Tightly Integrated Inertially-Aided Post Processed Virtual Reference Station Technique for Marine Hydrography

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Abstract

Today's primary positioning technique for near-shore, multibeam for Marine Hydrography involves integrating GPS and inertial navigation systems (INS). The Inertial Measurement Unit (IMU) aids in reducing GPS noise as well as providing high bandwidth, un-interrupted solutions during GPS outages. For high precision surveys (5 cm or better in X, Y and Z), the most common technique has been the post processed Inertially-Aided Kinematic Ambiguity Resolution (IAKAR) mechanization, which requires a reference station in the proximity of the survey area. The reference station helps to mitigate atmospheric and satellite biases and to resolve integer ambiguities. In these cases the GPS rover position is required to be within 20 km of the reference station. Otherwise the atmospheric biases degrade the accuracy of the results, imposing significant limitations and increased survey costs. This paper describes the Post Processed Virtual Reference Station (PPVRS) technique, which makes use of GPS network stations to determine atmospheric biases at the rover positions and which tightly integrates GPS with inertial data to provide a continuous, high-precision navigation solution with baselines of up to 100 km.

A standard NOAA hydrographic survey was chosen in the Chesapeake Bay to test the PPVRS work flow. Data acquisition was conducted aboard NOAA Ship RUDE (pronounced "Rudy") on October 18th 2007 as part of the acquisition of a multibeam reference surface. At 90 feet in length, 22 feet breadth, and 220 tons displacement, RUDE has a cruising speed of 10 knots and a range of 1,000 nautical miles. RUDE performs inshore hydrographic surveys along the east coast in support of NOAA's nautical charting mission and is equipped with some of the most technically advanced hydrographic and navigation equipment available. A Beta version of POSPac Version 5.0 was used to process the POS M/V Data and produce a Smoothed Best Estimate of Trajectory (SBET) file for import into Caris HIPS and SIPS, NOAA's Hydrographic Processing software.

Figure 1: The RUDE

The result is a positioning method for hydrographic surveying with the necessary precision for eliminating the need for dedicated GPS reference stations for all of the continental U.S. inland waters and near shore areas. PPVRS changes the way hydrographic surveys are acquired by reducing logistics and ensuring sub 5 centimeter positioning.

Introduction

GPS network positioning, often referred to as VRS, is the latest innovation in high precision positioning and there is a wide and growing variety of commercial applications for the technique.

A significant portion of the cost in hydrographic surveying is associated with the positioning task alone when the 3D positioning accuracy requirement is at the centimetric level. Centimetric positioning for hydrographic surveying is of particular interest today due to the current trend towards using ellipsoidal altitude instead of heave and tidal reductions. Utilizing network GPS, where the user accesses publicly available GPS base station data, significantly reduces the cost of surveying for centimetric positioning.

This paper describes a technique for centimetric positioning in hydrographic surveying using a network of GPS base stations to determine ephemeris, clock and atmospheric errors at the rover location. This technique uses the GPS observations from a Virtual Reference Station to compute a tightly integrated GPS / Inertial solution, with minimum baselines of over 100 km. Unlike the traditional loosely coupled GPS-Inertial integration, tight integration maintains an accurate position fix even if there are less than 5 satellites in view. Even after a complete GPS outage, the tight integration works to reestablish fixed integer ambiguities almost immediately after satellites are reacquired.

Background

PPVRS Workflow

Although hydrographic surveying has traditionally been based on real time delivery of position and orientation data to the echo sounder via asynchronous serial communication, today's trend is towards post processing such data, allowing for processing in both the forward and backward directions. This results in a "smoothing" effect on GPS outages and other aberrations in the data, thus producing the optimal solution.

The PPVRS workflow starts on the vessel where all raw positioning sensor data is logged for post processing. GPS reference station data for the same time period is logged on shore and often archived in databases with online access. For this test actual CORS station data were used as provided on NOAA's National Geodetic Survey's website.

Post mission processing begins with an extraction of the vessel raw data files and a check for completeness and data integrity. The extracted data is formatted for use in downstream processing in a directory structure suitable for standard desktop computers with average speed and storage capacity.

Reference Station Import

Once the extraction of the vessel data is complete, the reference station data is downloaded or imported locally. The reference station download tool automatically retrieves the data for the coinciding time interval of the survey. In the case of an internet download using an existing set of permanent GPS reference stations, the PPVRS software identifies those stations within a user defined radius from the middle of the survey trajectory. A database of stations is maintained within the POSPac software, along with an automated tool for FTP access to sites, making reference station data available for public use.

A minimum of 4 reference stations are required for PPVRS, although typically 5 to 10 are used. A search radius of up to 200 kilometers is recommended, less if there are stations near the survey area. In order to maintain centimetric accuracy at least one of the stations must be within 100 kilometers of the rover at all points of the survey (the closest station is allowed to change). In the figure below all stations within 200 kilometers of the survey trajectory are displayed. There are 38 stations within the recommended 200 kilometer search radius. For the final processing of data on this particular survey, 7 stations were used.

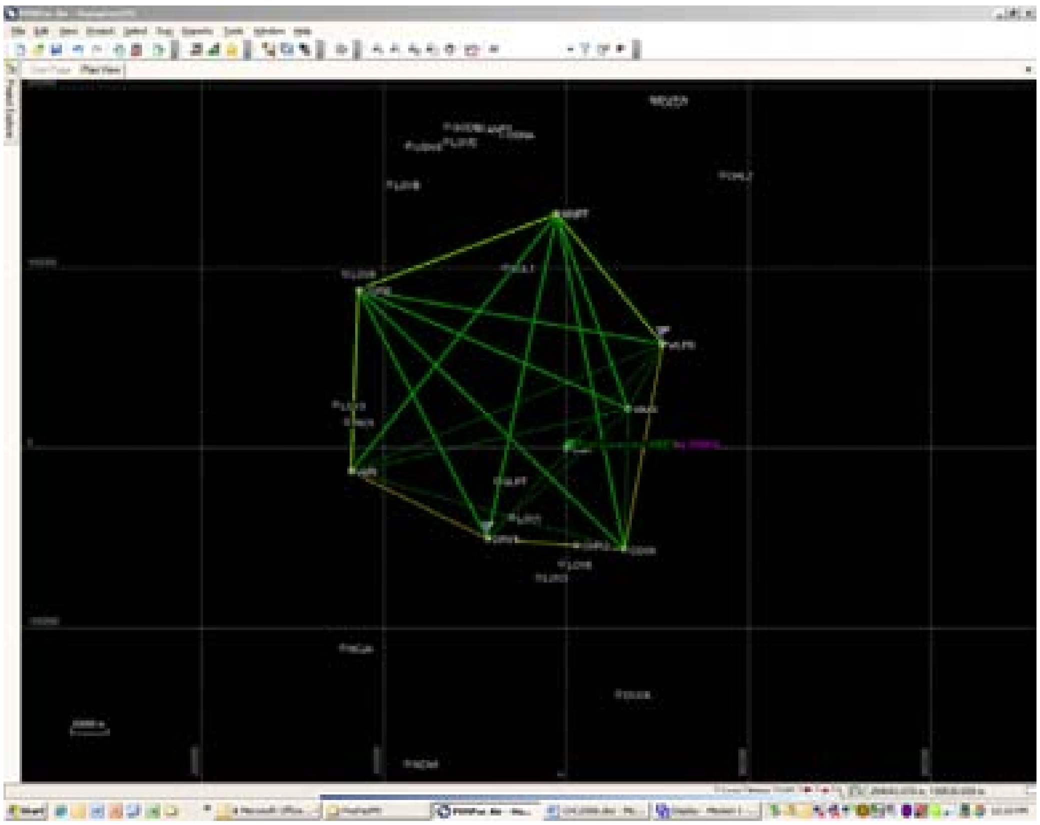

Figure 2: Preview of Network –Available reference stations and network stations selected for PPVRS

Reference Station Quality Check

Once the reference station data is downloaded a network adjustment is applied to check for accurate base station position and for reference station data integrity. The network adjustment uses GPS measurements, input base station coordinates, and computed baselines in a least squares adjustment. In the figure above, the stations included for network adjustment are connected by green lines. 24 hours of reference station data are required for this quality check in order to ensure the most accurate validation of base station coordinates. Note that this requirement extends only to the reference stations and not to the data collected on the vessel. The reference station data should be without cycle slips or data gaps. If a shorter time period is used, centimetric accuracy in the final rover position cannot be guaranteed. If 24 hours of continuous data is not available, then it becomes the user's responsibility to provide the final assurance of the integrity and quality of the reference, particularly the base station coordinates. The results of the network adjustment for the network described above are seen below.

Termination status : Normal

Station	Input Coords	Status	Horizontal	Vertical	Total	Time Span	Output Coords
VIMS	Control	Control	0.000 m	0.000 m	0.000 m	23.88 h	Control
VAWI	Original	OK	0.008 m	0.044 m	0.045 m	23.88 h	Original
VARI	Original	OK	0.008 m	0.007 m	0.010 m	23.88 h	Original
HNPT	Original	OK	0.008 m	0.030 m	0.031 m	23.88 h	Original
DRV5	Original	OK	0.006 m	0.022 m	0.023 m	23.88 h	Original
COVX	Original	Bad Estimate	0.006 m	0.015 m	0.016 m	9.38 h	Disabled
CORB	Original	OK	0.019 m	0.024 m	0.031 m	23.88 h	Original

Figure 3: POSPac Report on Network Adjustment

The POSPac software automatically disables reference stations according to predetermined thresholds. A station is disabled specifically when the horizontal and vertical differences in computed coordinates vary from the input coordinates by more than the default threshold of 5 cm, or when there is less than 24 hours of operational data with the time of the survey as the center of the time window, meaning 12 hours on each side of the mid time for the survey. If necessary it is possible for the operator to overrule the network adjustment results and force the software to include a station even if it has failed this quality check.

For the purposes of the network adjustment, the software automatically selects one station as the Control station. The coordinates of this control station are fixed in the network adjustment, and it is usually the closest station to the survey. The user can overrule the control station selection.

Generate PPVRS Corrections

The next step is PPVRS correction generation, when the data from the network of reference stations is used to generate a single set of corrections for the rover. The station closest to the survey with the cleanest data is selected by POSPac as the Primary station. The GPS observables from the primary station, together with atmospheric corrections computed from the network of GPS stations are used as a basis to compute the VRS observables at the Rover position. PPVRS generation is guaranteed to meet specifications if the rover survey trajectory is inside the area circumscribed by the network of reference stations. The PPVRS correction generator relies on consistency in the reference data, continuously checking for data gaps and cycle slips. If the operator chooses to use a station with gaps, PPVRS will use the station when available and rely on the remaining stations when it is not. The PPVRS operator report is shown below.

Reference Station Raw Data Analysis

Station_ID	Total_Gap	Max_Gap	Min_Gap	Unrepaired_CS	Simul_unrepaired_CS	REF2Traj_Centre(km)
VIMS	240.0	180.0	60.0	195	8	37.0
VAWI	0.0	0.0	0.0	501	0	75.0
VARI	0.0	0.0	0.0	105	0	121.4
HNPT	0.0	0.0	0.0	104	0	128.3
DRV5	0.0	0.0	0.0	69	0	69.8
COVX	5460.0	3630.0	1830.0	564	4	65.8
CORB	0.0	0.0	0.0	103	0	144.7

SmartBase Statistics

SmartBase Status: PROC_STATUS_OK
Primary Station ID: DRV5
Number of Reference Stations: 7
Percentage of Primary Station Measurement Usage: 94.9%
Average Number of satellites per epoch: 8.5
Total full data gap: 0 s
Total individual satellite data gap: 19800 s

Figure 4: POSPac report on PPVRS generation

Tightly Integrated Inertial Navigator

The final step in the PPVRS and IAPPK workflow is computing the tightly integrated position and orientation solution using the PPVRS observations and the raw GPS and inertial data extracted at the beginning of the workflow. The data is processed in both the forward and backward directions in order to produce the optimal solution, smoothing the effect of GPS outages and other aberrations in the data. This results in the best possible position and orientation solution for a given data set, maintaining centimetric accuracy for significantly more time and at longer distances from shore than would be possible with traditional GPS processing. The output from this process is referred to as the Smoothed Best Estimate of Trajectory or SBET. A quality check using a suite of statistical checks on the final solution is also performed.

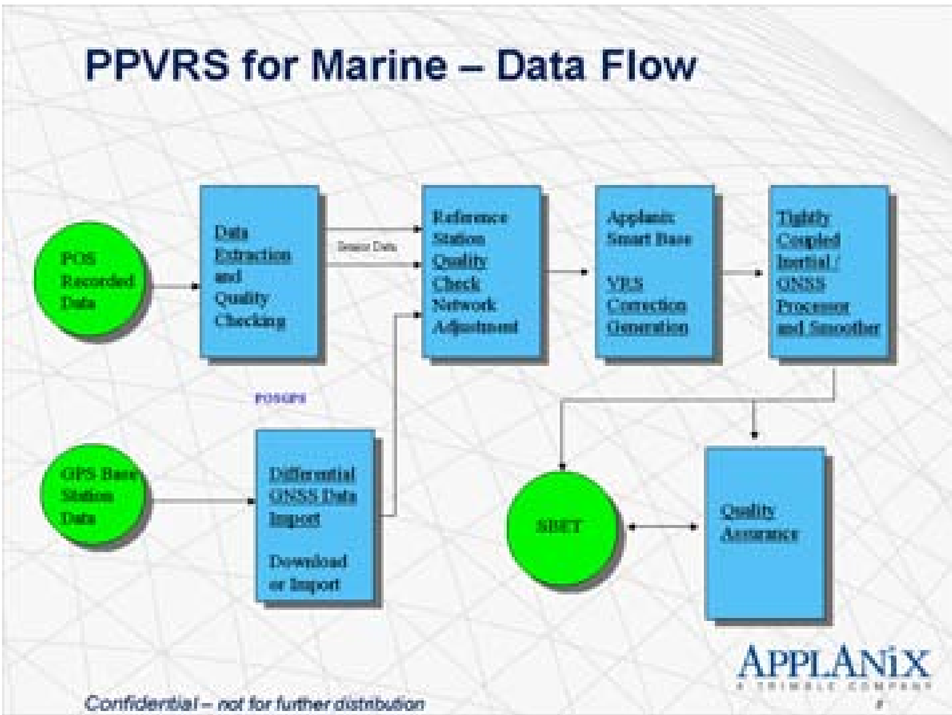

Figure 5: POSPac VRS and IAPPK Data Flow

Results

The result of tightly integrating the PPVRS data and vessel GPS and inertial observations in the inertial navigator are displayed below. The RMS results show that all data (with the exception of the start and end of line) are below 10 cm with the majority of the data accurate to better than 5cm in X, Y and Z. It should be reiterated that this was accomplished with no user installed base stations, using only Continuously Operating Reference Stations found on the NGS website, and with an average baseline of 50-100 km.

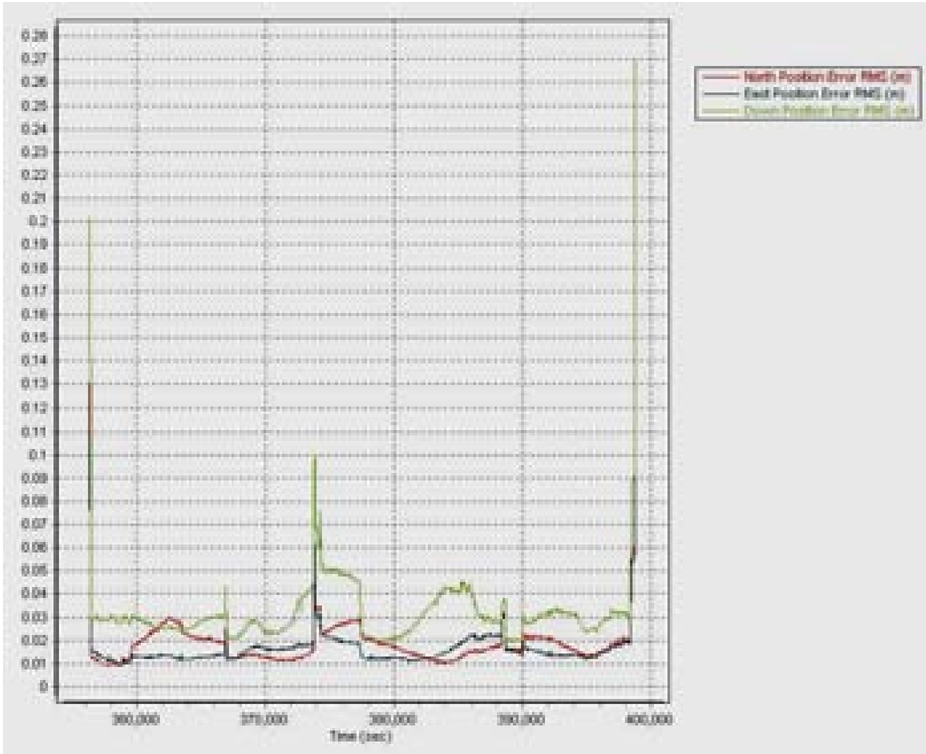

Figure 6: POSPac Display - RMS Estimates for Positional Error

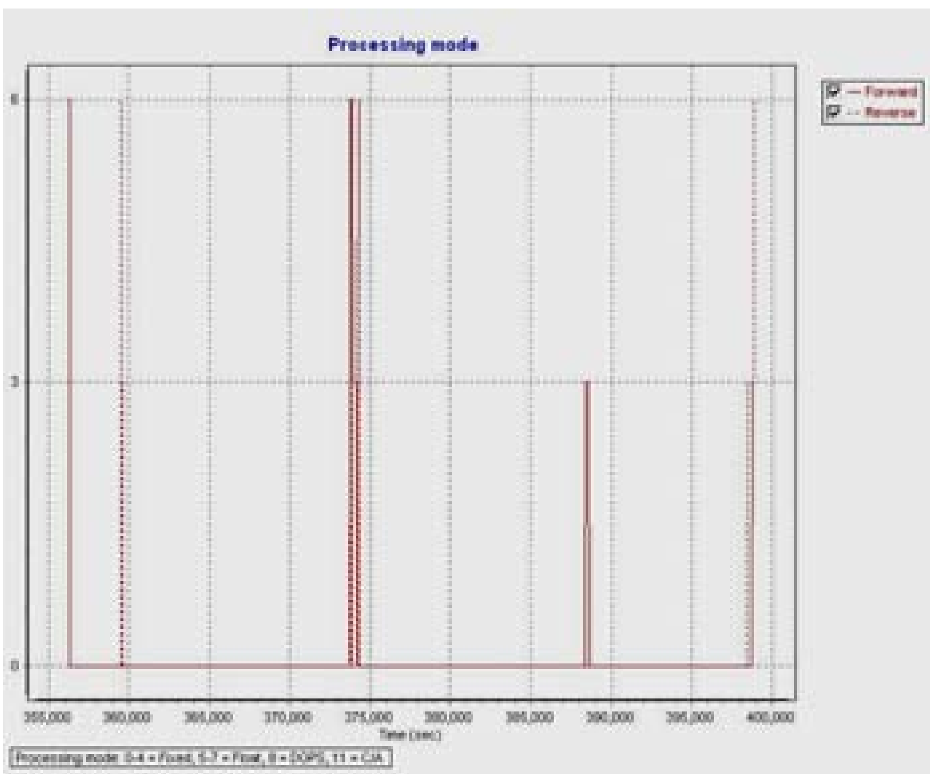

Figure 7: POSPac Processing Mode

The reason for these excellent results is found by examining the display of the Processing mode, where Mode 0 is equal to fixed integer narrow lane. In other words, all cycle ambiguities were solved for all GPS epochs. It is worth noting that the forward/backward smoother is effective in providing fixed integer mode in both the forward and backward direction.

The distance to the closest station is an important statistic for illustrating one of the key advantages of the PPVRS and IAPPK technologies. In the example above, centimetric accuracy is successfully maintained throughout the entire data set, even though the nearest base station in continuous use is at least 65 kilometers away (with a maximum of up to 72 kilometers distance in certain parts of the survey). Although some stations (notably VIMS and COVX) are closer to the survey area, the data for these receivers was incomplete. These stations are automatically included in the solution when available since they add considerably to the geometry of the network. It is worth noting therefore that, even during times when the network geometry is sub-optimal due to gaps in the data logged at these closer base stations, computation of the PPVRS solution is still possible.

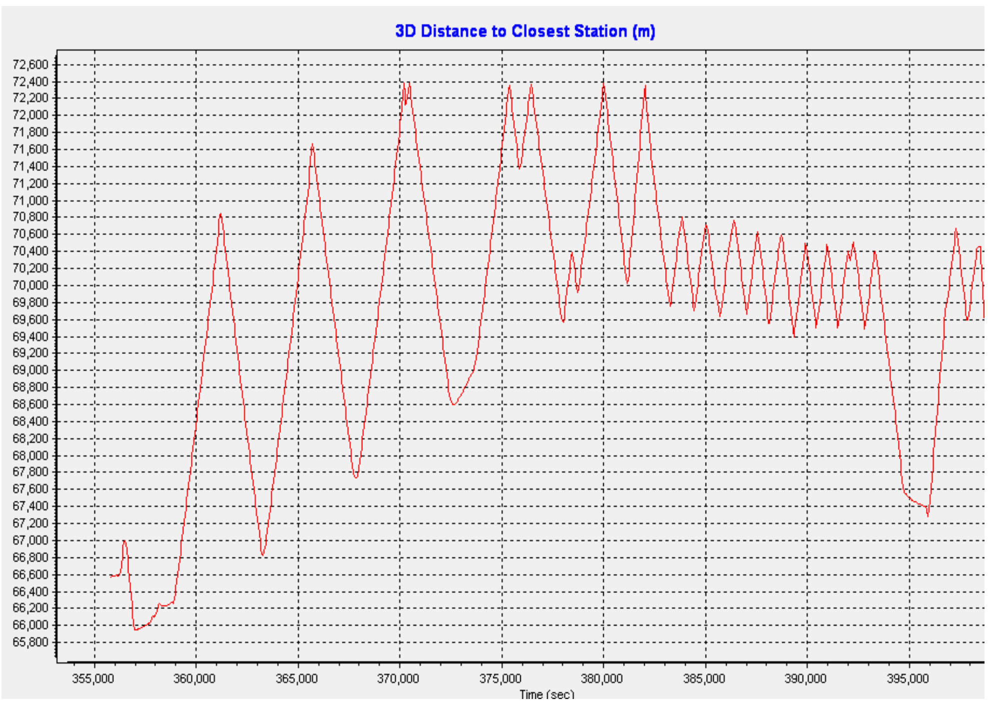

Figure 8: Applanix POSPac PPVRS

Distance to Nearest Reference Station

Data Quality

A DGPS real time position and orientation solution was computed for this case study (using the Applanix POS MV package) with typical accuracy at about the one meter level. As an additional quality check, the POSPac operator compared the results of various survey processing "runs". The difference graph below shows the difference in positions for the real time and post processed solutions. As might be expected, differences of up to 2 meters are evident, which serves to further underline the accuracy improvement inherent in the post processed solution.

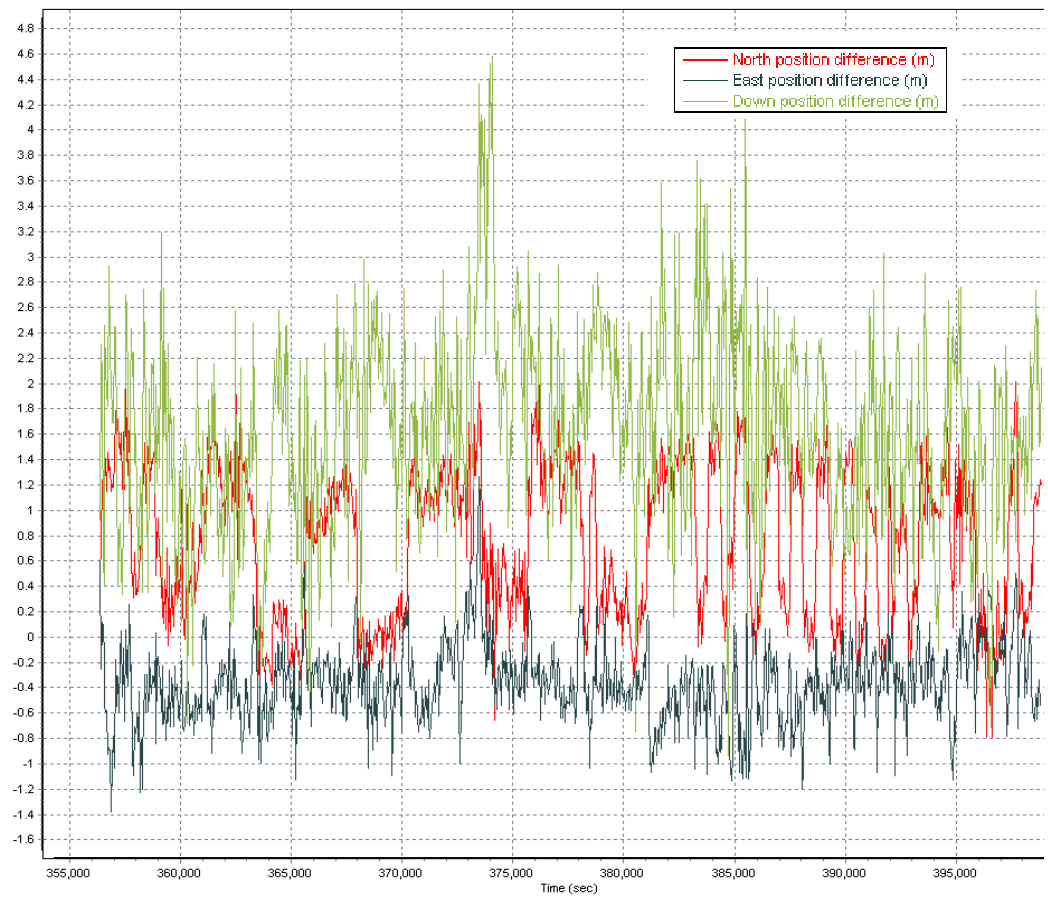

Figure 9: Difference between Real Time and Post Processed Positions

Quality Assurance statistics can be plotted in the Display tool. Some of the more relevant statistics and plots available include:

- Smoothed Best Estimate of Trajectory
- Performance Metrics, RMS for
    - Position in X, Y and Z
    - Heading
    - Roll

    - Pitch
    - Velocity
- Smoothed Error Estimates including
    - Accelerometer Biases
    - Gyro Biases
- Solution Status including
    - # of SV’s
    - PDOP
    - Processing mode
- PPVRS Baseline Data

Each of these statistics above may be examined to ensure they fall within prescribed limits. This ensures a statistically robust solution and smoothed best estimate of trajectory.

The Bathymetry Results

The gridded bathymetry produced aboard the RUDE show that results from the tightly integrated inertially-aided PPVRS technique using ellipsoidal altitude are superior to the tidally referenced bathymetry. Positional accuracies are greater by several orders of magnitude, and loading, dynamic draft, and tide effects are negated since the vessels vertical position is being accurately measured. The improved handling of dynamic draft can be seen in the difference surface where linear artifacts are present due to subtle changes in ship's speed as seen in Figure 10. Figure 11 is an image of the sand waves seen in the reference surface acquired by RUDE using PPVRS and Figure 12 is an image of the exact same location from the exact same angle created using the traditional method. Close examination reveals greater detail on the small objects within the survey areas as a result of the improved accuracy. Furthermore, the benefit of having positional accuracies on the order of 5 cm vs. 2 m is the increased ease with which the surveyor can isolate and identify errors in their system configuration, particularly in the offsets and biases. Previously a sign error in RUDE's configuration had introduced positional inaccuracies in the multibeam data and was evidenced by a general "unfocused" point cloud around distinct features on the seafloor. Through the use of the PPVRS process, the author was able to isolate this error and correct it. The result is more soundings properly positioned for a particular feature on the seafloor, which in turn means higher statistical validity for the feature in question.

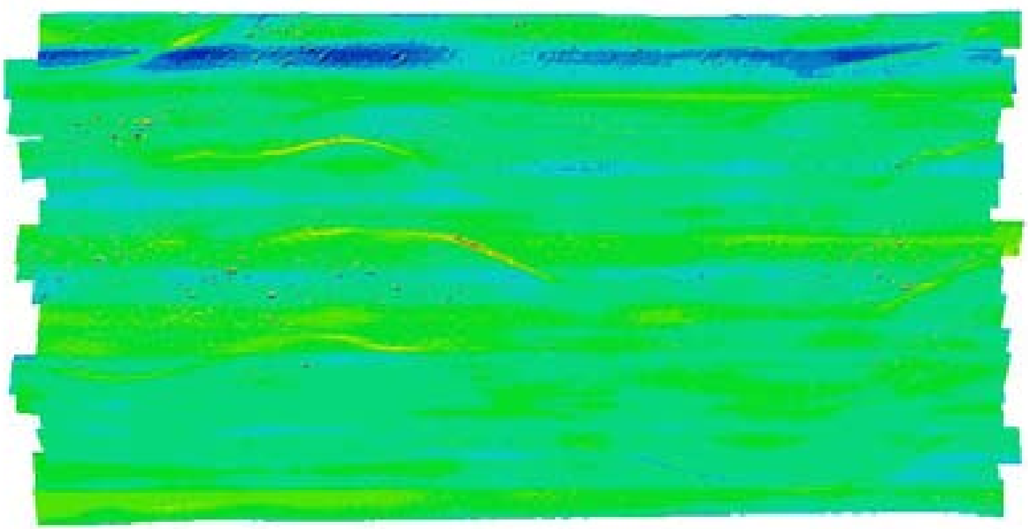

Figure 10: Difference surface showing the tidally referenced bathymetry minus the ellipsoidally referenced bathymetry.

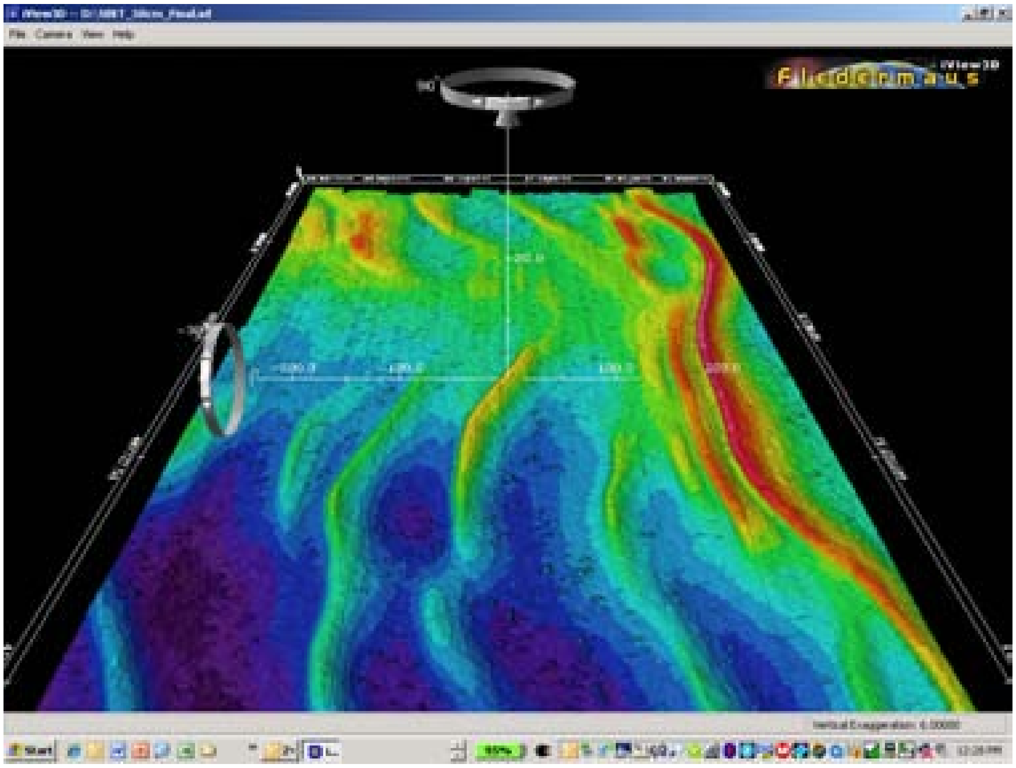

Figure 11: SBET Derived Sand Waves in Chesapeake

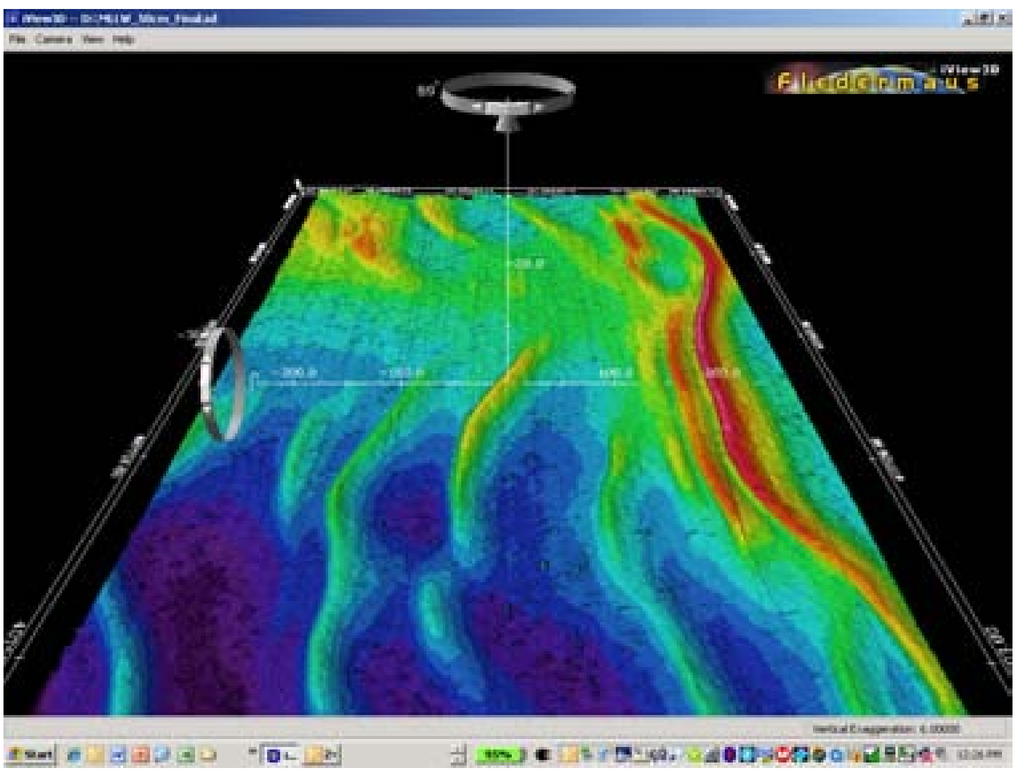

Figure 12: MLLW Derived Sand Waves in Chesapeake

Conclusions

The PPVRS process provides a logistically simple method, when compared with the traditional IAKAR mechanization, for achieving sub-decimeter accuracy without the need to install and maintain dedicated base stations. This is particularly true in locations with dense Continuously Operating Reference Stations such as the east coast of the continental United States where baselines of less than 100 km may be obtained. The overall process is simple and can be easily added to existing hydrographic data processing workflows without a significant decrease in processing productivity. And, the dividends gained from the increased accuracies far outweigh the small amount of time required to process the data. It is expected that survey companies will realize significant efficiency gains with PPVRS.

Much of Europe and North America, including the entire continental U.S. inland waters and near-shore areas, can now obtain centimetric positioning accuracy more efficiently by utilizing the existing reference station networks as we have described.

The PPVRS technique is commercially supported (we used Applanix POSPac) and offers the best solution for marine hydrographic surveying.

Author Biographies

LCDR Rick Brennan earned a B.S. in Civil Engineering from the Citadel in Charleston, South Carolina and a M.S. in Ocean Mapping at NOAA's Joint Hydrographic Center. With NOAA since 1992, has served on numerous assignments, including as Chief of NOAA's Hydrographic Systems and Technology Program, and as Commanding Officer aboard NOAA Ship RUDE.

LCDR E.J. Van Den Ameele, Chief of NOAA's Hydrographic Systems and Technology Programs of the Coast Survey Development Laboratory in Silver Spring, Maryland, USA, has worked in NOAA hydrography for 14 years, including aboard NOAA Ships MT MITCHELL, RAINIER, and most recently FAIRWEATHER, and in the Office of Coast Survey at the Atlantic and Pacific Hydrographic Branches.

Peter Canter earned his Master's Degree in GIS in 1980 followed by 25 years work experience in Marine positioning. He has worked as Marine Engineering Manager at Western-Geco (for 19 years), in Houston Texas and Oslo, Norway, on a wide variety of precise positioning projects. In 2002 Peter became Director of Marine Products at Applanix, in Toronto Canada. Peter can be reached at:

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