TEST RESULTS OF A NEW DGPS RAIM SOFTWARE PACKAGE

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BIOGRAPHIES

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Dr. van Diggelen is a GPS Design Engineer at NAVSYS Corporation. He served two years in the South African Navy, where he was Navigation Officer on his ship. Dr. van Diggelen received his PhD in control theory from Cambridge University in 1992 and has worked and published in the field of automatic control. He has organized and participated as demonstrator in control workshops for engineers in the aerospace, oil, automobile, and mining industries in England and South Africa. Dr. van Diggelen currently conducts research in the areas of real-time kinematic processing and integrity monitoring in GPS.

ALISON BROWN

Dr. Brown is the President of NAVSYS Corporation, which specializes in developing GPS technology. She has fifteen years experience in GPS receiver design and has seven GPS related patents. She has published numerous technical papers on GPS application and is on the editorial board for GPS World and GIS World magazines. Dr. Brown currently conducts research in various areas of GPS, including advanced GPS receiver design, high accuracy GPS, differential GPS techniques, GPS integrity monitoring, and low cost GPS sensors. Dr. Brown completed her graduate studies at MIT and UCLA. In 1987 she served as chairman for the RTCA SC-159 GPS Integrity working group. In 1987 and 1988 she was Technical and General Chairman, respectively, for the Institute of Navigation Satellite Division National Technical Meeting.

JOSEPH SPALDING

Mr. Spalding is an Electronics Engineer at the US Coast Guard Research and Development Center. He has been working in GPS and DGPS for eight years. He currently serves as Advanced GPS Research project manager. Current research includes DGPS integrity monitors, RAIM for DGPS users, GPS azimuth determination, and development of standards for maritime use of GPS and DGPS. He has an MS in computer science from the University of New Haven and a BE in Electrical Engineering from the State University of New York Maritime College. Mr. Spalding is a licensed Third Mate of Oceans, Steam, or Motor Vessels of any Gross Tons.

ABSTRACT

The problem addressed in this paper is navigation integrity using differential GPS (DGPS). A new Receiver Autonomous Integrity Monitoring (RAIM) software package, called "NavSafe," is presented. The specific requirement met by NavSafe is the provision of integrity guarantees for buoy positioning by the US Coast Guard (USCG). This task requires a navigation accuracy of 10 m (R95). NavSafe provides alarms whenever the required integrity is not achieved.

Test results show that differential GPS can provide the accuracy required by the USCG for marine navigation tasks such as buoy laying. However, navigation outages do occur, even during zero-baseline laboratory tests. The new RAIM software reliably computes the variance of the pseudo-range errors and detects biases when they occur, thus guaranteeing a predetermined level of navigation accuracy for DGPS.

The new RAIM software algorithm reduces integrity monitoring to a simple alarm structure. There are three alarm states, red, yellow, and green, analogous to a traffic light. A green alarm state guarantees that the required navigation accuracy has been met. A yellow alarm indicates a possible navigation outage but with a high probability of false alarm. A red alarm confirms that the required navigation accuracy has not been met.

The algorithm adapts to current satellite geometry and provides a measure of the noise on the corrected pseudo-range measurements. The user specifies the required navigation accuracy by setting the maximum Radial Position Error (RPE), the maximum Probability of Missed Detection (PMD), and the maximum Probability of False Alarm (PFA). A user-friendly graphical interface displays relevant navigation and satellite data, the alarm state, any biases on the pseudo-range measurements, the effect of the bias on the navigation solution, and the statistical distribution of the navigation solution. The user selected set-points (maximum RPE, etc.) may be changed on-line using hot keys.

A function has been derived which links the false alarm rate to the satellite geometry. This *integrity geometry* measures the change in HDOP after a biased channel has been removed from the navigation solution. It will be shown that integrity geometry is as important to integrity monitoring as HDOP is to navigation. The integrity geometry allows users to determine in advance what level of integrity monitoring performance they can expect in a particular area at a particular time.

INTRODUCTION

Government-provided DGPS service is currently planned for all coastal waters of the US to provide harbor harbor approach navigation. Positioning aids-to-navigation (AToN) was a major impetus to the DGPS implementation. The US Coast Guard currently maintains tens of thousands of navigational buoys using several methods of positioning. Through two years of field experience, DGPS has consistently proven to be the most reliable and accurate method of placing a buoy at its assigned latitude and longitude.

Over the past two decades, the Coast Guard has significantly improved its method of positioning buoys with horizontal sextant angles. This method has been refined to yield accurate positioning and create enough information to properly defend the Coast Guard from potential legal actions regarding AToN not being on their proper station. Extra observables are used to create an over-determined solution, and all the measurements are recorded so that the solution can be calculated at any point in the future.

DGPS has presented technical challenges to meet the legal requirements surrounding AToN. The current widespread use of 6-channel DGPS receivers in USCG AToN has enhanced positioning reliability, but does not provide the reporting and analytical features to resolve legal issues. To satisfy this requirement, the USCG R&D Center funded and directed the development of NavSafe, a RAIM system for DGPS. NavSafe measures the integrity of the DGPS position solution and indicates the quality of the solution, and can also record enough data to return the integrity equations for fault detection at a later date.

The specific challenge to be met by the NavSafe RAIM software was to provide integrity guarantees for the task of buoy positioning by the US Coast Guard. This task requires a navigation accuracy of 10 m (R95).

The NavSafe integrity software uses a Fault Detection and Isolation (FDI) algorithm that continually checks for biases on the GPS receiver's pseudo-range measurements and sets alarms whenever the required integrity is not achieved.

Development of this integrity software has discovered an essential relationship between pseudo-range residuals, integrity monitoring and navigation errors. It can be demonstrated that if a bias is present on one of the channels, then the navigation error estimate calculated by the FDI algorithm is precisely the difference between the biased navigation solution and the solution that would have been obtained if the biased channel had been excluded. This fact allows the FDI algorithm to be used not only for integrity monitoring (by detecting an error in the first place), but also for error correction (by removing the navigation error caused by a bias).

The association between pseudo-range residuals and integrity monitoring has also been used to derive an *integrity geometry* function which describes the relationship between the false alarm rate and the satellite geometry.

Tests show that DGPS can provide the accuracy required by the USCG for buoy laying and other marine navigation tasks. However, navigation errors do occur, even during zero-baseline laboratory tests. The NavSafe RAIM software reliably computes the variance of the pseudo-range errors and detects biases when they occur, thus guaranteeing a predetermined level of navigation accuracy for DGPS.

Test results from the field trials using the USCG DGPS network are described here. Final testing will include sea trials performed in conjunction with the USCG R&D Center at Groton, CT.

THE NAVSAFE RAIM ALGORITHM, AN OVERVIEW

The NavSafe RAIM algorithm uses pseudo-range residuals as its inputs. This makes the algorithm generic so it can be used with any GPS receiver that outputs the residuals (for example, using the $GPGRS NMEA message). The algorithm continually looks for biases on the pseudo-range measurements. Using the pseudo-range residuals, the algorithm calculates the most likely bias. This is standard in Fault Detection and Isolation [3, 4, 5, 7] and the US Coast Guard has proposed a new NMEA message, $GPGBS, which will be used for reporting the most likely bias. All RAIM calculations are a function of the noise on the measurements. The NavSafe RAIM algorithm uses a technique to compute the variance of the noise from the residuals. Tests done on NavSafe show that this variance calculation is accurate to within 5% of variance measurements calculated independently using the known receiver position.

Having computed the most likely bias, the algorithm uses a new and proprietary technique to compute the relative probabilities of any other biases on other channels. This allows the algorithm to consider all possible biases, not just the most likely, although when a significant bias is present the set of possibilities rapidly reduces to the single true bias.

The algorithm computes the worst case radial position error (RPE) that could result from any of the set of possible biases. The RPE is a function of the bias and of the noise on all the measurements. The standard mathematical model for the distribution of the RPE is the non-central chi-squared probability distribution function (PDF) [1, 2, 5, 6]. NavSafe uses a novel approach to solve the non-central chi-squared probability function in real-time. This allows the algorithm to calculate the expected error to any required accuracy (in the case tested here the accuracy is 10 m, R95).

The NavSafe package produces three alarm states, green, yellow, and red, to report on the current accuracy of the measurements. If the expected error is within the accuracy requirement, then a green light is shown and the user is assured that the required accuracy has been achieved. All the relevant data can be logged so that the calculations can be reproduced to verify the accuracy and satisfy the legal requirements surrounding aids-to-navigation. If the expected error is outside the accuracy requirement, then the NavSafe algorithm computes the probability of false alarm. If this is low, then a red alarm is raised, indicating a probable error. Otherwise, a yellow alarm is raised, warning the user that the test cannot be performed reliably.

The probability of false alarm can be shown to be a function of the change in HDOP that occurs after the suspected biased satellite has been removed from the computation. This change in HDOP is called the *integrity geometry* and is as important to RAIM as ordinary HDOP is to navigation. If the integrity geometry is bad (large), then even a small suspected bias will lead to a large distribution of possible error, and the algorithm must raise an alarm. So one can see that bad integrity geometry will lead to a high alarm rate. The worst case integrity geometry is, of course, predictable by using the almanac data to compute future positions of satellites. The NavSafe package provides a look-ahead feature that produces an on-screen plot of the expected alarm rate for any time period. Using this feature, users can plan critical navigation tasks to coincide with periods of good integrity geometry.

TEST RESULTS

The NavSafe RAIM package was tested at the USCG R&D facility at Groton, CT, during March 1993. Differential corrections were generated by a Coast Guard reference station, GPSREF, and biases were added by deliberately corrupting the corrections before they reached the remote receiver. The package was tested under static and dynamic conditions for five days. We report here on two typical tests, one static, one dynamic.

STATIC TEST

A test was done using the configuration of to see how well NavSafe detects a growing bias. A bias ramp of 0.2 m/s was applied to SV 19. The plot in shows the resulting RPE and the alarms that were activated in NavSafe.

Note that during this test, the number of visible satellites changed from 7 to 6 after 220 seconds, then back to 7 after 330 seconds. This is apparent in the RPE, which jumped up at 220 seconds, then down at 330 seconds. The only yellow alarms occurred for a short time when there were 6 satellites visible and the bias was not yet very large. This is an example of the increased probability of false alarm with large integrity geometry. (Like HDOP, integrity geometry always gets worse as a satellite is lost.)

NavSafe raised an alarm after 166 seconds, when RPE was 9.3 m. RPE crossed the 10 m limit after 171 seconds. There were no missed detections. The noise on the pseudo-range measurements was 1.5 m during this test.

DYNAMIC TEST

Dynamic tests were performed using the configuration shown . Two Novatel receivers were placed in a van and driven up and down a road while collecting data. A ramping bias was placed on SV 3. One of the Novatel receivers (the "test" receiver) received this biased pseudo-range and calculated erroneous positions. The other Novatel receiver (the "control" receiver) was set up to ignore SV 3, and so calculated unbiased positions.

The positions calculated by the control receiver were used as the true position. The computed positions of both receivers are shown in . One can see in the track of the control receiver how the vehicle was driven up and down the same road. The position computed by the test receiver was practically the same as the control receiver initially, then, as the bias on SV 3 was applied, the position calculated by the test receiver got increasingly worse.

The radial position error was calculated by subtracting the test receiver position from the control receiver position. This radial position error and the real-time NavSafe estimate of the radial position error are shown in . The effect of the ramping bias is obvious. Note that the bias was switched off after 1050 seconds. The error steps down, as does the error estimate.

It is clear from that NavSafe estimates the error very well. To see whether the correct alarms were set, we plot RPE and the alarms in . RPE is shown every tenth second, for clarity. A circle indicates that a green alarm was set at that time, a cross indicates that a red alarm was set at that time. The false alarm rate was 3.5% and there were no missed detections.

TESTS USING OPERATIONAL BEACONS

The system was tested using differential corrections from operational USCG differential stations, with no deliberate biases. The results of these tests are shown in and . The tables show the percentage of missed detections (MD), false alarms (FA), green (G), yellow (Y), and red (R) alarms, and the number of samples.

The results from the beacon at Montauk Point were just as good as those obtained in zero-baseline tests. The results for the more distant beacon at Cape Henlopen, however, were poor.

The differential corrections from Cape Henlopen were only received once or twice a minute. The problem with this long baseline appears to be the weakness of the signal from the beacon. The results indicate that at a distance of 236 miles, the corrections from the radio beacons provide an accuracy of 10 m for less than 50% of the time, and NavSafe can only give a Green light for 6% of the time. It is reassuring to note, however, that the Missed Detection rate remained small, even under these conditions.

CONCLUSION

The test results showed that the NavSafe RAIM package accurately computes the variance of the noise on the pseudo-range measurements, and reliably detects biases whenever they occur. The calculation of the expected error is achieved in real-time so that alarms occur as soon as the actual error approaches the limits set by the user. The system performance with operational differential reference stations was found to be good at distances of 23 miles, showing similar results to those achieved in zero-baseline tests.

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