An analysis of carrier phase differential kinematic GPS positioning using DynaPos

Karen M. Cove · Marcelo C. Santos

Abstract A series of activities have been carried out at the University of New Brunswick in an effort to evaluate advances in long-range marine kinematic differential positioning. These activities involved processing and analysis of GPS carrier phase kinematic data sets. Some of the data was collected by UNB and some was provided by The XYZs of GPS Inc. Data were collected using Trimble 5700 and Ashtech Z-12 receivers. The data sets were processed using the software DynaPos provided by the The XYZs of GPS Inc. The best results obtained in our analysis indicate an agreement of 5 cm RMS for the horizontal component and 12 cm RMS for the vertical component between two ionospheric-delay free solutions, in baselines varying from 40 to 100 km.

Introduction

There has been an on-going effort to obtain (sub-)centimeter-level accuracy with GPS carrier-phase measurements for long baselines (i.e., static). The challenge poses itself as an even greater one if kinematic GPS positioning is of interest. The problem of area coverage is related to ambiguity resolution, which is typically possible up to some limiting distance from the reference station. Various ambiguity resolution techniques exist (Han and Rizos 1997). The solution of ambiguities becomes more difficult due to the de-correlation of systematic effects in the GPS measurements. GPS measurements are influenced by different atmospheric and satellite biases as distances between reference and remote stations increase (Tiberius et al. 1999).

Various approaches for carrier-phase long-range differential kinematic GPS positioning have been proposed. For example, Han (1997) examined three techniques. These included an on-the-fly ambiguity resolution algorithm, an ambiguity recovery technique for long-range kinematic positioning, and a technique that involved determining the ambiguities using the known positions at the starting and ending points of the survey (assuming that only the trajectory of the rover needs to be of high accuracy). In another example, Kim and Langley (2000, 2001) suggested a generalized procedure that included a functional model that takes into account all significant biases, a stochastic model that is derived directly from the observation time series, a quality control scheme that handles cycle slips (or outliers), and a parameter-estimation scheme that includes a simultaneous ambiguity search process. Another alternative is to accept the fact that fixing the ambiguity is riskier with increasing distance to the base station, and treat it as float after a certain distance.

In this paper, we have tried both approaches, either solving the ambiguities or leaving them float. We used kinematic GPS data collected by UNB and by The XYZs of GPS Inc. For the data processing, we have used the DynaPos software, provided by The XYZs of GPS Inc.

Long-range carrier-phase kinematic GPS positioning has also been successfully demonstrated in non-differential mode. Zumberge et al. (1997) first mentioned the term precise point positioning (PPP) associated with global centimeter-accuracy positioning for static locations and sub-decimeter accuracy in the kinematic mode using precise orbits and satellite clock information. The Jet Propulsion Laboratory (2004) (JPL) developed this capability based on its GIPSY software and has been operating a free Internet-based processing service for several years. JPL has also developed an Internet-based global differential real-time system with demonstrated global accuracies of 10-cm horizontal and 20-cm vertical. This service is available from a commercial provider.

Another PPP solution has been proposed by Héroux and Kouba (2001). It also uses precise orbits and clocks coming from a large network, in this case, the Canadian Active Service. Recently, a new on-line service for GPS users was announced (Geodetic Survey Division 2003). The Canadian Spatial Reference System-Precise Point

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Positioning (CSRS-PPP) service allows GPS users in Canada (and abroad) to recover carrier-phase-level accuracy positions from a single GPS receiver by submitting their observed data over the internet, without the need of a reference station.
This paper provides a general summary of features of DynaPos GPS processing software, followed by a description of data collection and analysis of results, and a discussion of how the software performed.

Processing in DynaPos

DynaPos is GPS positioning software that was developed with real-time kinematic applications in mind. It employs both real-time and playback processing styles. Real-time capabilities are available when the software is used in conjunction with a GPS receiver interface module (GRIM). The playback mode is actually an exact replica of events that would have occurred in real-time but played back in post-processing. A modified Hopfield model can be applied to estimate tropospheric delay. Precise orbits can also be processed.
DynaPos uses a Kalman filter algorithm to process GPS data in order to solve for position. Remondi and Brown (2000) describes the Kalman filter algorithm used in DynaPos. Essentially, it is capable of performing pseudorange and carrier-phase double-differences and carrier-phase triple differences. The measurement equation for the latter has the general form:

$$z_k = H_k x_k + J_k x_{k-1} + v_k \,, \tag{1}$$

where H is the design matrix, J_k is just $-H_{k\text{-}1}$ (in this particular application) and the independent white sequence v_k is that associated with either difference carrier or code observation. In DynaPos, single difference multipath combined with any remaining unmodeled systematic effects is modeled as a first order Markov process (i.e., one per satellite).
DynaPos is a powerful GPS processing tool that can be used for both real-time and post-processing application. The overview presented in this section was intended to introduce the reader to some of the main features and was not meant to be inclusive of all the features and capabilities of the DynaPos software. The interested reader should refer to the DynaPos user's manual (*The XYZs of GPS* 2001) for further details concerning the features discussed in this section.

Data collection campaigns

Data sets used for processing shown in this paper were the result of two well-controlled kinematic surveys. One data set was collected in spring 2002 with Trimble 5700 receivers with Zephyr and Zephyr Geodetic antennas on board the Heron, a survey launch operated by the Ocean Mapping Group of the University of New Brunswick. An additional data set was collected using Ashtech Z-12 receivers on board a hydrographic survey vessel in the lower Chesapeake Bay (Virginia). Most of the data processing performed during the project was similar in design and scope. All data sets were processed using the real-time playback mode.
The first marine kinematic survey was performed during a hydrographic surveying camp project in Saint Andrews Harbor, New Brunswick. The survey took place between Navy Island and the mainland. Two rovers were mounted on the top of the Heron and the base station, station NBCC, and were located on the mainland. The rovers remained approximately 2–4 km away from the base station throughout the survey. Data collection lasted for 3 days in roughly 6–8 h sessions with a data rate of 1 Hz.
The second marine survey took place in the summer of 1999 on the Chesapeake Bay (see Fig. 1). The data were collected at a rate of 1 Hz using Ashtech Z-12 receivers. Two base stations were used, one (TANG station) approximately 1 km away from the boat at dockside, and the other (DENY station) approximately 65 km away.
The vessel remained at dock near Tangier Island for about 50,000 epochs and then traveled a distance away from the dock and back again. The distance traveled translates to a maximum baseline length of 35 km to TANG station and a maximum of 100 km from DENY station.

Data processing and analysis

An extensive amount of time and effort has gone into exploring the data processing capabilities of the DynaPos software. Due to the added time spent on data collection, some of the processing features were not explored as fully as possible. Many features of the software such as the mapping features, ionospheric modeling and application of precise orbits were not applied in this paper. All results shown in this report were processed using one of two data processing techniques, ionospheric-free carrier and L1+L2 code or an integer fixed combination of techniques, in the playback mode.

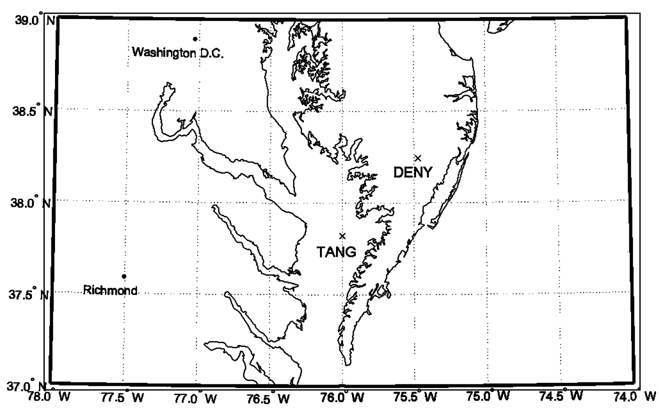

Fig. 1
Survey area in Chesapeake Bay showing TANG and DENY stations

The ionospheric-free carrier and L1+L2 code processing mode (hereinafter referred to as ionospheric-free) is chosen as it provides a relatively risk free solution that minimizes the effect of the errors associated with the ionosphere. This mode does not employ integer fixing and can result in an extended time for convergence. This could be overcome, however, by processing the data backwards in a post mission setting to achieve a higher accuracy solution for the entire data set. The combination of processing techniques (hereinafter referred to as integer fixed) simply means that the data were processed using a mixture of wide lane and narrow lane integer fixed and floating processing techniques. This allows the user to achieve both a higher accuracy solution, as well as quick convergence. Figure 2 is an example of a screen capture during the integer fixed processing technique. In this figure, the convergence of the three components is shown in the three plots in red, green and blue. An ambiguity status window showing the double difference ambiguities that have been fixed (in yellow) and the ones that have not yet been fixed (in red) is also presented.

Results, comparisons and analysis of the processing modes will be presented for the marine kinematic survey in Chesapeake Bay since it explores baselines longer than 10 km, situations when ambiguity resolution is difficult to accomplish (Santos et al. 2000) pushing DynaPos to its limits.

For the marine survey in Saint Andrews, we will only refer to Fig. 3. This figure shows the effect on standard deviations of using an integer fixed processing techniques. Based on previous experiments, the estimated noise level for the narrow lane solution is less than 1 cm in the horizontal and less than 3 cm in the vertical. The processing technique starts with a narrow lane carrier float solution and then switches to a wide lane float at epoch 1,015 and then to a fixed solution at epoch 1,412. The very high accuracies, in the sub-centimeter-level in the horizontal, were achieved when the fixed wide lane solution was switched back to a narrow lane float solution at epoch

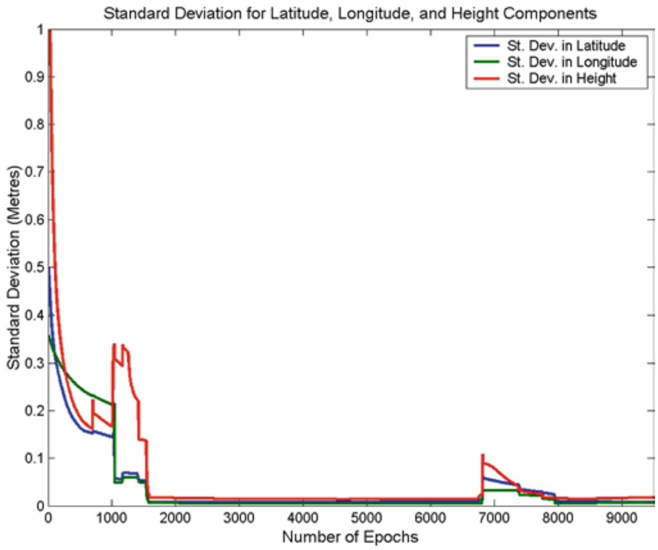

Fig. 3
Standard deviations for Heron solution in latitude, longitude and height components using the integer fixed processing technique

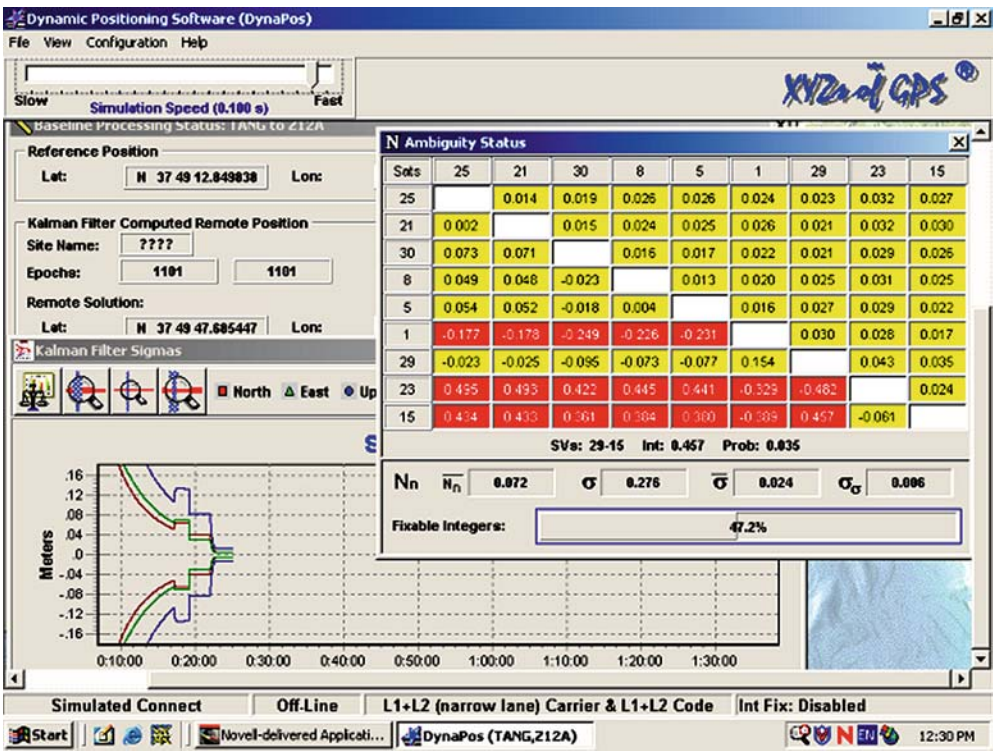

Fig. 2
Screen capture during integer fixed combination of techniques processing session

1,545. This gives the solution the benefits of an integer fixed solution combined with the low noise associated with the narrow lane processing. The jump visible at approximately epoch 6,800 can be attributed to the Kalman filter reinitializing after an event such as loss of lock on the satellites resulting in missing epochs of data.

The results of the kinematic marine data set collected in the Cheasapeake Bay are as follows. The relative distances the boat traveled from base stations TANG and DENY are shown in Fig. 4.

The standard deviations for the height component of the boat solution processed using the ionospheric-free technique and the integer fixed technique with TANG as the base station is shown in Fig. 5.

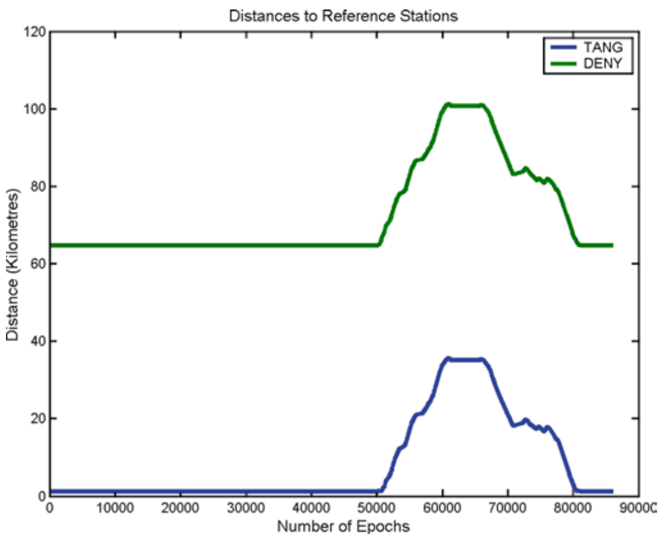

Fig. 4
Distance from stations TANG and DENY while boat is in dock and in motion

The standard deviations for the ionospheric-free solution converge to below 10 cm at about 1,000 epochs in the horizontal components (not shown in the figure) and at about 2,000 epochs in the vertical. Using the integer fixed techniques the integers are fixed at approximately 1,000 epochs allowing a sub-centimeter-solution in the horizontal (not shown in the figure) and a 1–2 cm solution in the vertical. The solution processed with the integer fixed technique shall be taken, in this case, to be very close to the "true" position of the boat due to the short baseline length and high accuracy involved. The apparent spikes and inconsistencies that appear in both plots are likely due to the changes in satellite geometry that took place during data collection and are not due to any manipulation during post-processing.

Figure 6 shows a comparison of the solutions, in difference in latitude, longitude and height, for the boat achieved using the two different processing techniques described above using the closer station TANG as base station.

It can be seen that the solutions for the boat while docked, epochs 0 to approximately 50,000, generally agree within 10 cm with an root mean square (RMS) value of less than 2.5 cm for the difference in the horizontal and less than 4 cm for the difference in the vertical while the boat is in dock. The solutions for the boat while it was in motion, epochs from approximately 50,000 to 80,000, tend to diverge owing to the increase in error due to the effects of the atmosphere as the boat moves further away from the base station, TANG when this happens, it resulted in an RMS value of less than 6 cm in the horizontal and 8.1 cm in the vertical.

The next plot, Fig. 7 shows the standard deviation of height components of the boat solution achieved with the ionospheric-free mode and the integer fixed technique using DENY as base station. The standard deviation in the

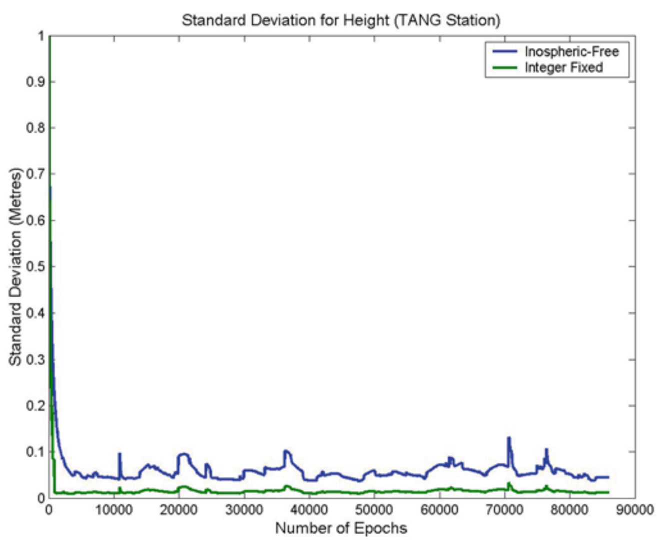

Fig. 5
Standard deviation in height component processed with the ionospheric-free and the integer fixed solutions computed for the vessel from (the closer) station TANG

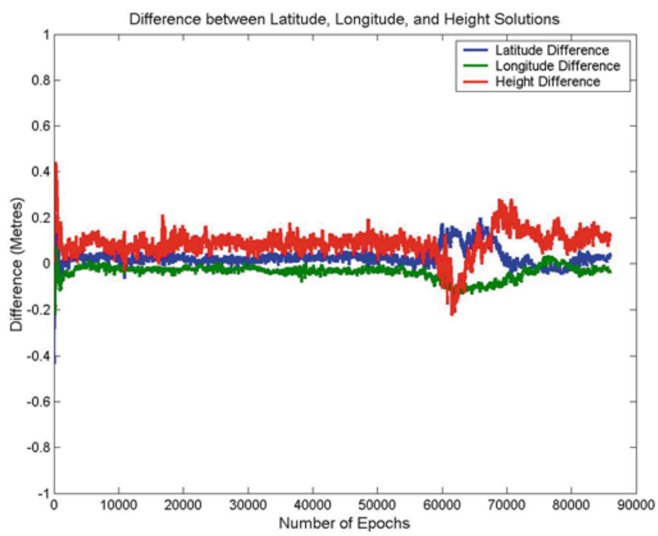

Fig. 6
Difference in latitude, longitude and height between the integer fixed and the ionospheric-free solutions computed from TANG while vessel was in dock and in motion

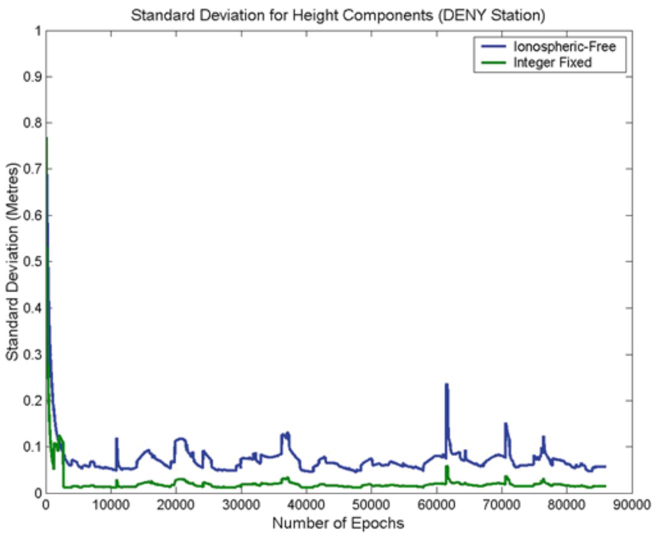

Fig. 7
Standard deviation in height of the ionospheric-free and integer fixed solutions computed from (the farther away) station DENY while boat was in dock

components takes slightly longer to converge than those in the ionospheric-free solution using TANG station.
Here the horizontal component (not shown in the figure) converges at approximately 1,200 epochs and the vertical converges at approximately 2,200 epochs. Again the spikes and peaks that appear are due to events not related to processing. The standard deviation plot shown in Fig. 7 indicates that the integers were fixed for the solution computed using the integer fixed technique. The possibility of an incorrectly fixed integer is likely at long baseline lengths such as these. An incorrectly fixed integer would result in an incorrect position solution. This may explain the differences shown in Fig. 8 when the fixed integer solution is compared to the higher integrity ionospheric-free solution.

The possibly incorrectly chosen integer value results in differences between the solutions in the range of 20–30 cm in all three components while the boat was in dock and in the range of 15–25 cm while in motion. It can be concluded therefore that the more reliable solution using DENY station would be the ionospheric-free carrier and L1+L2 code solution.
Figure 9 gives an indication of the internal consistency of two ionospheric-free solutions computed using the closer TANG and the farther away DENY stations. The figure presents a plot of the differences in latitude, longitude and height between solutions for the boat processed with the two different base stations while boat is in dock and in motion.
The solutions differed by RMS values of less than 5 cm in the horizontal and 10.5 cm in the vertical, for the motion in dock. The differences increase due to the increased baseline distances as the boat moves away from the two base stations. The RMS differences in the horizontal remain at less than 5 cm, however the RMS values in the vertical rise to 11.6 cm.
The last solution comparison, seen in Fig. 10, is between the integer fixed combination of techniques computed from the closest station TANG and the ionospheric-free carrier and L1+L2 code data combination computed from the farthest away station DENY. These would represent, theoretically, the optimum solutions obtainable for the two base stations based on their respective baseline lengths.
The low noise narrow lane integer fixed solution is derived from TANG station while docked and within a few kilometer of the station and the ionospheric-free solution is determined using DENY station. These solutions agree within a RMS value of 10 cm while the boat is docked and within 16.5 cm while the boat is in motion. The solutions for the latitude and longitude components are even closer with a RMS value of 5 cm while the boat was docked and

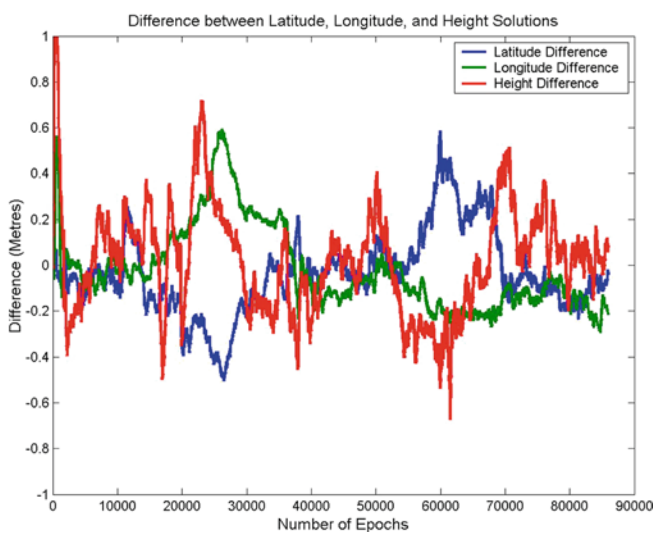

Fig. 8
Difference in latitude, longitude and height between the integer fixed and the ionospheric-free solutions computed from DENY base station while the boat is in dock and in motion

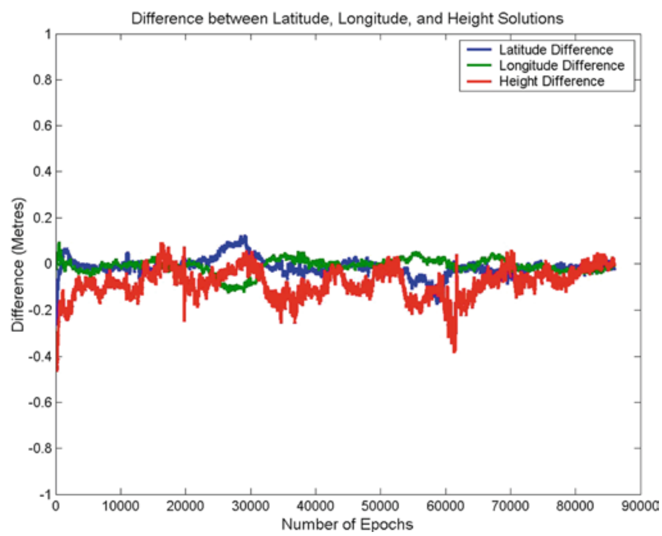

Fig. 9
Difference in latitude, longitude and height between two ionospheric-free solutions computed from TANG and DENY while the boat was in dock and in motion

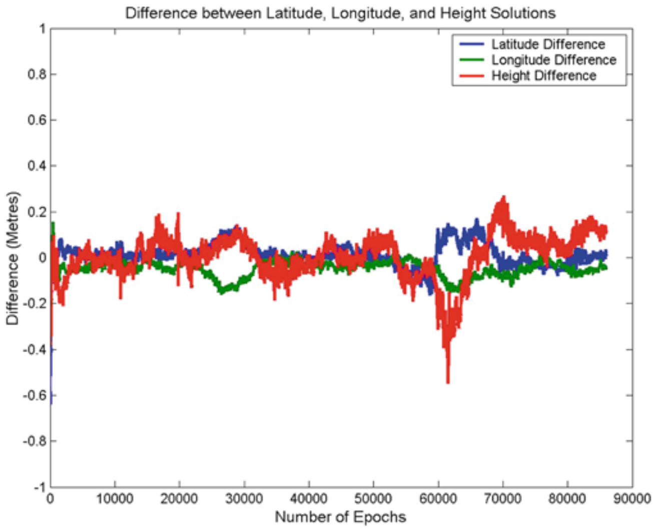

Fig. 10
Difference in latitude, longitude and height between the ionospheric-free solution computed from DENY and the integer fixed solution computed from TANG while the boat was in dock and in motion

within 7 cm while the boat is in motion. These differences can mostly be attributed to errors due to the effect of the troposphere. As mentioned, the narrow lane integer fixed solution can be taken as very close to the true position of the boat. This indicates that the ionospheric-free solution is a viable option for applications requiring accuracies in these ranges.

Results in RMS values between the solutions in differences in latitude, longitude, and height are summarized in Tables 1 and 2.

Concluding remarks

In this paper, we have presented results and analysis of the processing of marine kinematic GPS data sets using DynaPos software. DynaPos is a very powerful tool for data processing. In general, the software was found to be difficult to use at the beginning. There were problems with configuring the input files correctly. But after the first job was successfully processed the remaining jobs were much simpler to configure. It was also difficult to trouble shoot with respect to the content of the input files if something has been set incorrectly. We understand that a more comprehensive manual with tutorials is being prepared. This will provide the users with a handbook of sorts indicating what procedures should be followed in certain data processing conditions and situations. For the low end user, the options, especially the Kalman filtering settings, are quite complex and could easily be set incorrectly. The software is clearly meant for a well-informed user and is a powerful tool in the right hands. With that, we believe that the software can be fully explored. We are aware that DynaPos is a program under constant development and that improvement in the software are expected with newer versions.

The results presented here for the Chesapeake Bay were definitely consistent with what we would have expected. All of the behaviors apparent in the processed solutions can be justified. It has been shown that ionospheric delay free solutions are capable of delivering few-centimeter-level accuracy at ranges of up to 100 km.

In our study, we have used predominantly Trimble and Ashtech receivers. Further study should include the use of other kinds of receivers. Based on our data analysis, DynaPos performs better when dealing with Ashtech data. It became clear that the software also requires a relatively longer time to converge in comparison with the Trimble's native processing suite (such as Trimble Geomatics Office) when dealing with Trimble data. As stated earlier, the data can be post-processed backwards in DynaPos so full accuracy can be achieved for the full data set.

We believe that there still exists a need for more experimentation with DynaPos using different receivers and data collection scenarios including real time processing using GRIM.

Table 1
RMS values for Chesapeake Bay solution comparisons while the boat was in dock

Solution comparisons while in dock	Latitude difference RMS (m)	Longitude difference RMS (m)	Height difference RMS (m)
Iono-free vs. integer fixed using TANG	0.022	0.019	0.038
Iono-free vs. integer fixed using DENY	0.214	0.225	0.292
Iono-free TANG vs. iono-free DENY	0.045	0.045	0.106
Integer fixed TANG vs. iono-free DENY	0.042	0.043	0.104

Table 2
RMS values for Chesapeake Bay solution comparisons while the boat was in motion

Solution comparisons while in motion	Latitude difference RMS (m)	Longitude difference RMS (m)	Height difference RMS (m)
Iono-free vs. integer fixed using TANG	0.059	0.044	0.081
Iono-free vs. integer fixed using DENY	0.200	0.154	0.245
Iono-free TANG vs. iono-free DENY	0.049	0.022	0.116
Integer fixed TANG vs. iono-free DENY	0.067	0.044	0.166

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