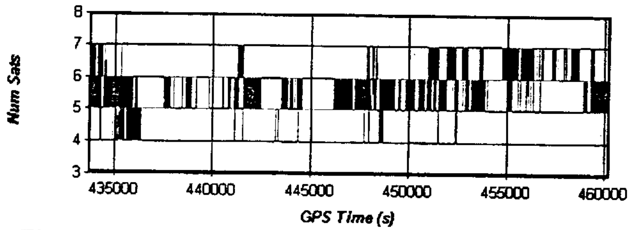


Figure 13: Number of satellites R1-R2 (i.e. AzDeterm)

In order to test the distance constraint ambiguity algorithms, RtDLL was engaged every 1000 seconds (i.e. 16 minutes). Software testing was performed after data collection, but used the same parameter set and software normally utilized in real-time. RtDLL was also engaged in real-time, but was only restarted at re-powering. This resulted in 7 tests that all passed. These results are not presented due to the very small sample size. By restarting every 1000 seconds *in post-mission*, 28 tests were extracted from the same data.

Processing used an elevation mask of 10 degrees. In addition, the distance constraint utilized an R1-R2 separation of 11.93 m with a 3 cm standard deviation. A minimum time of 5 minutes was used for each test. KAR fixes are validated using the following criteria:

a) Visual inspection of L1 RMS value. The L1 RMS rises or shows systematic trends if the OTF intersection is false.
b) The RtDLL solution (after the fix) is compared to a post-processed solution in reverse mode.
c) Inspection of RMS and reliability values. Failed intersections tend to have higher RMS values and lower reliability numbers.

The results for the 28 tests using the distance constraint are plotted in Figure 14. Each test was started without any a priori position information. Of the 28 tests, one solution resulted in a failure at 443600 (seconds of the GPS week). Both R1 and R2 were wrong by the same number of lanes causing a position error of 20-40 cm. The effect on azimuth was very negligible because the error was nearly the same on both R1 and R2. 27 out of 28 correct solutions translated into a 96.4% success rate.

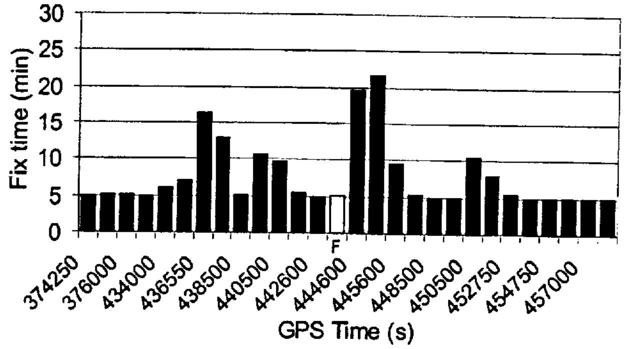


Figure 14: R1/R2 RtDLL fix times using distance constraint model (minimum time is 5 minutes)

Most of the ambiguity fixes occurred on or very close to the 5 minute mark, while 8 tests took significantly longer. The average fix time is 7.8 minutes, which is very good for single frequency GPS, especially under these harsh conditions and often poor geometry. Figure 15 shows the average number of satellites used for each of the KAR solutions. Many solutions used less than 5.5 satellites. Note that the non-integer values are due to the averaging process and the fact that satellites are dropping out because of cycle slips. The periods with fewer satellites are correlated with longer fix times. This is expected as the software using this extra data to compensate for poorer reliabilities under these conditions.

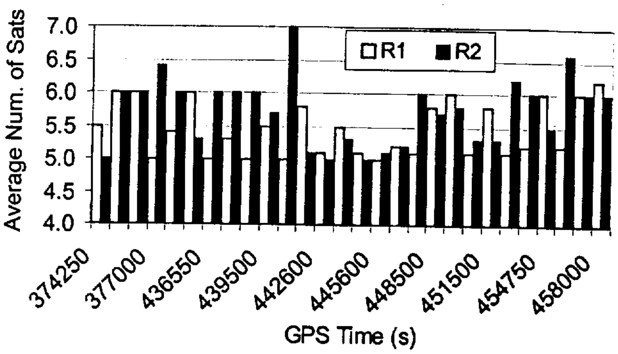


Figure 15: Average numbers of satellites for the M-R1 and M-R2 distance constraint KAR solutions

In order to gauge whether the distance constraint model is an improvement over older NAV-LAH/GPS_EMB (i.e. independent methodology), M-R1 and M-R2 were processed separately. The KAR fix times are shown in Figure 16.

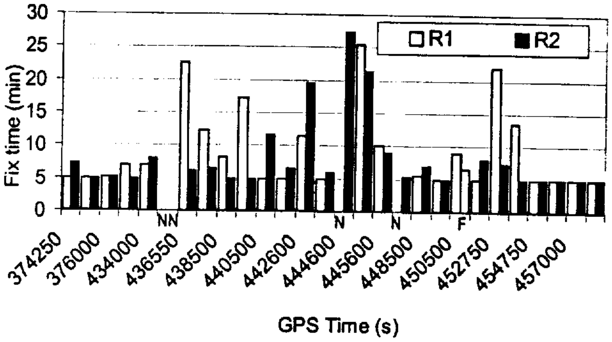


Figure 16: KAR fix times using the *older* NAV-LAH/GPS_EMB methodology

In Figure 16, it is noticeable that with the absence of the distance constraint model, KAR was not able to resolve R1 and/or R2 on a few tests. These are denoted 'N'. In some cases, such as 435000 and 447600, only 15 minutes of data was available. This is due to the fact that the system was stopped and restarted. Given a full 30 minutes, these baselines may have resolved but with longer initialization times. In terms of reliability, R1 had no failures, but R2 had one at 450500.

For the independent methodology, the combined fix time occurs when both R1 and R2 have a fix, which is the maximum of the two times. Figure 17 compares this fix time against that of the distance constraint method. The distance constraint model almost always fixed faster. It should be noted that for the distance constraint, both R1 and R2 must pass together. In contrast, the independence of the older method sometimes results in a faster fix, as there is no link between R1 and R2. Each can resolve at their prospective optimum times, which are extended times of 6 or more satellites. However, such is not the case here, and the distance constraint showed the best times, especially in periods where there were only 5 common satellites. In periods with 6 or more satellites, the initialization time improvement is much less since the independent KAR already performs well. The average initialization time for the combined independent solution (i.e. old method) is 9.26 minutes, which is about 20% longer than the distance constraint. However, 3 intersections had no solution and are not included in the average. If it is assumed that a solution would have been determined in 25 minutes, then the old method average grows to ~11 minutes, which is ~40% longer than the distance constraint.

Finally, the data between R1 and R2 is processed in azimuth determination mode using RtDLL. This used a minimum time of 2 minutes, as the azimuth determination is usually more reliable due to an absence of atmospheric errors.

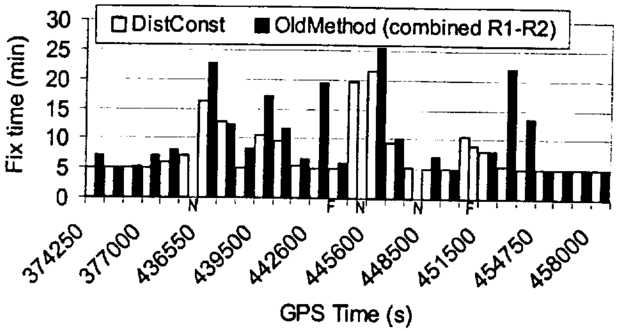


Figure 17: Comparison of fix times between old and new methods

Figure 18 shows the azimuth determination fix times. Since there were fewer satellites in common (due to blockages), the azimuth determination sometimes took longer than the distance constraint. This is not normally the case, especially if the two antennae are close together (i.e. 1-2 m). Two tests were not able to solve, but these again happened with only 15 minutes of data was available. Very poor geometry is also a factor. However, there are no false solutions. The average fix time is 7.15 minutes, but this does not take into account that two solutions did not solve.

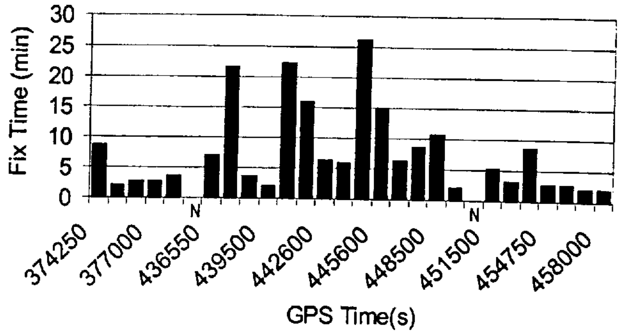


Figure 18: R1-R2 azimuth fix times

ROAD TEST (ONE METRE SEPARATION)

In order to test GPAD/RtDLL and the distance constraint model using a 1.0 metre separation, a road test was performed on October 27, 1998 in Japan. Although the base to remote distances were very short (i.e. <500 m), there were many obstructions and a considerable amount of multipath present. Figure 19 shows the C/A code plot of M-R1 baseline for the entire test period. The RMS is 2.27 m. The C/A code RMS is very indicative of multipath and peaks to over 6.0 m. This is much more severe than on the dredge data. Figure 20 shows the number of satellites for the M-R1 baseline, while M-R2 is very similar. Figure 20 shows that there are noticeably more satellites for this (car) test than for the shipborne test.

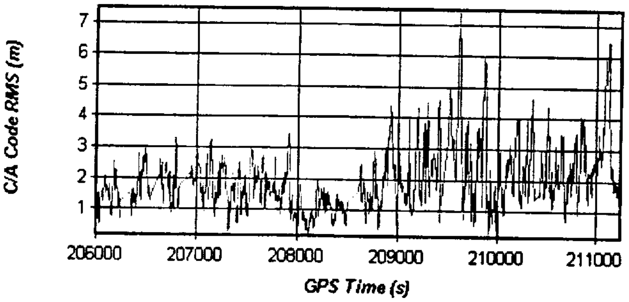


Figure 19: C/A code RMS for M-R1 baseline

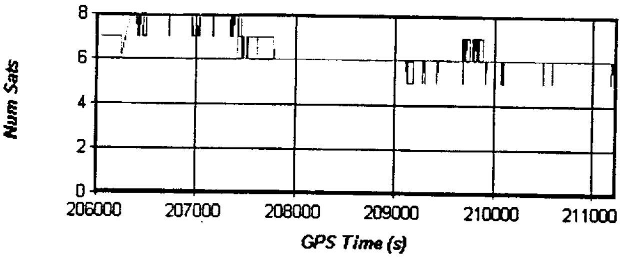


Figure 20: Number of GPS satellites for M-R1 car test

For a period of approximately 1½ hours, the system was stopped and restarted 5 times, which resulted in 6 tests.

Test periods ranged from 4 to 20 minutes and were determined by the initialization time and return statistics of RtEngine in the field. For each test, both the distance constraint and azimuth determination solutions are computed using RtDLL. Due to the short time spans of some of the test periods, which are due to a very optimistic minimum time initially, the older independent methodology is not evaluated. It often requires 10 or more minutes of continuous data. The short times spans also compelled the usage of a shorter minimum time for the distance constraint (i.e. 3 minutes). Normally, 5-8 minutes is used for reliability considerations.

The distance constraint and azimuth determination fix times are shown in Figure 21. KAR selected the correct intersection for all tests, indicating that the shorter minimum time used for the distance constraint did not affect reliability. However, the sample size is not very large at 6 tests, and other testing has shown than 5-8 minutes to be more reliable. In 5 out of six tests, the azimuth determination resolved faster than the distance constraint, which is due to more satellites in common between the two very close antennae. This can be observed in Figure 22, which shows the average number of satellites for both solutions.

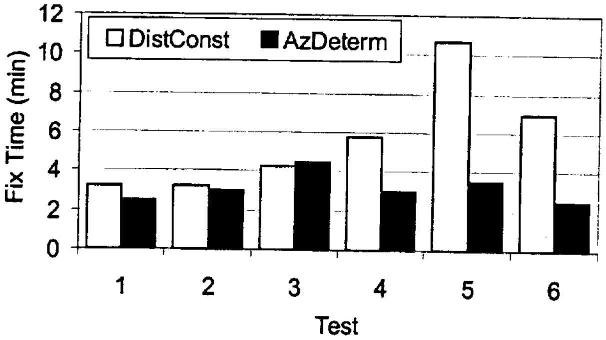


Figure 21: Initialization times for distance constraint and azimuth determination RtDLLs

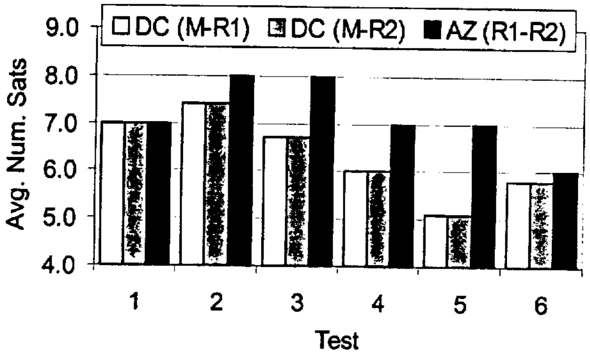


Figure 22: Average number of GPS satellites for car tests

For these tests, the average fix time is 5.7 minutes for the distance constraint and 3.1 minutes for the azimuth determination, which compares to shipborne times of 7.8 and 7.1 minutes, respectively. Initialization times were much faster here due to more satellites available, but the shorter 1.0 m baseline may also be an advantage, but this is difficult to ascertain given the different geometries between the two tests.

In order to estimate azimuth accuracies, the azimuth standard deviation is shown in Figure 23 for the entire time span. The R1-R2 azimuth processing used the default 2 cm carrier phase standard deviation used in the RtDLL Kalman filter. However, this may be somewhat pessimistic, and a 1 cm standard deviation value is more representative of the L1 phase RMS observed in the data (see Figure 24). In such a case, Figure 25 shows the estimated azimuth accuracies to be ~0.5 degrees.

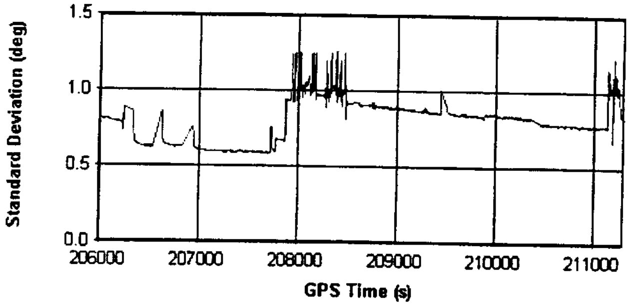


Figure 23: Estimated azimuth accuracy (2 cm carrier phase standard deviation)

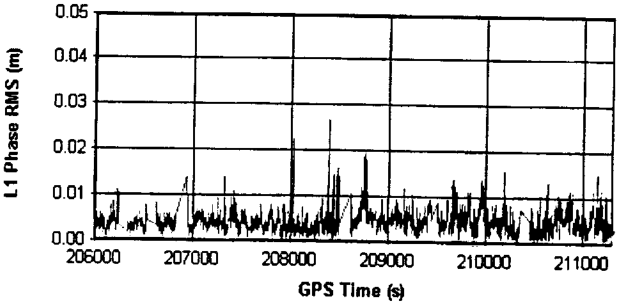


Figure 24: L1 carrier phase RMS for R1-R2 AzDeterm

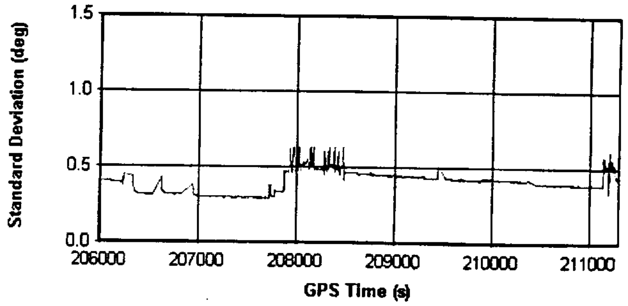


Figure 25: Estimated azimuth accuracy (1 cm carrier phase standard deviation)

CONCLUSIONS

The shipborne results show that the distance constraint model clearly improves KAR initialization times without any reduction in reliability over the existing single frequency RTK system, which treats M-R1 and M-R2 independently. In a sense, reliability is increased since the independent system is more susceptible to not obtaining a solution at all. In the testing here, the distance constraint always obtained a solution. These results show that dual antenna single frequency RTK is a very viable alternative to dual frequency. It reliably resolved 96% of the time in an average time of 7.8 minutes. This is under difficult conditions due to many satellite blockages caused by the dredge's anchoring pillars (i.e. spuds). The initialization time is most likely not as fast as dual frequency, but it is more than fast enough for this application. Moreover, a byproduct of such a system is accurate azimuth, which is not available from a single antenna dual frequency system costing more, thereby making such a system much more cost effective than a dual frequency plus gyrocompass based methodology.

The car tests employing a 1.0 m separation indicated that faster initialization times could be achieved using a shorter antenna separation. However, this is difficult to confirm given that there were more satellites in view (or unobstructed) for this test. Future shipborne testing of the 1.0-2.0 m separation is required (and planned) to obtain a better estimate of reliabilities and accuracies using such a separation.

Using a one cm L1 phase standard deviation, ~0.5° accuracies are estimated for azimuth computed from a 1.0 m antenna separation. Such accuracies are sufficient for this application. Further investigation into a 2.0 m separation is also planned since it will provide twice the accuracy. The question is if there will be degradation in fix times.

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