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Performance of Multi-Beacon DGPS

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Performance of Multi-Beacon DGPS

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BIOGRAPHY

Simon P. Barr is pursuing an M.S. degree in Electrical Engineering at the University of Rhode Island (URI) and is an active-duty Lieutenant in the U.S. Coast Guard (USCG). He received his B.S.E.E. degree from the U.S. Coast Guard Academy (USCGA) in New London, CT, graduating in 2006. He then spent two years as a Student Engineer on the U.S. Coast Guard Cutter MIDGETT in Seattle, WA, and three years at Naval Engineering Support Unit New Orleans, LA. His research interests include signal processing and control systems.

Peter F. Swaszek is a Professor in the Department of Electrical, Computer, and Biomedical Engineering at URI. His research interests are in statistical signal processing with a focus on digital communications and electronic navigation systems. He spent the 2007-08 academic year on sabbatical at USCGA working on a variety of RF navigation systems.

Richard J. Hartnett is a Professor in Electrical and Computer Engineering at USCGA, having retired from the USCG as a Captain in the summer of 2009. He received his B.S.E.E. degree from USCGA, the M.S.E.E. degree from Purdue University, and his Ph.D. in E.E. from URI. His research interests include efficient digital filtering methods, improved receiver signal processing techniques for electronic navigation systems, and autonomous ground vehicle design.

Gregory W. Johnson served on active duty in the USCG from 1983 to 2002 including tours managing Advanced Communications at the USCG Research and Development Center (RDC) and teaching Electrical Engineering at USCGA. He continues to serve as a Captain in the USCG Reserve. Since 2002 he has managed the Alion Science & Technology, New London Office, primarily supporting RDT&E efforts for the USCG RDC, USCGA, and C3CEN. Dr. Johnson has over 20 years of experience in electrical engineering and project management. He has published over 75 technical papers. He is a member of the IEEE, ION, ILA, and a Life Member of AFCEA.

ABSTRACT

Historically, maritime organizations seeking accurate shipboard positioning have relied upon some form of differential GNSS, such as DGPS, WAAS, or EGNOS, to improve the accuracy and integrity of the GPS. Ground-based augmentation systems, such as DGPS, broadcast corrections to the GPS signal from geographically distributed terrestrial stations, often called beacons. Specifically, pseudorange corrections for the GPS L1 C/A signal are computed at each reference site, then broadcast in the nearby geographic area using a medium frequency (approximately 300 kHz) communications link. The user then adds these corrections onto their measured pseudoranges before implementing a position solution algorithm. Within the United States, the U.S. Coast Guard operates 86 DGPS reference beacons. Similar DGPS systems are operated in Europe and elsewhere around the globe.

While current DGPS receiver algorithms typically use one set of pseudorange corrections from one DGPS reference site (often the one with the “strongest” signal), many user locations can successfully receive two or more different DGPS broadcasts. This brings to mind obvious questions: “If available, how does one select the corrections to use from multiple sets of corrections?” and “Is it advantageous to combine corrections in some way?” We note that a number of factors might influence the effectiveness of any particular station’s corrections. Some of these refer to the effectiveness of the communications link itself, including concerns about interference from other beacons (skywave interference from far-away beacons on similar frequencies, a notable problem in Europe) and self-interference (skywave fading). Other factors refer to the accuracies of pseudorange corrections. For example, ionospheric storm-enhanced plasma density (SED) events can cause the corrections to have large spatial variation, making them poor choices even for users close to a beacon.

Earlier work in the area of DGPS beacon selection has identified several options including choosing the beacon closest to the user or the beacon with the least skywave interference. There have also been suggestions on how to combine corrections when multiple beacons are available.

The most common of these is a weighted sum of the corrections, where the weights are typically inversely proportional to the distance from the user to the individual beacon.

This paper reexamines the concept of multi-beacon DGPS by evaluating methods of combining beacon corrections based on spatial relativity. Of relevance to this topic is our recent observation that DGPS accuracy performance is biased. The mean of the error scatter with DGPS corrections does not fall on the actual receiver position. We established this both by processing GPS L1 C/A observables from hundreds of CORS (Continuously Operating References Station) sites around the U.S.A. and via simulation using a Spirent GSS8000 GPS simulator. Specifically, we found that the position solution computed using DGPS beacon corrections is typically biased in a direction away from the beacon, and that the size of the bias depends upon the distance from the beacon. This bias grows with a slope of approximately one-third of a meter per 100 km of user-to-beacon distance.

This paper compares the performance of several multi-beacon algorithms assessed using GPS simulator data. These algorithms include the nearest beacon, a weighted sum based on distances, and a spatial linearly-interpolated correction using the actual locations of the transmitters (distance and angle).

We note that as part of this research effort we developed a DGPS receiver using software-defined radio (USRP). A complete description of this system is included in the paper.

INTRODUCTION

The U.S. Coast Guard is a user, developer, and supplier of a variety of maritime radio-navigation systems, including Differential Global Positioning System (DGPS). In brief, DGPS provides correction information to the user so as to improve the accuracy of GPS measurements. Pseudorange corrections for the GPS L1 coarse acquisition (C/A) signals are computed for each satellite at a reference site, and then broadcast in the nearby geographic area using each beacon's assigned radio frequency (between 285 kHz and 325 kHz, with 500 Hz width) using minimum-shift keying (MSK) modulation at 100 or 200 bps. Messages are encoded using the RTCM SC-104 standard [1] [2]. Figure 1 is a diagram of typical DGPS operation. For user safety, these DGPS corrections must be both reliably transmitted and accurate. In recent years, expansion to a greater number of beacons in the Nationwide DGPS (NDGPS) network has increased DGPS coverage, with the intent of reaching a stated goal of 99% coverage of the continental United States. Now, in most areas of the United States and its surrounding maritime waterways, at least two overlapping beacons are "visible" to littoral DGPS users—in many areas, three or more beacons are visible (see Figure 2). In typical implementations, DGPS receivers apply the corrections from the "strongest" beacon—the beacon with the highest signal-to-noise ratio (SNR) received at the user's location. The availability of additional information from multiple beacons raises the possibility of combining (also termed "networking" in this paper) the corrections to increase both system robustness and the accuracy of the resulting position solutions. This paper proposes and evaluates various methods for networking DGPS corrections with comparison against the current method.

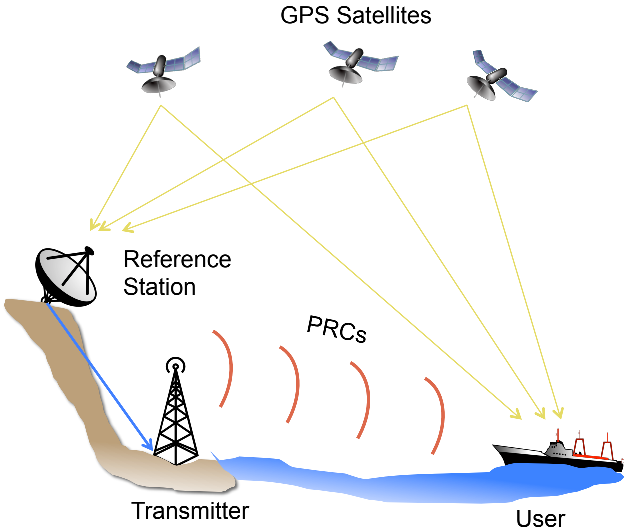


Figure 1. Typical DGPS implementation. The reference station receives and calculates pseudoranges to visible GPS satellites, then determines the error in each satellite's pseudorange by comparison to the reference site's surveyed position. The error corrections (pseudorange corrections, or PRCs) are then broadcast from the transmitter between 285-324 kHz to the user, who adds the PRCs to his own calculated pseudoranges.

The DGPS radio-navigation system maintained by the U.S. Coast Guard is critical to the U.S economy and national security, assuring reliable and accurate positioning capability. Eighty-six DGPS stations throughout the country broadcast signals containing correction information about GPS satellites [3]. Broadcast of a parallel Coast Guard electronic navigation signal, LORAN-C, was terminated in 2010, leaving the North American continent with only GPS-based navigation systems. Because a loss of the positioning accuracy provided by DGPS is hazardous to navigation, ensuring robustness and accuracy of the DGPS signal is important to both the Coast Guard and the user base.

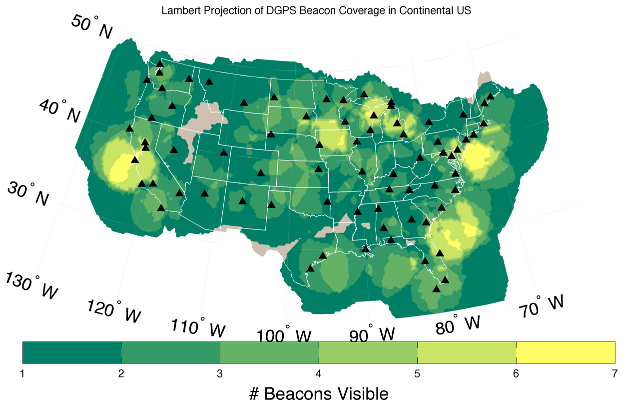


Figure 2. Coverage map of the continental U.S.A. displaying number of DGPS beacons available (assuming signal strength greater than 37.5 dB/µV). Note the typical presence of three or more beacons along the three coasts, Mississippi River, and Great Lakes areas.

Networking DGPS broadcasts has the potential to improve both position accuracy and system robustness over the current DGPS solution method. Previous work indicates that positions corrected with a DGPS beacon display a bias away from the beacon used, which increases in magnitude and variation as the user travels farther from the beacon [4]. This research shows that a user's mean position and 95% scatter radius (relative to the mean position) are nearly linearly proportional to the user's distance from the beacon, representative of spatial decorrelation for typical DGPS-corrected GPS positions [4]. Figures 3a-b show the bias and scatter radius decorrelation. Currently, a modern DGPS receiver collects and adds the pseudorange corrections from a single beacon to its calculated GPS satellite pseudoranges. Typically, the beacon with the highest signal-to-noise ratio is selected as the beacon to use, which may or may not be the beacon closest to the user [5]. Some DGPS receivers offer the user options as to the beacon selection algorithm, with typical choices including "highest SNR", "closest beacon", and "manual selection". Typical SNR is calculated from the ratio of beacon signal strength, in dB, to atmospheric noise level.

While single-beacon solutions currently meet U.S. Coast Guard positioning specifications (10 meters 2DRMS everywhere, and 3 meters 2DRMS in critical waterways [1]), why not take advantage of all the available correction information? Knowing there is an inherent bias in the user's position because all users employ a single-beacon correction method necessitates evaluation of a better positioning algorithm [4] [6] [7]. Ionospheric SED events have been shown to cause disruptions to wide areas of DGPS service [8] [9], again raising the question: if it's possible that the user's primary beacon is compromised, why not use the information from a wider area of beacon coverage? Because a user's receiver can potentially collect information from two or more DGPS beacons, it is very likely that the use of information from multiple beacons can improve the DGPS user's position accuracy. A user becomes more confident that their navigation system is operating properly if they know that the receiver is applying correction information from more than just one beacon, potentially mitigating sources of error (such as thermal noise, SED effects, and latency error) while simultaneously increasing position accuracy.

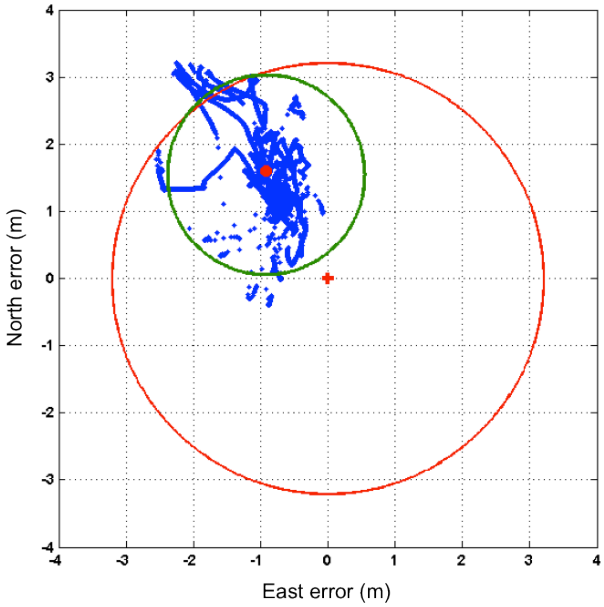


Figure 3a. Typical DGPS-corrected GNSS simulator position plot for a user, showing a characteristic bias of a user's static position solutions away from the beacon in use. Courtesy of [6].

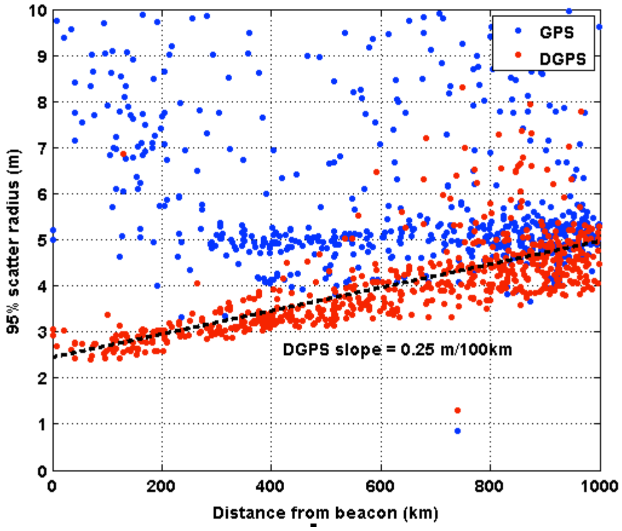


Figure 3b. Comparison of DGPS and GPS position scatter radii vs. distance from Saginaw Bay DGPS station (applied to CORS data), courtesy of [6], showing spatial decorrelation in the form of an increase in 95% scatter radius as the user's distance to the beacon increases.

DISCUSSION OF RELATED WORK

Certain aspects of networked DGPS have been previously examined by a number of authors: discussion of enhanced beacon availability in Europe; existing and novel methods of beacon selection; sources of beacon errors; and proposing some methods of networking DGPS. Below is a brief discussion of those research efforts pertinent to the topic of networking multi-beacon DGPS.

Grant considers various methods for choosing amongst multiple Differential Global Navigation Satellite System (DGNSS) beacons [5]. He considers two obvious methods: choose the "nearest beacon" by distance to user or the "strongest beacon" measured by SNR using atmospheric noise only. He also proposes including two other noise sources in the "strongest beacon" category: "self-to-skywave" and "signals-from-other-beacons". In addition to existing integrity measures, Grant proposes adding time-to-alarm, recognizing that weak stations have latency in data between time-of-arrival, subsequent calculation of DGPS corrections, and broadcast time to user. Grant's work introduces new sources of error and emphasizes the strategy for selecting appropriate beacons to maximize algorithm productivity.

Last, William, and Ward's research into Europe's differential GNSS examined the value of DGNSS PRC interpolation and whether this would cause problems for the user [10]. The clock bias question arises from the difference between user and GPS satellite time, which is usually resolved by calculating this difference during locking to the frequency and phase difference. With DGNSS, there is another latency introduced by the time-to-calculation of the reference station, which is typically not of concern since all the latencies introduced are the same for a single station. The authors assessed the quantity of multi-beacon coverage areas in the U.K., where three beacons was common and seven beacons was the maximum—interestingly, the maximum in the North Sea was 23! Testing consisted of using four DGNSS receivers to record transmissions and an Ashtech receiver locally-placed for actual values, which were recorded for 24 hours. They discovered that the effect of merging different clock biases was minimized due to the averaging and weighting process when combining the PRCs, and therefore was negligible. The combination method weighted the inverse of the user-beacon ranges, resulting in an improvement in correlation between calculated PRC and actual PRC (termed Regional Area Augmentation System, RAAS). Also compared were the solutions computed using single-beacon (23 km away) and RAAS (219, 358, and 419 km away) methods. They found that the single-beacon position solutions were better, but only slightly, suggesting that RAAS solutions might be useful. Their work also suggests that further work should explore a combination of two beacons, and that a RAAS could extend the boundaries of the current DGNSS system.

METHODS OF NETWORKING DGPS

Methods of networking DGPS, both previously-proposed and novel, were considered for inclusion into this research. The main criterion for evaluation in this research was the ready availability of information to a typical user: namely, could a considered algorithm be easily employed on existing equipment? Candidate algorithms should be mathematically simple to perform and dependent only on the data broadcast through the existing DGPS. These two requirements ensure that the algorithm is capable of deployment on low-cost hardware and requires no further changes to infrastructure for the user and no changes for the DGPS provider. In the case of this research, only DGPS within the United States is considered. While Mueller's minimum-variance algorithm showed promising performance, it was excluded from this research because station-specific beacon characterization data are not available [11].

Two categories of combining DGPS beacon PRCs were considered: (1) to weight the PRCs using various criteria and (2) to recalculate the PRC based on a beacon grouping's spatial orientation to the user. The first category includes three algorithms, each using different criteria to weight each available satellite's PRC, where the PRC is weighted as such:

$$\mathrm{PRC}_s = \sum_{b=1}^{B} a_b \mathrm{PRC}_{b,s}$$

where s denotes the target satellite, a_b is the weight a applied to beacon b, and B is the total number of beacons available.

The first DGPS networking algorithm considered is an average of the available beacons. In particular, the pseudorange corrections are weighted equally and a single PRC is applied to the satellite at that time. This weighting is described as:

$$a_b = \frac{1}{B}$$

where B, again, is the available number of beacons. This algorithm is proposed with the assumption that a region of tightly-spaced beacons will broadcast relatively similar pseudorange corrections and this method might serve as a good way to remove small perturbations between the beacons' PRCs.

The second DGPS networking algorithm considered is based on weighting the PRCs by the inverse of the range from the user to the beacon. This method of combining multiple beacons was first proposed by Last, et al. in [10], with the intent to minimize the effect of beacons distant from the user's position. The user's position may, in this case, be established a priori via a rough GPS fix, since the distances in question are typically expressed in kilometers, such that the error in a rough GPS fix is negligible in comparison. The weights for the inverse-range method are calculated as:

$$a_b = \frac{1}{r_b}\left(\sum_{k=1}^{B}\frac{1}{r_k}\right)^{-1}$$

where r_b is the range from the user to beacon b, and the second term normalizes the weights.

The third DGPS networking algorithm considered is based on weighting the PRCs by the inverse of the range-squared from the user to the beacon. This method is newly proposed to further reduce the effects of long-distance beacons on the user's position. Particularly, since it is known that a user in close proximity to a beacon (less than about 50 km) will have a small bias length and scatter radius when applying a single DGPS beacon's corrections, therefore, that particular beacon's weight should dominate within the range-based algorithm. As with the inverse-range method, the user's position is established a priori with a GPS fix. The weights for the inverse-range-squared algorithm are calculated as:

$$a_b = \frac{1}{r_b^2}\left(\sum_{k=1}^{B}\frac{1}{r_k^2}\right)^{-1}$$

where the variables are represented in the same manner as the inverse-range method.

The fourth and final DGPS networking algorithm considered is based on fitting a hyperplane to the known locations and distances of the beacons relative to the user's location. In effect, this method describes linear interpolation between three points and the user's general location (however, for the sake of brevity, this algorithm will be referred to as the hyperplane method). This method is proposed because it takes into account the spatial geometry and orientation of the beacon grouping (i.e.: ranges and azimuths to the beacons) relative to the user, which, as described previously, are a factor in DGPS-user position bias. Because the precise locations of all the U.S. DGPS beacons are known, this information may be stored so the user may apply received PRCs to a grid representing the local area. The beacons' positions are transferred onto the grid as the *x, y* coordinates and the PRCs assume the *z* values. The three points that are created form the basis of a hyperplane, which is evaluated at the user's assumed location (which, again, may be provided through a rough GPS fix). If only two beacons are available, a linear interpolation of those sites relative to the user is calculated. The hyperplane method is described by:

$$\mathrm{PRC}_s = ax + by + c\Big|_{\mathbf{p}_\mathrm{r}}$$
$$\mathbf{p}_b = [D_\mathrm{N}, D_\mathrm{E}, \mathrm{PRC}_{b,s}]$$

where *x* and *y* denote the grid coordinates (akin to latitude and longitude), *a, b,* and *c* denote the equation of the plane through the three beacon-PRC points ($\mathbf{p}_b$), $\mathbf{p}_\mathrm{r}$ is the position vector of the rover (the user), and D_N and D_E are the great circle distances North and East of the rover (in kilometers).

APPLICABLE SOFTWARE

Simulator testing was performed on a Spirent GSS8000 GNSS simulator, governed by the SimGEN software package. Data were logged in SimGEN and post-processed in the MATLAB environment, using L3NAV Systems' GPS toolbox.

SIMULATOR TESTING OVERVIEW

Testing the effectiveness of the various networked DGPS algorithms was performed on a Spirent GSS8000 simulator. This GNSS simulator provided a reliable and verbose output log of the settings and states of the variables-of-interest, such as distinct satellite ranges, pseudoranges, ionospheric and tropospheric offsets. Because southeastern New England contains good multi-beacon coverage (sufficient quantity and spatial variety of DGPS beacons), a balanced mix of land and water that forms the entrance to New York harbor, this area was chosen for the testing region. The software was configured so as to best allow comparison of the networking algorithms against each other, and not necessarily how closely the simulator approximates real-world conditions. In this vein, the simulator was set to produce ionospheric and tropospheric delays. Ionospheric effects were generated using the Klobuchar model; tropospheric effects were generated using the NATO STANAG 4294-1 model. Error modeling with thermal and spurious noise sources is outside the scope of this paper and is part of future work. Receiver-GPS clock bias was turned off, and the rover maintained a static position for the duration of each test. All simulations used the World Geodetic System 1984 geodetic reference ellipsoid (WGS84) and user reference positions of 0 meters altitude for the sake of simplicity.

First, the simulator was used to produce a representation of the atmospheric offsets at a single time, across the New England region. The New England area tested was a grid originating with its Southwest point at 40° N, 74.5° W (approximately Joint Base McGuire-Dix-Lakehurst, located in Northeast New Jersey) and advancing approximately 400 km to the North and East. The area chosen encompassed the DGPS beacons of interest, with the intent of determining the appearance and behavior of the atmospheric corrections over a geographic area. Data points were collected every 10 km North and East from the origin for the same time. This representation allows us to provide a baseline for comparing the suitability of each networking algorithm. Figure 4 shows the grid and contours of the simulation for a single satellite; of particular note is the near-planar behavior over the region of interest.

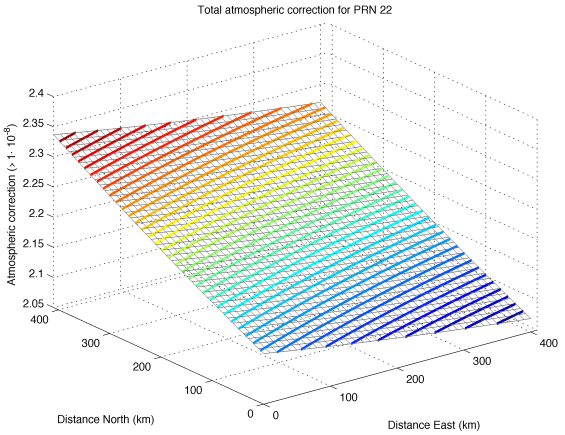


Figure 4. Total atmospheric correction (iono + tropo) observed across 400 km × 400 km area over New England during GNSS simulation. This is referenced in this paper as the "actual PRC" plot.

The second simulator test plotted the position solutions calculated by the networking algorithms over a 24-hour period and specific DGPS beacon groups. Two beacon groups were selected to be "visible" to the rover/user, on the basis of their spatial geometries. Group 1 was intended to represent the region's actual atmospheric effects most accurately, and was comprised of a widely-spaced beacon group including Acushnet, MA, Hudson Falls, NY, and Moriches, NY. The Group 1 beacon geometry could be considered as "optimal" to a user because it is well-spaced geographically. Group 2 was intended to be a "realistic" set of beacons that might be typically visible to a marine user, comprised of a nearly-linear beacon group including Acushnet, MA, Moriches, NY, and Sandy Hook, NJ. Rover positions were labeled "A" through "F", and were chosen to place the rover and beacons in unique and interesting configurations, such as: "optimal"—rover in the center of the beacon triangle, "rover between two beacons", and "rover outside the beacon triangle". Figure 5 indicates the beacon positions, beacon group outlines, and rover static positions used during testing.

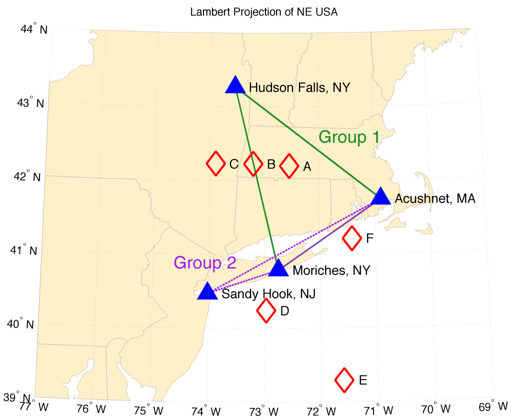


Figure 5. Map of simulator testing locations (red diamonds) and DGPS beacons (blue triangles), with beacon groups labeled.

In order to understand the behavior of each networking algorithm, visualizations were generated using the Group 1 beacon set and the same geographic region and similar time window represented in Figure 4. Figures 6a through 6d show the beacon grouping and associated PRCs overlaid on the PRC solution for each networking algorithm. Figure 6e shows the hyperplane algorithm's behavior overlaid on the "actual PRC" plot from Figure 4 (in gray mesh), as well as rover position D, demonstrating how the hyperplane is extended to the user's position. The slight vertical offset between the "actual PRC" grid and the hyperplane is due to a 100 ms time difference.

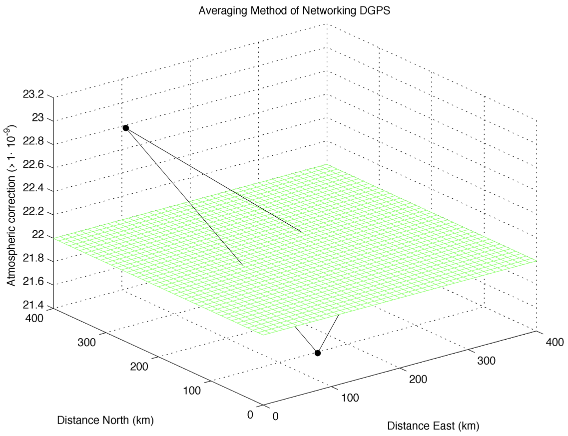


Figure 6a.

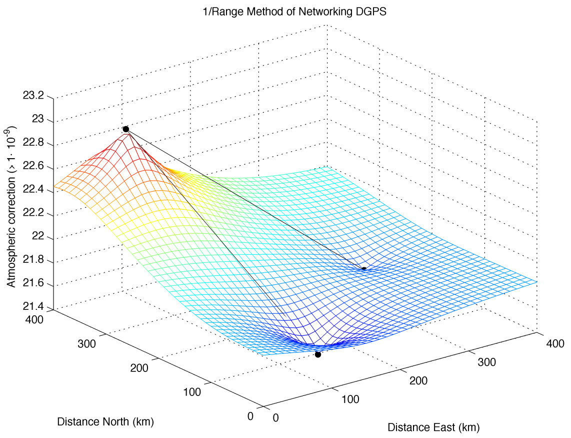


Figure 6b.

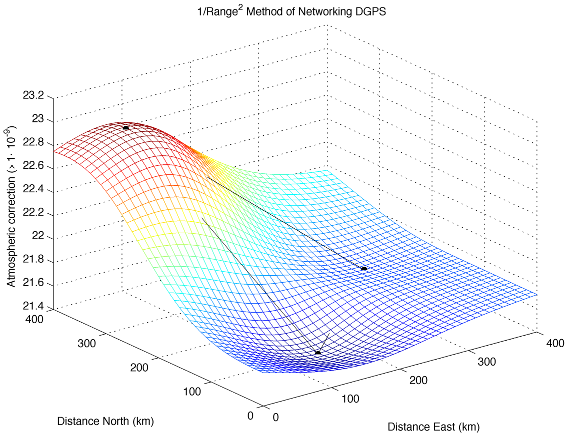


Figure 6c.

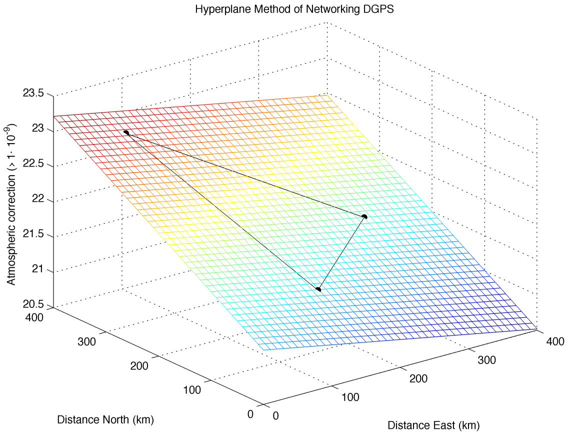


Figure 6d.

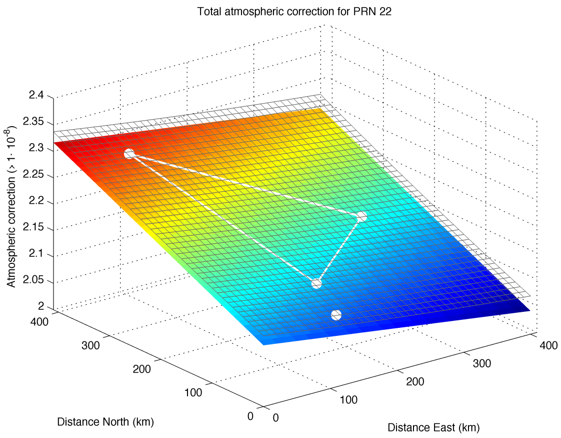


Figure 6e.

Figures 6a-e. Representations of the networking methods, plotted with respect to the area covered by Figure 5 and Group 1 beacons: (a) simple-averaging, (b) inverse-range, (c) inverse-range-squared, (d) hyperplane (spatial linear interpolation), and (e) hyperplane overlaid on the "actual PRC" plot from Figure 4 (gray grid), with DGPS beacon triangle and rover position D plotted in white.

SIMULATOR TESTING RESULTS

In evaluating performance, the networking algorithms should be compared against each other, as well as to the performance of single-beacon position solutions. Of particular interest are three values: (1) the time-averaged position bias length, (2) the radius containing 95% of the position solutions from the bias length, termed the scatter radius, and (3) the 2 times distance-root-mean-squared (2DRMS) value for each method's 2-dimensional position solutions. The bias length is the distance between the mean position solution and the true position. The scatter radius, with respect to the bias length, helps determine the precision of the solution method (note: this is not the commonly-known R95 measure, which describes the radius including 95% of positions with respect to true position). The third measure of performance, 2DRMS, describes a common measure of horizontal accuracy, referencing both true position and position precision, given by:

$$2\text{DRMS} = 2\sqrt{\sigma_x^2 + \sigma_y^2}$$

where σ_x and σ_y are the standard deviations of the x and y position values, respectively.

The positions for the DGPS beacon groups and rover locations are plotted in Figures 7a-p. Also plotted are the time-averaged bias lengths, denoted with a large dot placed at the center of mass of positions, the 95% radius (denoted with a dotted circle, and the true position (0, 0) point overlaid with thick black crosshairs.

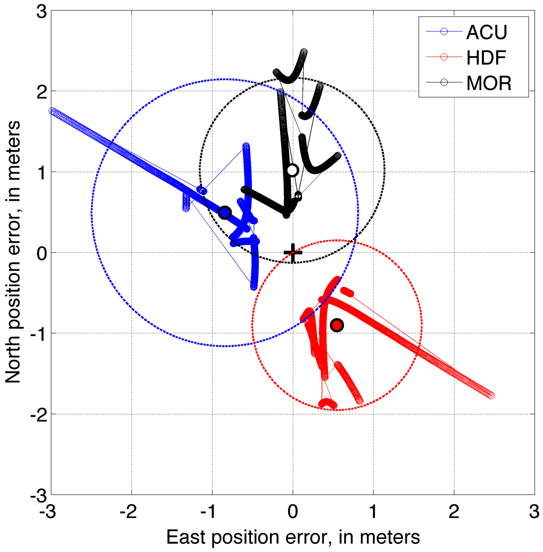


Figure 7a. Point-group 1A, single-beacon.

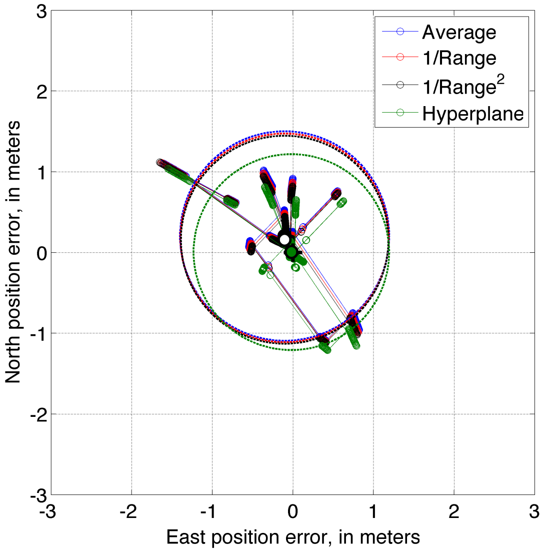


Figure 7b. Point-group 1A, networked-beacon.

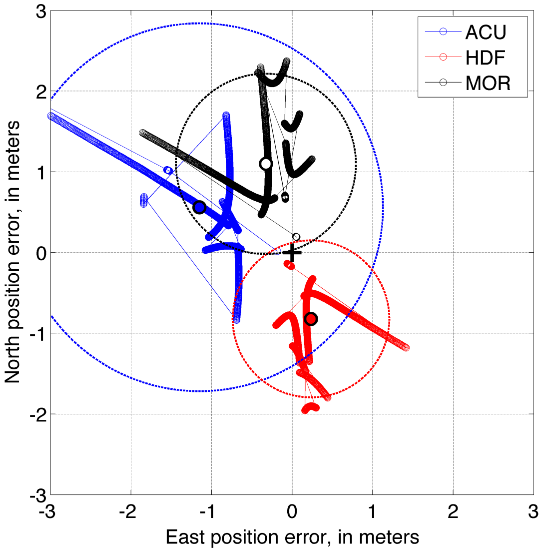


Figure 7c. Point-group 1B, single-beacon

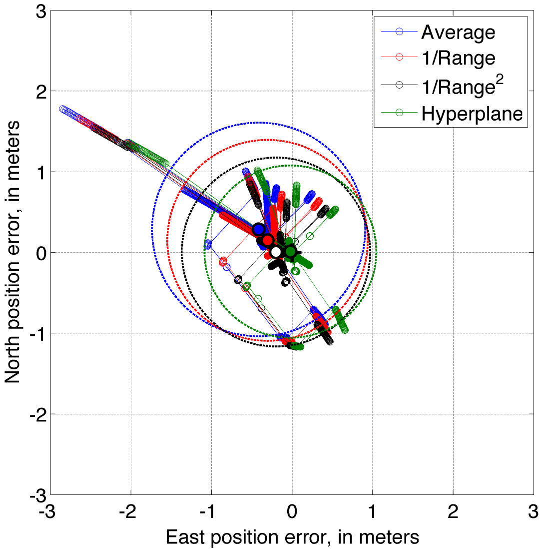


Figure 7d. Point-group 1B, networked-beacon

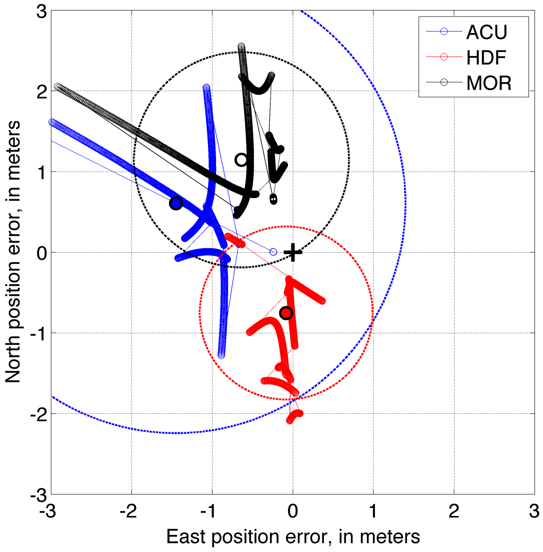


Figure 7e. Point-group 1C, single-beacon

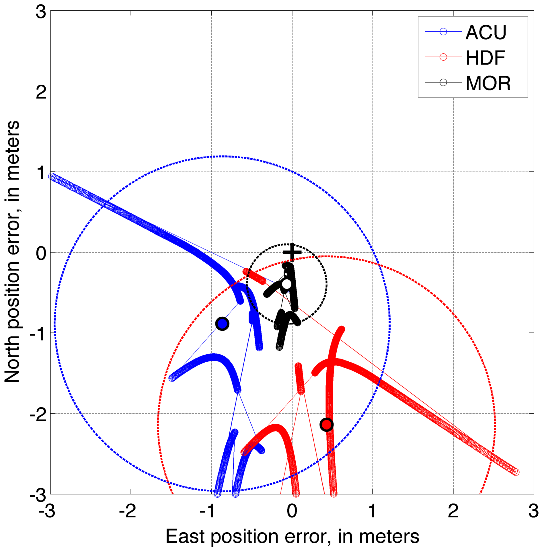


Figure 7g. Point-group 1D, single-beacon.

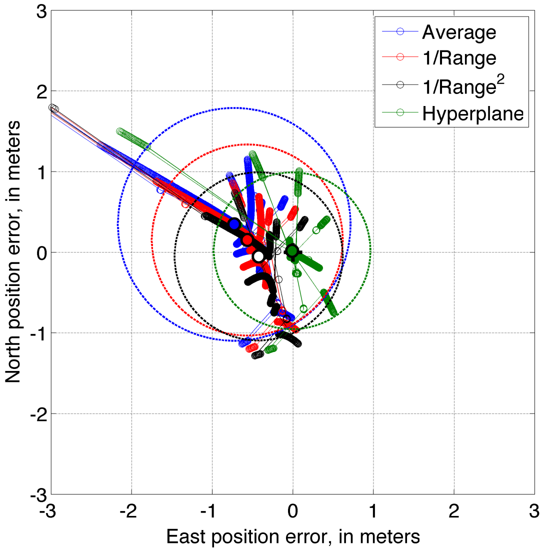


Figure 7f. Point-group 1C, networked -beacon

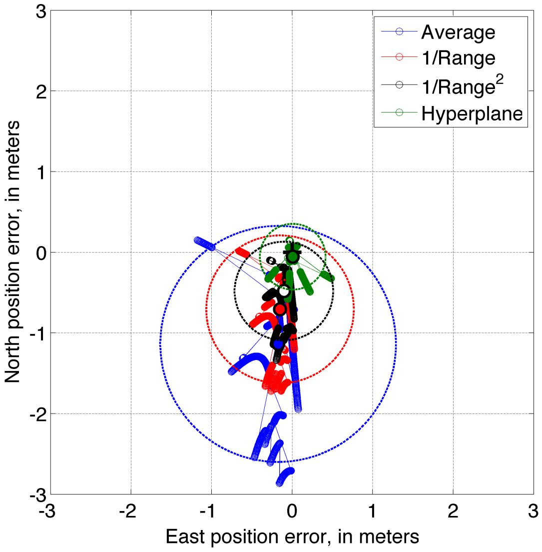


Figure 7h. Point-group 1D, networked-beacon.

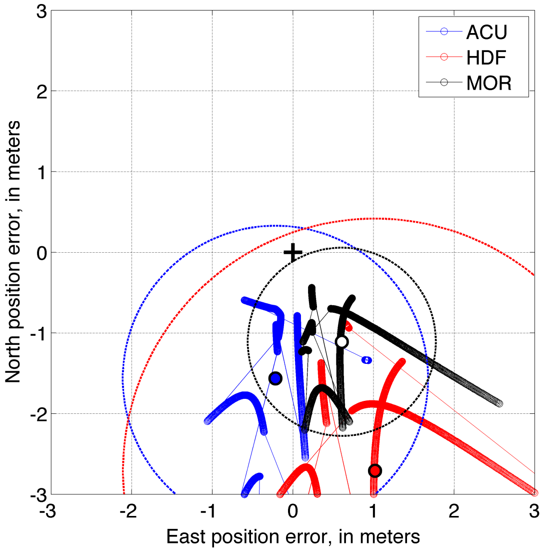


Figure 7i. Point-group 1E, single-beacon

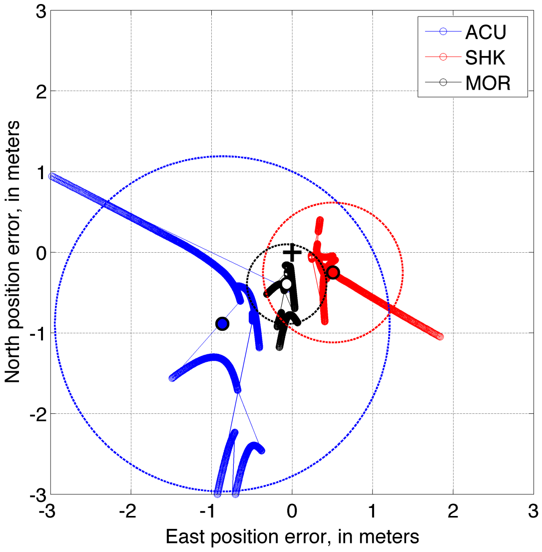


Figure 7k. Point-group 2D, single-beacon

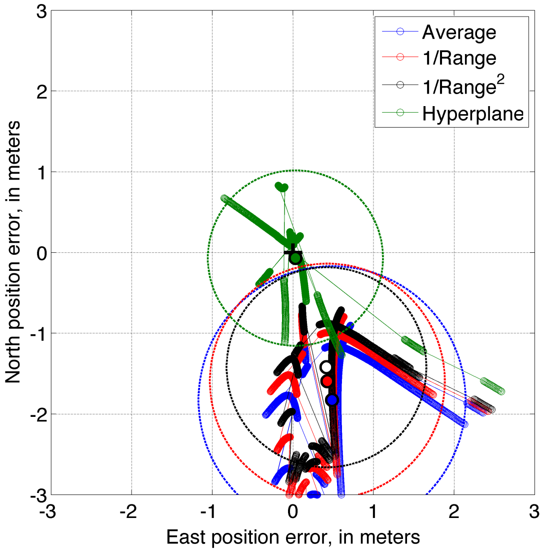


Figure 7j. Point-group 1E, networked –beacon

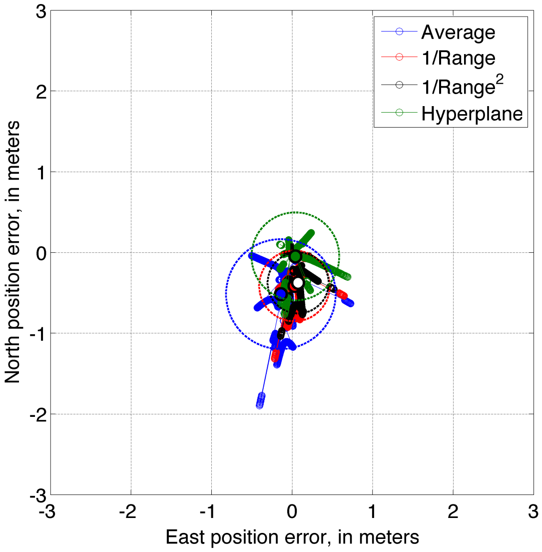


Figure 7l. Point-group 2D, networked -beacon

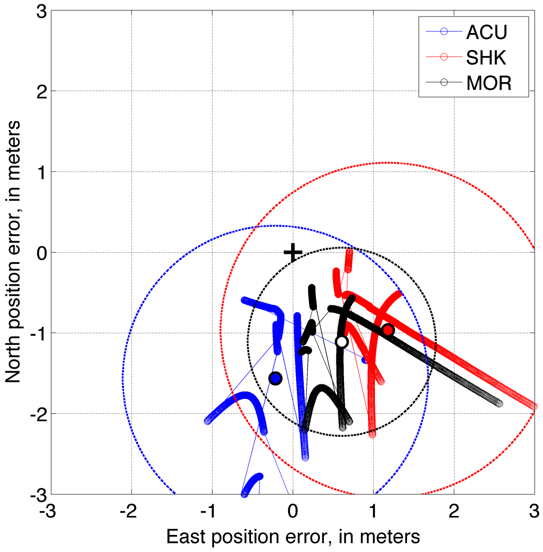


Figure 7m. Point-group 2E, single-beacon.

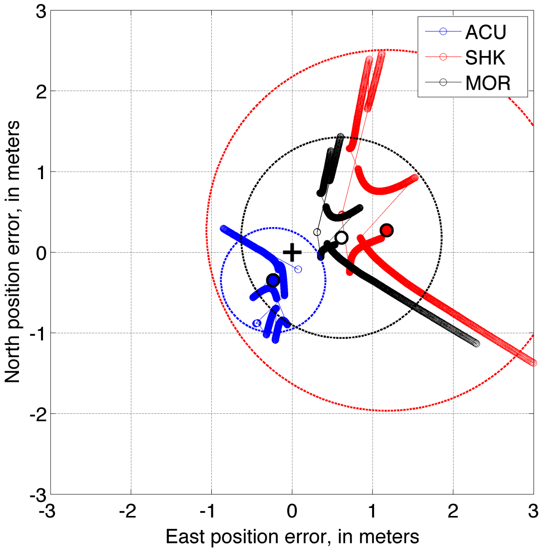


Figure 7o. Point-group 2F, single-beacon

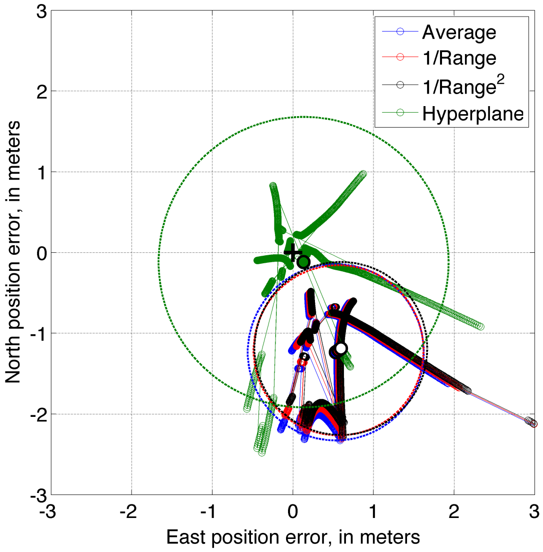


Figure 7n. Point-group 2E, networked-beacon.

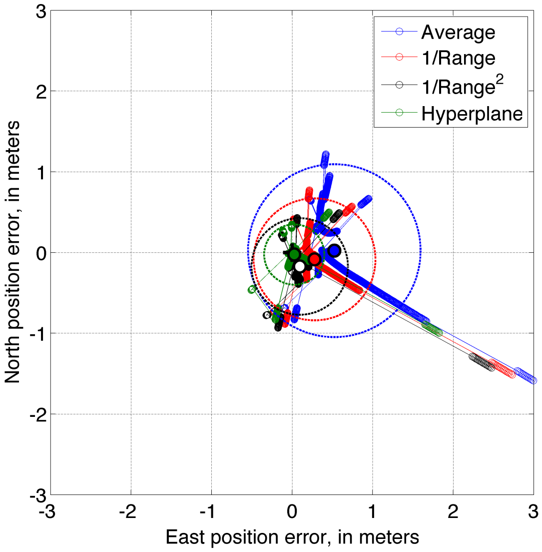


Figure 7p. Point-group 2F, networked -beacon

Figures 7a-p. Position plots of interesting beacon-user groupings. ACU is Acushnet, MA, MOR is Moriches, NY, SHK is Sandy Hook, NJ, and HDF is Hudson Falls, NY.

DISCUSSION OF SIMULATOR RESULTS

Figures 8a through 8c demonstrate the performance metrics for each of the single-beacon and multi-beacon algorithms, categorized by Group-Point. As expected, the position solutions using corrections from a single DGPS beacon exhibit a bias away from the beacon. This is evident in every test case, with the magnitude of the bias being proportional to the distance away from the beacon. The azimuth of the bias remains constant, as expected. The 95% scatter radii magnitudes are also proportional to the distance away from the beacon. 2DRMS values suffer for those beacons that are far away from the rover. These results corroborate the results from previous work on DGPS bias.

Position solutions generated from multi-beacon algorithms tend to be better than those generated from single-beacon solutions, in terms of all three performance metrics. The exception to this is the set of unique cases in which the rover is very close to the beacon whose corrections are being applied.

Between the four multi-beacon algorithms, the simple-averaging method shows the greatest average values of bias length, scatter radius, and 2DRMS in all cases. This was expected, however, as the simple-averaging method does not take into account the rover's position relative to the beacon, nor the beacon group geometries—it simply accounts for differences in beacon PRCs, which may be useful in an especially noisy environment or when the beacons are very close together. This method exhibits a very obvious bias away from the beacons, only mitigated when the rover is located equidistant to and in the center of all three beacons (see Group 1 Point A, denoted '1A'). As can be surmised, this method's 2DRMS values approximate an average between the three single-beacon 2DRMS values.

In all three metrics, the inverse-range and inverse-range-squared methods performed at least as well or better than the simple-averaging method. Again, this is to be expected, as these methods de-weight the beacons farther away, and thus, remove the greater biases (both length and scatter radius) from the position solutions. Consequently, the 2DRMS values for the inverse-range and inverse-range-squared methods are lower than those obtained from simple averaging. Performance of all three metrics is better for the inverse-range-squared method than for the simple inverse-range because the exponent places a greater emphasis on the closest beacon, even when all three are approximately the same distance from the user (see test Group 2 Point E). However, in all cases, these two methods exhibit a definite bias away from the beacons, caused by the algorithms' indifference to the beacon geometry. Because of this, these methods are more precise than the simple-averaging method, and slightly biased.

The hyperplane (spatial linear-interpolation) method performs uniquely when compared against both single-beacon and other multi-beacon networking methods. In all cases, the bias length value for this method is smaller than for all other solution methods and the 2DRMS value is almost always the smallest. In any case, the 2DRMS values are significantly lower than all single-beacon solutions. This is particularly expected due to the calculated hyperplane correction's close approximation to the near-planar "actual" atmospheric correction grid from the first simulator test. However, the 95% scatter radius exhibits interesting properties when the beacon geometry is nearly linear and the rover is located at a tangent to the beacon line. In this case, the hyperplane solution is accurate, but with a greater scatter radius, and a 2DRMS value lower than all other solutions. In that peculiar arrangement, the hyperplane's large scatter radius is caused by the orientation of the GPS constellation to the beacon group: as the satellites rose and fell, they would come into and disappear from each beacon's view at different times. Therefore, as a new satellite rose into view, the hyperplane would be, temporarily, based entirely on a single satellite, and the position solutions would behave with the bias of a single-beacon solution. Based on these results, the hyperplane method produces, in most cases, the best 2DRMS performance when compared with other multi-beacon and single-beacon solution methods.

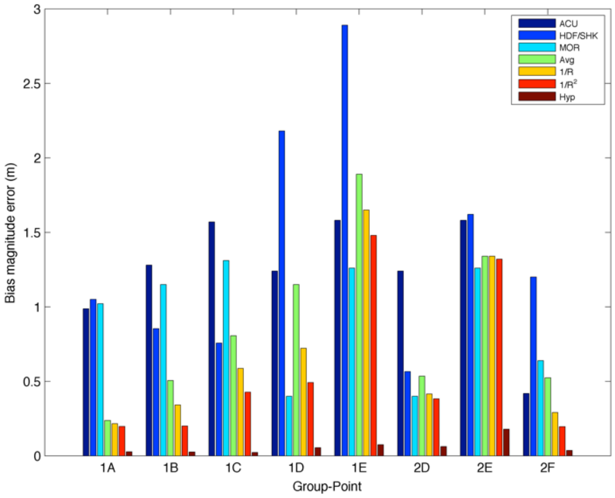


Figure 8a.

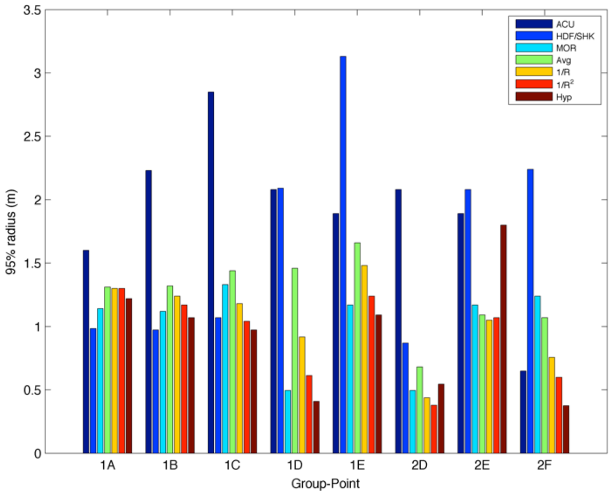
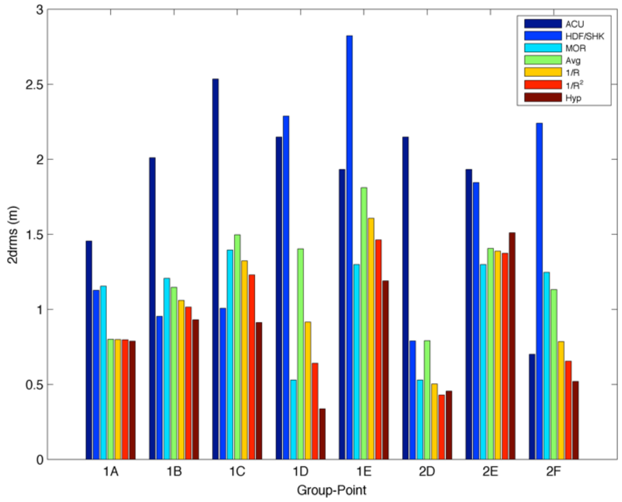


Figure 8b.



Figures 8a-c. Bar graphs of (a) bias length, (b) scatter radius containing 95% of the positions, and (c) 2DRMS.

REAL-WORLD TESTING

A software-defined radio (SDR) system was designed to capture and post-process DGPS data from multiple beacons. Ettus Research's Universal Software Radio Peripheral (USRP) model N210 was chosen as the SDR vehicle because of its wide user base, ease of integration within the MATLAB environment, and system capabilities.

The system setup consisted of a four-ft DGPS E-field antenna, low-loss coaxial cable (LMR-400), low-noise Krohn-Hite bandpass filter-amplifier, a USRP with LFRX daughterboard (capturing 0-30 MHz band), and a computer running MATLAB R2012b. While the USRP is capable of sampling rates up to 100 MSamples/s, a sampling rate of only 100 kHz is required to capture the entire DGPS band. Using the USRP system driver (UHD version 003.002.003) developed by Ettus and Mathworks, the device decimation was set at 400 on the LFRX daughterboard, effectively setting a 250 kHz sampling rate. These quantized data, now in MATLAB format, were then downconverted to baseband for each of the target DGPS station frequencies and processed through a Viterbi decoder set up to accommodate the 100 and 200 bps MSK modulation. Finally, the resulting bitstream was read by an RTCM SC-104 parser and output to the user. Additionally, the USRP was configured to synchronize and step its 10 MHz and 1 pulse-per-second local oscillator to an HP cesium frequency standard to ensure accurate timing. The system diagram for post-processing DGPS data from the USRP is shown in Figure 9.

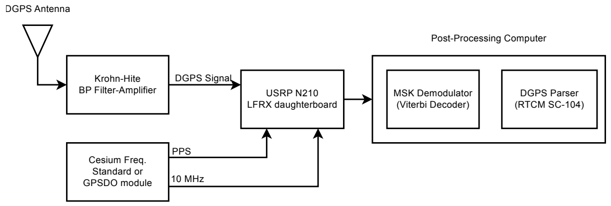
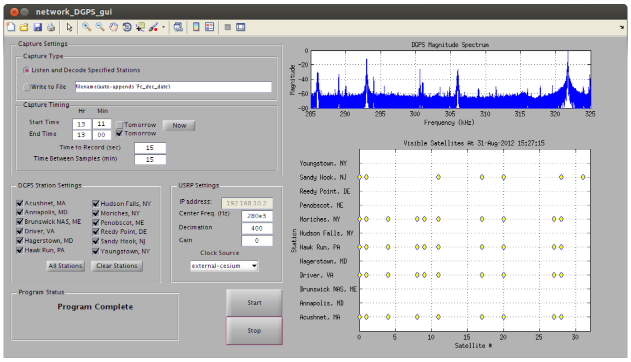


Figure 9. System diagram of real-world test using USRP to collect entire DGPS spectrum for post-processing.

A MATLAB graphical user interface, building on related work by Wyman [12], was created to select and process DGPS information from multiple DGPS beacons, tailored to use the above system configuration. Figure 10 shows a screenshot of this application, and displays two plots: a Fourier transform of the DGPS frequency band with DGPS frequencies-of-interest highlighted, and a scatter-plot of satellites observed at each DGPS station for a 15-second time window. These data were captured with an antenna placed atop the engineering building at USCGA, MacAllister Hall. Not surprisingly, the three closest beacons (Acushnet, MA, Sandy Hook, NJ, and Moriches, NY) were decoded. Of particular note here is the reception of beacons much farther from the user's location, most likely from skywave propagation. At the USCGA recording location, beacons from as far as Driver, VA, and Annapolis, MD, are at high signal strengths, even higher than those from Sandy Hook, NJ. Later tests showed reception of up to 90% of the broadcast messages from Annapolis, MD. Because of this, a program designed to select the beacons with the three highest SNRs might yield a surprising set of results.



● Listen and Decode Specified Stations
○ Write to File: filename(auto-appends 'Fc_dec_date')

Start Time: Hr 13, Min 11 ☐ Tomorrow
End Time: Hr 13, Min 00 ☑ Tomorrow
Time to Record (sec): 15
Time Between Samples (min): 15

☑ Acushnet, MA
☑ Annapolis, MD
☑ Brunswick NAS, ME
☑ Driver, VA
☑ Hagerstown, MD
☑ Hawk Run, PA
☑ Hudson Falls, NY
☑ Moriches, NY
☑ Penobscot, ME
☑ Reedy Point, DE
☑ Sandy Hook, NJ
☑ Youngstown, NY

IP address: 192.168.10.2
Center Freq. (Hz): 280e3
Decimation: 400
Gain: 0
Clock Source: external-cesium

Program Status: Program Complete

Figure 10. DGPS multi-beacon signal processing program.

OTHER CONSIDERATIONS

There are a number of real-world conditions that complicate the application of networked DGPS algorithms, which were not under consideration while testing on the simulator. Of note are two types: sub-optimal and complex conditions, where sub-optimal conditions are those events that cannot be controlled by the user and complex conditions are those things that the user (or receiver equipment) should take into consideration.

Sub-optimal conditions could include: reception of fewer than three beacons, poor GPS constellation, and ancillary noise sources. Of course, application of a hyperplane solution is predicated on receipt of three or more beacons. One potential solution for receipt of only two beacons is a simple linear interpolation with selection of the PRC at the point nearest to the rover, which is simply 2-dimensional linear interpolation, taking into account beacon distance and azimuth. A poor GPS constellation reduces dilution-of-precision performance for standard GPS-only position solutions and is common in high-latitude regions, such as the Arctic Ocean. Ancillary noise sources, as discussed previously, can cause wide variations in DGPS PRC accuracy, particularly in SED events, which cause distortions to PRC accuracy across wide geographic areas and could be tracked and compensated-for in a networked DGPS algorithm. Consideration of these sub-optimal conditions presents itself as future work.

Complex conditions such as poor beacon geometry and areas with more than three DGPS beacons are interesting areas of further concentration. Poor beacon geometry is common in littoral areas, presenting issues with the 95% scatter radius discussed above. Poor beacon geometry can also include the geometry of the beacon group relative to the GPS constellation. For example, a case in which the beacons are lined parallel to a poor GPS constellation low on the horizon is likely to produce unfavorable correction behavior. In an area where four or more beacons are available to a user, the hyperplane solution can be applied to a number of different three-beacon groups. Most coastal areas nearby large seaports of in the U.S.A. can receive up to six beacons. In this case, how should the beacon groups be selected? Or should a least-squares hyperplane be fitted to all four-plus beacons? Perhaps a multi-dimensional plane could be considered. In addition, beacons low on the horizon tend to possess poor signal strengths, so it may be worth considering weighting each satellite based on SNR.

FUTURE WORK

This paper presented several methods of networking multiple DGPS beacons to improve position accuracy. However, discussion of error modeling for each of these methods has not yet been discussed and presents a good area for further study. It has also been demonstrated that DGPS information from multiple beacons can be captured simultaneously under real-life conditions, and actual application of networked DGPS methods should be explored. It would be useful to collect DGPS data from multiple beacons simultaneously and apply them to GPS data concurrently published on the CORS network. This method of capturing and processing data allows particular flexibility in researching the effect of networked DGPS on potentially hundreds of regional CORS sites, providing a significant variety of data.

CONCLUSIONS

Networking multiple DGPS beacons can provide marine users with a greater degree of accuracy and precision in their position solutions than current single-beacon methods. In particular, the hyperplane, or spatial linear interpolation, is the only networked DGPS method that proposes the use of the beacon grouping's geometry to remove beacon bias from the solution, and does so quite effectively. The methods proposed and evaluated here are simple enough to be implemented on low-complexity, low-cost hardware and require minimal infrastructure changes to the user and none to the DGPS broadcasting agency, minimizing the cost of potential improvement. It is also worth noting that the application of these methods would alter only one component of the typical DGPS-GPS system employed by users, the DGPS receiver—the two antennas, GPS receiver, and user interface require no changes.

DISCLAIMER

The views expressed herein are those of the authors and are not to be construed as official or reflecting the views of the U.S. Coast Guard.

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