High Accuracy-Nationwide Differential Global Positioning System Test and Analysis: Phase II Report

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U.S. Department of Transportation
Federal Highway Administration

Research, Development, and Technology
Turner-Fairbank Highway Research Center
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FOREWARD

The Nationwide Differential Global Positioning System (NDGPS) Modernization Program is a multiagency effort to examine the viability of long baseline carrier phase differential correction techniques. Phase I of this program analyzed the broadcast of GPS observables from a single NDGPS site, Hagerstown, MD, to aid in determining the appropriate signal structure and compression techniques to support long range carrier phase operations. In Phase II a second facility near Hawk Run, PA, was installed, enabling multiple baseline carrier and code phase navigation solutions.

This first report verifies the original accuracy achieved (10 cm, 95 percent horizontal) and addresses several additional research objectives such as the use of multiple reference stations to achieve even more accurate solutions.

Toni Wilbur
Director, Office of Operations
Research and Development

Notice

Quality Assurance Statement

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16. Abstract

The High Accuracy-Nationwide Differential Global Positioning System (HA-NDGPS) program focused on the development of compression and broadcast techniques to provide users over a large area wit very accurate radio navigation solutions. The goal was achieve 0 cm in real time over 322 kilometer baselines.

The focus of the Phase II effort was on several aspects of HA-NDGPS to refine the navigation solution and demonstrate its usefulness. To that end this report provides a description and analysis of these tasks as well as conclusions reached. The tasks include:

- Provide a basic examination of the utility of using data from two reference stations.
- Develop and implement a prebroadcast integrity algorithm.
- Develop interface software for various brands of GPS receivers.
- Rewrite the modular software.
- Evaluate lower baud rate messages more than once every epoch.
- Demonstrate driver analysis based on the HA-NDGPS navigation solution.
- Examine multipath noise levels at the Hagerstown, MD facility.

The approaches and results provided in this report offer significant insight into the success of the overall HA-NDGPS program and its approach to meeting the needs of many users.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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CHAPTER 1—INTRODUCTION

BACKGROUND

When the Department of Defense (DoD) originally developed the Global Positioning System (GPS), it was a military system. GPS quickly became a tool for both military and civilian applications worldwide. Initially, DoD intentionally degraded GPS signals. To compensate, civilian engineers placed equipment at specific sites to determine intentional errors. These errors were then broadcast to users who would use them to correct their measurements. Because these corrections did not compromise security, Differential GPS (DGPS), as these corrections came to be known, flourished with little opposition from DoD. Because of this improved accuracy and greater reliability, the U.S. Coast Guard developed a version of DGPS for use in the marine surface environment.

The success of this system encouraged other government agencies to make such capabilities available in other parts of the country, particularly in the West and Midwest. This national extension is known as the Nationwide DGPS (NDGPS). The NDGPS is advertised as a 1- to 3-m system with 99.97 percent availability. The new vision, High Accuracy-NDGPS (HA-NDGPS), is designed to broadcast additional information from the same NDGPS network using a new carrier frequency to achieve fixed or moving centimeter (cm)- decimeter (dm)-level **accuracies** while maintaining as much integrity as possible.

Because greater precision is needed to support many of the safety enhancements envisioned for the future, the U.S. Department of Transportation, in conjunction with the Interagency GPS Executive Board, is supporting the development of HA-NDGPS to provide 10-cm horizontal and 20-cm vertical (95 percent) corrections to users. The addition of a diplexer and transmitter to the existing HA-NDGPS stations allows the existing infrastructure to broadcast the additional signal, keeping implementation costs low. In addition, the signal will be monitored to ensure it provides the accuracy needed to meet safety-of-life applications.

The HA-NDGPS program is implemented through funding made available from the Interagency GPS Executive Board. Participating agencies include the U.S. Department of Transportation's Federal Highway Administration and Federal Railroad Administration; the Department of Homeland Security's U.S. Coast Guard; and the U.S. Department of Commerce's National Geodetic Survey and Forecast Systems Laboratory.

In 2001 and 2002, HA-NDGPS was successfully demonstrated at the Hagerstown, MD site. All the target objectives were met and exceeded. The initial effort report, "Support of the System Test and Analysis Program for the NDGPS Modernization Program," was published July 12, 2002.

This report on Phase II activities documents the continuation of that effort with a new set of objectives. In general, Phase II objectives included signal analysis, data collection, data analysis, operational convenience and ease, multiple reference stations, integrity, format translation, bandwidth conservation, improved HA-NDGPS facilities and communication, and examples.

Phase II of the HA-NDGPS research and development project began March 14, 2003, with a meeting to schedule tasks, set priorities, and establish a plan to accomplish the government objectives. The government assignment was to secure spectrum approval; obtain demodulator receivers and antennas; provide hardware modifications to the Hagerstown, MD, and Hawk Run, PA, USCG NDGPS reference stations; install and operate the contractor's software at these sites; and manage the HA-NDGPS project.

Various segments of the real-time navigation systems for the robust positioning over long baselines were developed by a contractor, which had eight tasks:

- Task 1—Meet with other demonstration participants, communicate progress, and document findings. Throughout the year, the participants maintained weekly and often daily correspondence on the test and evaluation, development, and documentation. This final report completes this task.
- Task 2—Collect, process, and report information from the Hawk Run and Hagerstown stations. There were five developmental subtasks:
  - Pretest installation**,** configure a new modulator program**,** and update GRIM™ (GPS Receiver Interface Module) with transmission control protocol/Internet protocol (TCP/IP) at Hagerstown and Hawk Run.
  - Implement modulator feedback to GRIM.
  - Implement Restricted Active Mode (R.A.M.) at Hagerstown and Hawk Run.
  - Gather broadcast GPS data from Hagerstown and Hawk Run simultaneously and process the information at an in-between user site.
  - Describe the algorithm used to combine independent solutions from Hagerstown and Hawk Run.
- Task 3—Develop and implement a prebroadcast integrity algorithm. There were three subtasks:
  - Detect errors in the GPS constellations and its broadcasts**.**
  - Discuss methods of inserting integrity information into the data stream**.**
  - Describe possible techniques and algorithms**.**
- Task 4—Develop interface software for multiple brands of GPS receivers. There was one subtask:
  - Convert the demodulated output format into Radio Technical Committee for Maritime Services Special Committee 104 (RTCM-SC104) type 18/19 compatible with existing user GPS equipment and deliver the source code.
- Task 5—Rewrite the modulator interface. There were two subtasks:

  - Rewrite the existing modulator interface to implement a remote control capability through a TCP/IP interface and deliver the source code.
  - Add limited commands to control GPS receiver parameters such as data rate and elevation mask and deliver the source code.
- Task 6—Evaluate a low-baud-rate message such as 100 baud to 300 baud and user processing based on a HA-NDGPS data rate less than once every epoch.
- Task 7—Collect observations on one or more highways in real-time kinematik (RTK) mode to demonstrate driver analysis. This task had two subtasks:
  - Collect data for mapping one or more highway segments.
  - Compare the driver's control of the vehicle.
- Task 8—Consider studying noise levels and possible noise reduction at the Hagerstown site. This task had two subtasks:
  - Locate a GPS antenna high above possible nearby multipath sources and compare the cleanliness of the measurements there with measurements from current NDGPS equipment.
  - Use identical models of the same antenna at both the reference site and a nearby user site to gather observations and fix the integers to establish the level of site cleanliness.

This report follows the order of the remaining tasks (after Task 1) listed in this introduction.

CHAPTER 2—PHASE II TASK REPORTS

TASK 2: COLLECT, PROCESS, AND REPORT INFORMATION SIMULTANEOUSLY FROM THE HAWK RUN AND HAGERSTOWN STATIONS

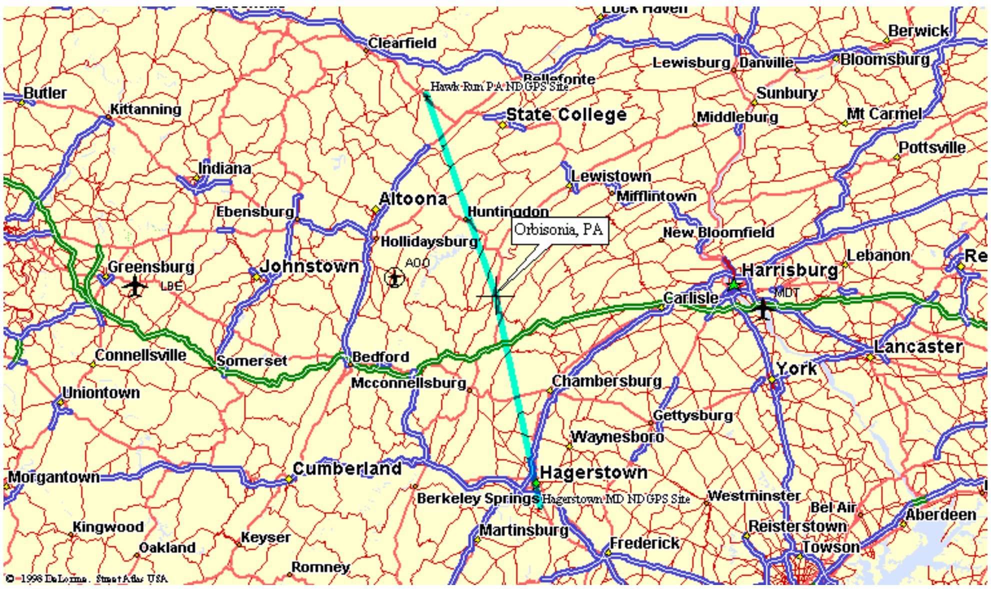
Task 2 had several aspects. One was to add a second HA-NDGPS reference station. Subtask 2a was to conduct a pretest installation and configuration of a new modulator program and GRIM with TCP/IP at the Hagerstown and Hawk Run stations. The TCP/IP feature had a role in this task as well as in Task 5. It added to the remote control capability, eliminating the need for two modulator computer communications ports. Subtask 2a also updated the Hagerstown HA-NDGPS station with the latest reference station software. The main three features this upgrade added were to eliminate the two communication ports plus the features described in subtasks 2b and 2c.

Subtask 2b was to implement modulator feedback to GRIM. As originally implemented at a HA-NDGPS reference station, the GRIM serves two distinct functions. First, it interfaces the GPS receiver to the device or software that needs data from the receiver. In this capacity, it collects GPS observables from the existing GPS receiver in the NDGPS equipment hut. Second, it compresses and packages the observables for the modulator. Unfortunately, the initial modulator software and the modulator computer did not provide an indication that more data was needed until the modulator buffer was empty. Consequently, the messages began to fall further and further behind because the operating system did not allow immediate access to the modulator buffer. When the modulator buffer was empty, it would send out a message to that effect; but because of the non-deterministic operating system, the request could not be serviced instantaneously, and a few milliseconds would be lost. These small losses would accumulate unless the bandwidth was intentionally and artificially underutilized by planning unused bits or wasted bandwidth. Under Phase II, a modulator feedback feature was added. This feature allows software to determine the available bandwidth and allows the bandwidth to be efficiently utilized. GRIM provides many other functions such as data archival, data sharing, and user demodulation.

Subtask 2c was to implement R.A.M. at Hagerstown and Hawk Run. Task 5 requires TCP/IP for remote control, including a feature to modify reference station GPS receiver parameters. In addition, the GRIM software has a passive mode so that USCG GPS receiver settings cannot be changed accidentally. This R.A.M. feature gives official USCG technicians and the U.S. Coast Guard’s Navigation Center (NAVCEN) operators the ability to modify a restricted set of GPS receiver parameters, while preventing others from being changed. R.A.M. has been implemented at Hagerstown and Hawk Run.

Subtask 2d was to gather broadcast GPS data from Hagerstown and Hawk Run simultaneously and process the information at an in-between user site.

The researchers traveled to Hagerstown, MD, and Hawk Run, PA, to reset Hagerstown and Hawk Run and reconfigure the sites to operate at 1 Hz (Hertz) and to broadcast one of the highly compressed XCOR formats. After completing this configuration change, the researchers returned a few days later (May 10, 2004) to collect data from HAG1 (the active Hagerstown antenna element for HA-NDGPS) and HRN2 (the active Hawk Run antenna element for HA-NDGPS) simultaneously. The researchers selected Orbisonia, PA, on Route 522, shown in figure 1, because it is more or less halfway between HRN2 and HAG1 and 48 miles from both.



Map used with permission from DeLorme..

Figure 1. Map of South-Central PA showing Hawk Run, PA; Hagerstown, MD; and Orbisonia, PA. The latter test site is approximately 80 kilometers (km) from the reference stations.

At Orbisonia (designated R522), the researchers demodulated data from HRN2 and HAG1 using two demodulators. The user GPS antenna signal was split two ways, using an antenna splitter device, and then fed into two different laptop computers. One of the laptops received demodulated data from HRN2; the other received demodulated data from HAG1. Both laptops ran the application program, DynaPos.exe™, in kinematic mode to achieve two separate RTK solutions for the user. During real-time processing, coordinates from HRN1 rather than HRN2 were used. Nevertheless, nearly correct baseline vector results were computed, although the results were offset. Therefore, this solution was reprocessed using the correct Hawk Run coordinates. Such reprocessing does not improve the accuracy because the data used in reprocessing was exactly the same data as that received in real time. This allowed the inadvertent setting to be corrected rather than requiring collection of new data. In other words, the reprocessed results are exactly the same as those that would have been achieved in real time if the correct reference station coordinates had been used.

HRN2, R522, and HAG1 are along a more or less north-south line, leading to the expectation of some systematic error cancellation in the north-south component when HAG1R522 and HRN2R522 are combined in a weighted average. Likewise, there would be little expectation of systematic error cancellation in the east-west component. The height error from HRN2 to R522 can be opposite that of the height error from HAG1 to R522 when there is a temperature and humidity gradient from HAG1 to HRN2. Consequently, the combined solution can benefit from error cancellation. An example of that would be a west-to-east moving thunderstorm. Such conditions were not observed on the day of the test.

Figures 2, 3, and 4 show plots for the north, east, and height components respectively. In all cases y = 0.0 represents geodetic truth. While the data were collected at a fixed location, the measurements were processed with medium dynamics; the Kalman filter had no knowledge that the site was static and assumed the antenna was moving several meters every second. Processing static data as kinematic with medium dynamics is a well proven and theoretically correct approach often used when it is not convenient to run a course and set up an additional local truth reference site.

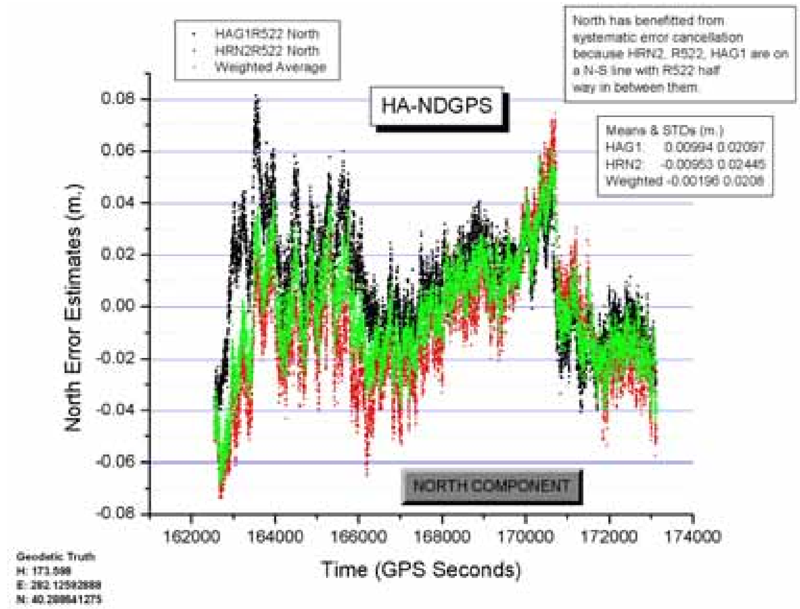


Figure 2. North component determined from HAG1 (black) and HRN2 (red), and the weighted average solution (green).

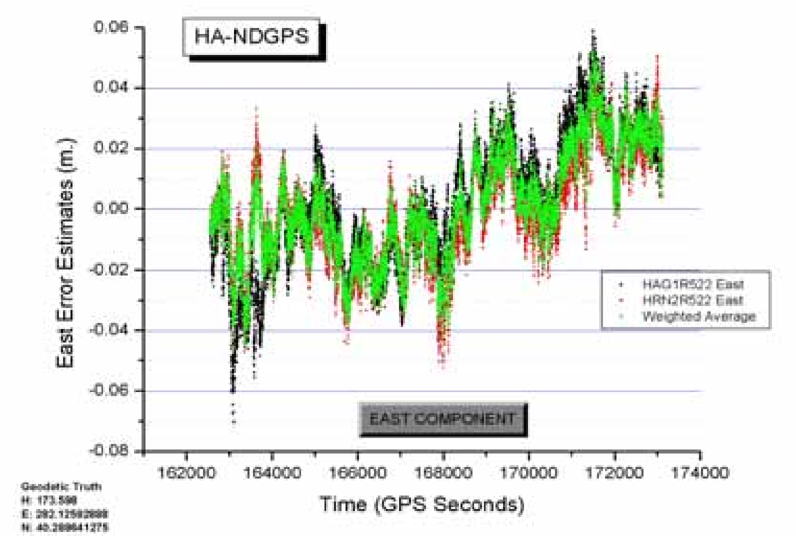


Figure 3. East component determined from HAG1 (black) and HRN2 (red), and the weighted average solution (green).

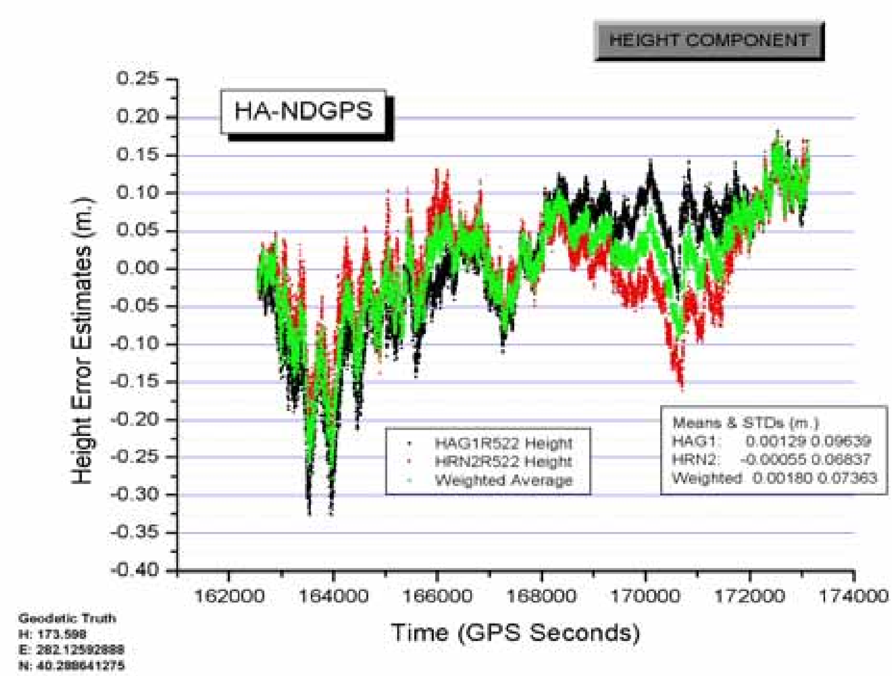


Figure 4. Height component determined from HAG1 (black) and HRN2 (red), and the weighted average solution (green).

The north-south component benefited from the weighted average of the two solutions. This can be seen in the north-south plot as the weighted average solution appears to be closer to the truth. The east-west component in figure 3 did not appear to benefit from the combined solution; however, figures 5, 6, and 7 indicate both north-south and east-west component improvement. Thus, the benefit from averaging random errors might be greater than the benefit from systematic error cancellation. On the test day, height did not seem to benefit either. Note that near the end of the height plot Hag1R522 increased while HRN2R522 decreased. This opposite behavior becomes exaggerated in passing thunderstorms and hot, humid conditions where there is a gradient; a two-reference-station solution can reduce this significantly; however, this particular day was warm and calm.

This particular data experiment was almost too good to expect much benefit from weighted averaging. Normally there is a small random multipath reduction benefit from averaging user solutions from multiple reference stations. This is useful when baselines are short and multipath is the predominant error source. Every reference station to user solution will have a different reference station multipath; with enough reference stations, it might be possible to eliminate reference multipath. Unfortunately, this does nothing to reduce user multipath; therefore, after two or three reference stations are applied, the reference station multipath component becomes insignificant. In summary, there are both random error and systematic error components to reduce.

There is a more important error type to eliminate if possible—systematic error. For dual frequency processing, ionospheric delay errors are largely eliminated and tropospheric errors are usually the primary systematic error source. On the other hand, for single frequency DGPS, ionospheric path delay error is an important systematic error that can be reduced using multiple reference stations. Systematic broadcast orbit error contributions to position determination are on the order of 1 cm per 50 km, perhaps less, small when compared to the systematic error caused by tropospheric path delay (tropo), particularly in the user's vertical component. Thus, a primary reason to combine dual-band solutions based on different reference stations is the benefit from systematic tropospheric delay error cancellation.

For completion, figures 5, 6, and 7 show the east-north horizontal X-Y plots. These plots contain the same information as the north versus time and east versus time plots shown in figures 2, 3, and 4, but here they are presented in a more traditional manner where time is not explicit. The combined solution yields the better of the two solutions, seen in the tighter scatter plot in figure 7.

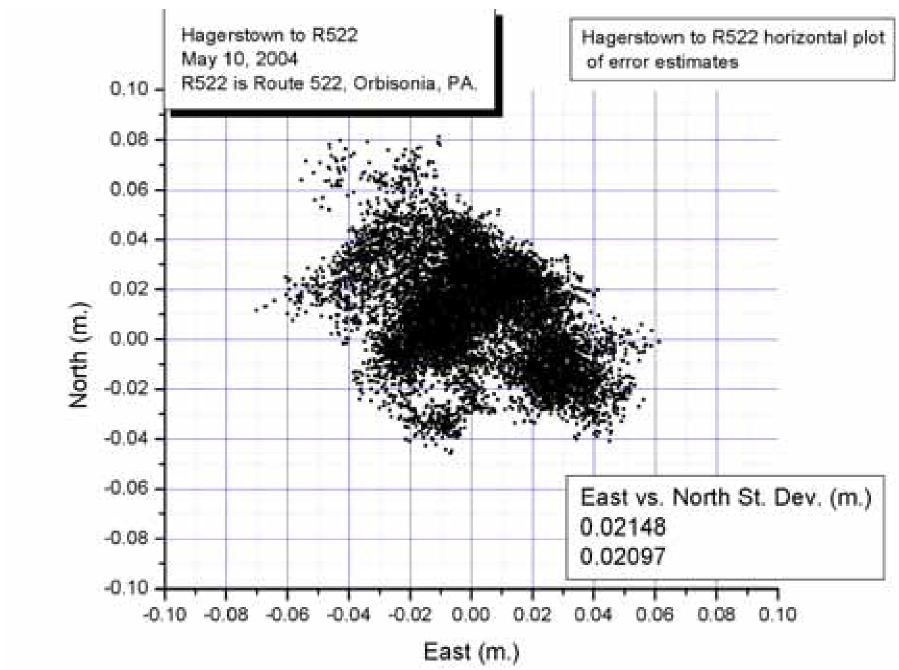


Figure 5. North component versus east component cross plot determined from HAG1.

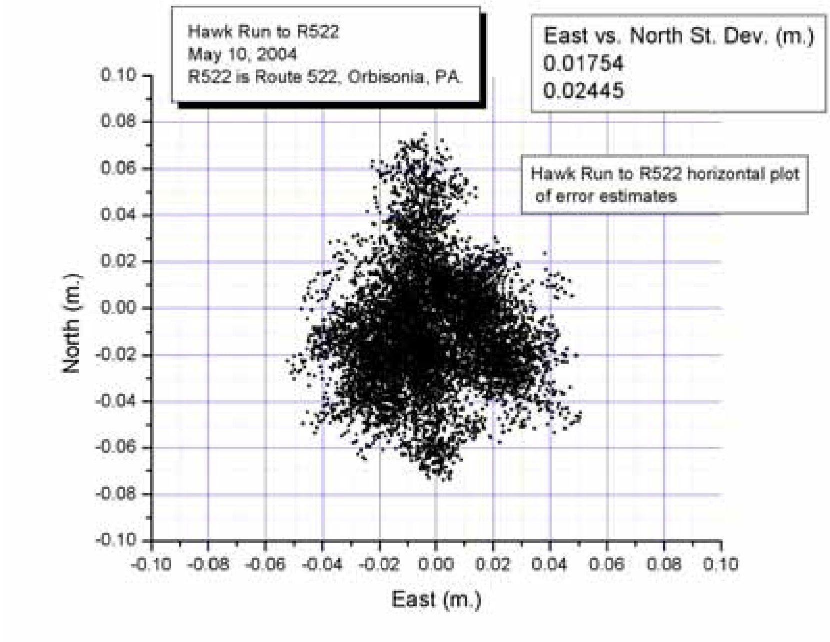


Figure 6. North component versus east component cross plot determined from HRN2.

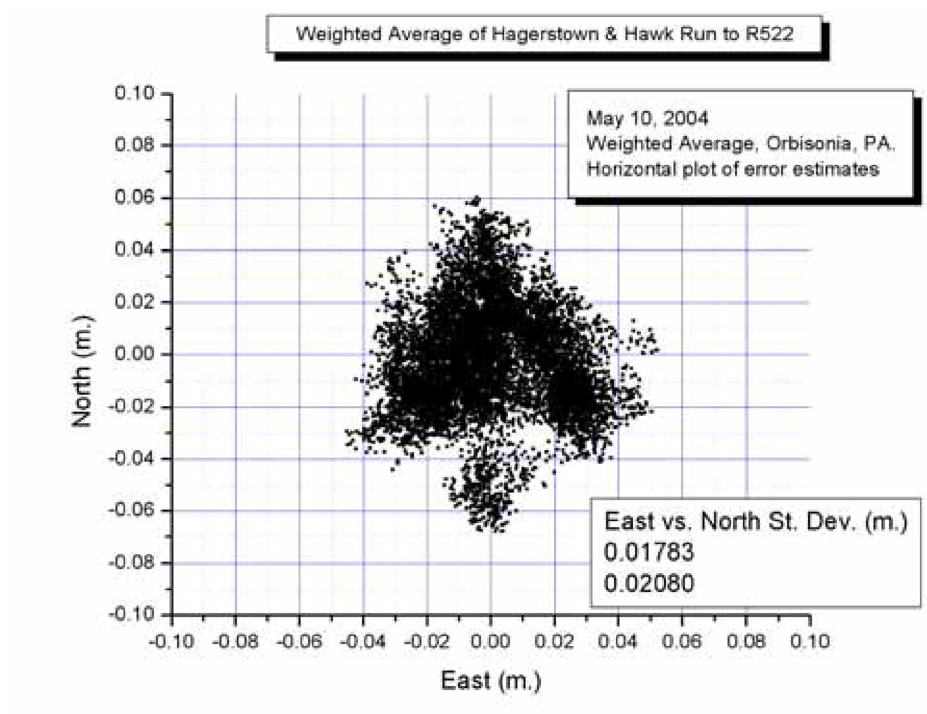


Figure 7. North component versus east component cross plot of HAG1 HRN2 combined.

The plot in figure 7 has somewhat better scatter properties resulting from the combination of the HAG1R522 and HRN2R522 plots. Under certain weather conditions, the combining of multiple simultaneous solutions can have an even greater improvement than experienced in this example.

Subtask 2e was to describe the algorithm used to combine independent solutions from Hagerstown and Hawk Run.

HAG1R522 and HRN2R522 solutions were combined as follows:
Let X_1, Y_1, Z_1 represent the HAG1R522 solution at Orbisonia, PA.

Let X_2, Y_2, Z_2 represent the HRN2R522 solution at Orbisonia, PA. For each of these six random variables, there is an associated standard deviation (i.e., σ) output from the two Kalman filters. The following equations describe the algorithm used to combine solutions:

$$x = \frac{(\frac{x_1}{\sigma_{x_1}}) + (\frac{x_2}{\sigma_{x_2}})}{(\frac{1}{\sigma_{x_1}^2}) + (\frac{1}{\sigma_{x_2}^2})} \qquad (1)$$

$$y = \frac{(\frac{y_1}{\sigma_{y_1}}) + (\frac{y_2}{\sigma_{y_2}})}{(\frac{1}{\sigma_{y_1}^2}) + (\frac{1}{\sigma_{y_2}^2})} \qquad (2)$$

$$z = \frac{(\frac{z_1}{\sigma_{z_1}}) + (\frac{z_2}{\sigma_{z_2}})}{(\frac{1}{\sigma_{z_1}^2}) + (\frac{1}{\sigma_{z_2}^2})} \qquad (3)$$

This algorithm does a fair job of combining solutions and giving the better solution component more weight. (A simple alternative that could be used, but which is generally not recommended, is to average the solutions for all the participating reference stations.

This simple solution will be reasonable as long as all the Position Dilution of Precisions (PDOP) are in reasonable agreement; however, if the PDOPs differ greatly, this procedure should be avoided.) The combining of standard deviations to achieve a single standard deviation is more problematic because the correlated nature of systematic errors has not been developed. The current method is simply to take the smaller of the two standard deviations. Combining solutions from two reference stations yields a 13.4 percent reduction of random component error, which continues as reference stations are added. With enough reference stations, this random component reduction can be as great as 29.3 percent. For traditional code DGPS users, this would be welcome because code multipath can be several decimeters to meters in magnitude. For carrier-based RTK users, reduction of this relatively small component is not of great help.

On the other hand, the code plays an initial role in RTK, so that multiple reference stations speed up initial convergence because of this random reduction factor. After steady-state is reached, reduction of reference station carrier multipath is not as important as systematic error cancellation of tropo, iono, and orbit error. As stated above, orbit error is quite small, and iono error is essentially eliminated by forming iono-free combinations of measurements. This leaves tropo error as the most problematic systematic error source. Activities are underway at National Oceanic and Atmospheric Administration (NOAA)/National Geodetic Survey (NGS), USCG/Command and Control Engineering Center (C2CEN), and NOAA/Forecast Systems Laboratory to develop real-time data that can be broadcast to RTK users to reduce the tropo path delay errors. This can take the form, for example, of wet zenith delays relative to the broadcast site. (Note: Reference station-to-user distance weighting was not used in the combining algorithm, and it might be a consideration, depending on the Kalman filter assumptions.)

The photograph in figure 8 shows the configuration of the van used in this test. Two demodulator antennas were used—one received HAG1 broadcast XCOR messages, the other received HRN2 broadcast XCOR messages. The van's local GPS antenna, located in the back on the driver's side, was fed to a signal splitter and subsequently input to separate laptop computers. The fourth antenna shown in the photograph, located just above the driver, is unrelated to this test.

Figure 8. Antenna configuration on van used for collecting data broadcast from HAG1 and HRN2 simultaneously. The van is equipped with one GPS marine antenna and two demodulator receiver antennas.

TASK 3: DEVELOP AND IMPLEMENT A PREBROADCAST INTEGRITY ALGORITHM

Task 3, to develop and implement a prebroadcast integrity algorithm, had several aspects.

Subtask 3a was to detect errors in the GPS constellations and its broadcasts. The coordinates of the reference site are ostensibly known. In practice, this was a minor point of confusion during the research and development phase. It is possible to broadcast data from HAG1 but wrongly supply coordinates for HAG2. This is just one integrity reason why the local point-position solution should be checked when the configuration of the HA-NDGPS reference station is changed. While point-positioning solutions are not highly accurate, it is usually possible to discriminate between reference station sides by inspecting the GRIM point solutions as part of any setup procedure.

Adding reference station code corrector-type residuals for integrity is a possible solution. Generally a residual is the difference between something expected and something actual. For example, it is possible to compute a GPS range based on a geodetic location and a satellite location. The actual measurement may differ by a few centimeters, which is the residual, or the left over amount. Large residuals indicate poor measurements, poor orbits, or incorrect geodetic coordinates, or other problems. Small errors are a necessary but not sufficient condition for integrity. Subtask 3b begins to address this issue. The site technician or the control station operator must verify that code residual errors are within specified tolerances.

As an example, compare the two screen shots shown in figures 9 and 10. In figure 9, the correct coordinates were used; in figure 10, the wrong coordinates were used. The intentional error in figure 10 was 100 meters in each component. There are large positional errors (top three lines) and large residuals (lower lines below section divider line) caused by wrong coordinates.

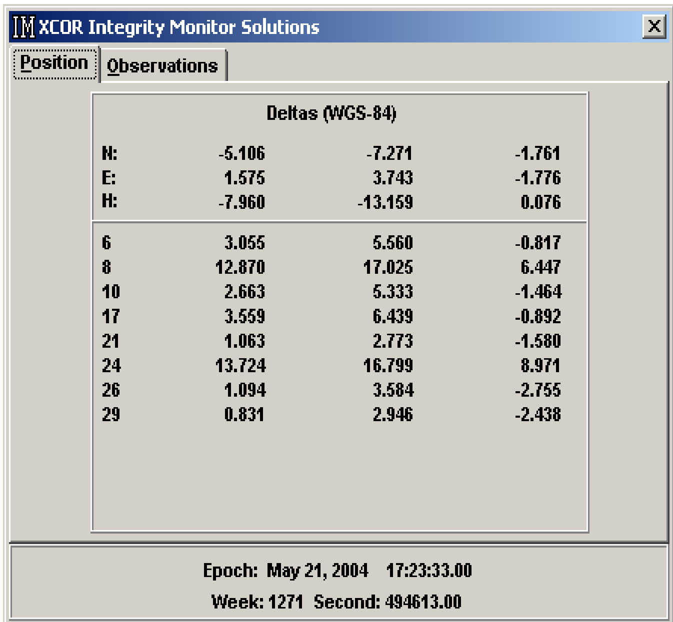


Figure 9. An example screen shot of prebroadcast positional integrity with the correct site coordinates.

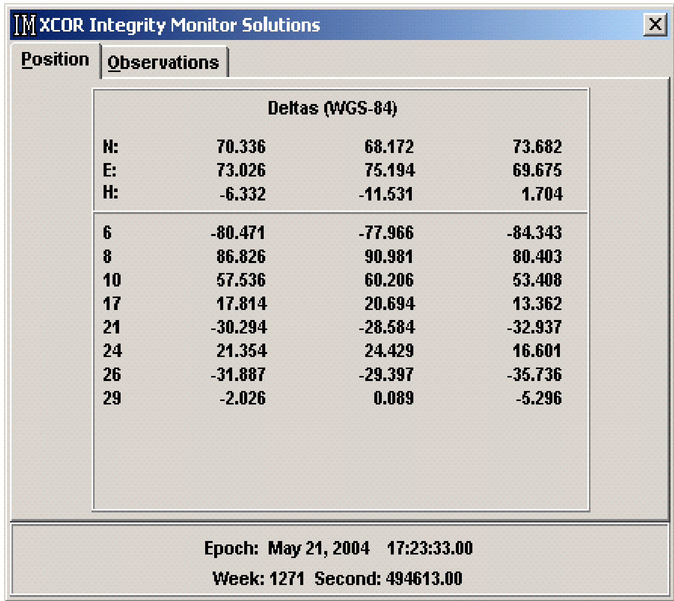


Figure 10. An example screen shot of prebroadcast positional integrity with the wrong coordinates.

These large residuals indicate an error with the reference station coordinates. This could be extended to a differential check by using data from a second NDGPS GPS receiver as a prelude to accepting the modulated message for transmission to users. In differential mode, the code DGPS residuals would be about 1 m and NDGPS Integrity Monitor **(**IM) residuals are about 1 meter. In local RTK differential mode, all of the two-station, two-satellite carrier double differences are expected to about 1 cm.

An unpack feature has also been added to the message formation process. After forming XCOR messages to be broadcast to users, but before the actual broadcast is consummated, the software unpacks the message and compares it with the original data.

Figure 11 shows a comparison of original data with the unpacked data at the reference station before broadcasting the data to users. This comparison allows the reference station to evaluate what will be sent to the user. Unpacking the message before it is broadcast provides the opportunity to catch a problem and prevent the transmission of bad data.

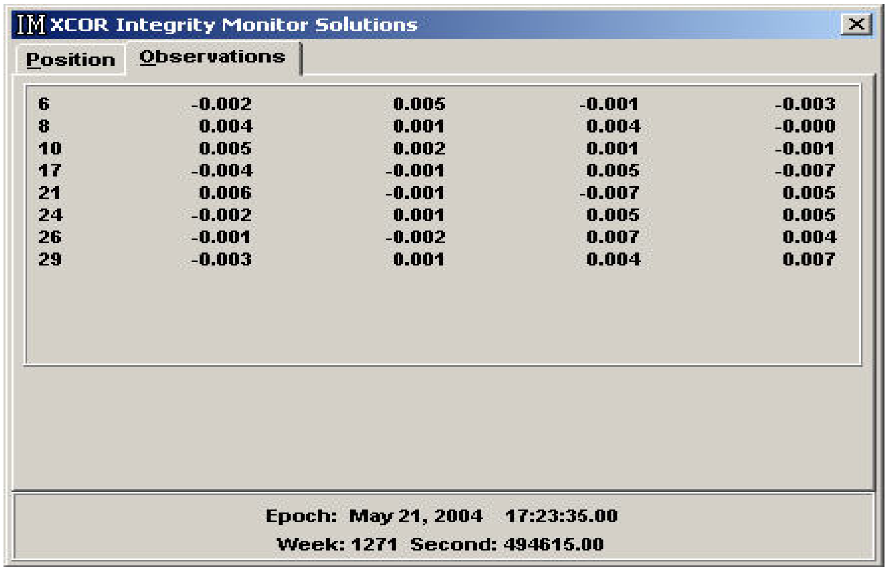


Figure 11. An example screen shot of prebroadcast measurement integrity. The four columns to the right show the difference between raw measurements and what is about to be broadcast.

Subtask 3b was to discuss methods of inserting integrity information into the data stream.

One method that has been considered for inserting integrity information into the data stream is to provide a single bit to indicate an integrity message in the data stream at a fixed and known location. The integrity message length would be variable to allow expanded integrity messages. Four to eight bits would be required to accommodate a suite of possible messages, including some combinations. Following are some possible messages:

0—Unreliable; do not use

1—Test and evaluation use only.

2—Code and carrier positioning use.

3—L1 only code navigation use.

4—Multifrequency code navigation use

5—General code and carrier navigation use.

6—Change of site coordinates, caution.

Subtask 3c was to suggest possible techniques and algorithms. This includes unpacking messages before transmission and verifying that unpacking returns the original data. It also includes verifying that one-way code residuals are small. It also includes verifying that point-positioning solutions agree with a priori known reference station coordinates. This is similar to subtask 3a.

Integrity monitoring could be dramatically enhanced by exploiting the availability of the NDGPS IM receiver or any other local receiver. Even a non-local GPS receiver could be used through network scenarios. The data from a second receiver could be ingested into the reference station software for code and carrier positioning in RTK mode. If the second receiver is on the same reference station site (for example, within 100 meters of the primary reference receiver), then the baselines are short and individual solutions could be performed for each data type. Currently that would comprise R1 and R2 code solutions and L1 and L2 carrier solutions. The carrier solutions could be of two varieties—float and fixed. With these solutions, the correct vector and second site coordinates would be necessary conditions, or there is a problem such as the sites might be confused. The code solutions would be accurate at the 1-meter level; fixed RTK solutions would be accurate at the 1-cm level on an epoch independent basis. Float RTK solutions would converge slowly like a distant user. Residual computations can provide an equally powerful validation of the data. The discussion of subtask 3a also addresses residuals.

Task 3 covers four types of integrity solutions: point positioning, code differential, carrier differential, and IM single-epoch solution.

TASK 4: DEVELOP INTERFACE SOFTWARE FOR MULTIPLE BRANDS OF GPS RECEIVERS

Task 4 had several aspects.

Subtask 4a was to convert the demodulated output format into RTCM 18/19 compatible with existing user GPS equipment.

A new software module, HAtoRTCM.EXE, translates the GRIM-demodulated XCOR message into messages RTCM 18 and 19. These messages are compatible with existing RTCM 18 and 19 compatible user equipment.

The outputs of this module were studied in two different ways. In the first effort, RTCM 18 and 19 messages were converted into Receiver Independent Exchange (RINEX) format and compared with the original data before RTCM 18 and 19 formation. These data compared correctly.

The second and more practical method of testing was to output these RTCM 18 and 19 messages from a PC comport into RTCM 18/19-capable user GPS equipment. For this test, existing dual frequency GPS receivers were used. The receivers needed to be configured according to the user manual. This specific receiver has an installed "Carrier Phase Differential Remote RTK" option, ideal for such a test. The receiver RTK positioning results were output to a different RS-232 port and returned to the original PC that formulated the RTCM messages, which then were sent to the receiver. The returned results were gathered using the data-capture function of a terminal emulation program such as the Thales Navigation's Micro-Manager™ Pro, Remote32 software, or Terminal Window program. Any commercial terminal window program could be used to capture this data as well. The plotted captured data are shown in figure 12.

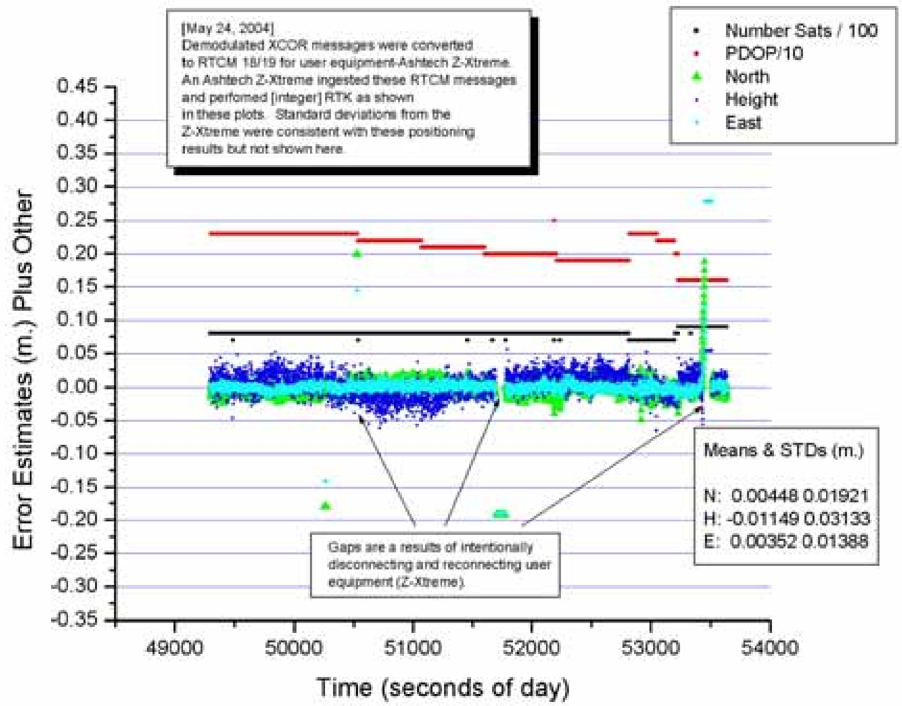


Figure 12. Demonstrated proof that GRIM to RTCM 18/19 works.

These results show that RTCM 18 and 19 capable user GPS receiver equipment accepted these messages and performed RTK positioning. To test the capability somewhat further, the RTCM 18/19 stream was intentionally disconnected and reconnected. These breaks show up in the plot in figure 12. The number of satellites (divided by 100) and the PDOP (divided by 10) are included in the plot.

In the discussion of Task 4, there is only one method of access to the HA-NDGPS signals: demodulator receiver to GRIM, GRIM to HAtoRTCM.EXE, HAtoRTCM.EXE to user GPS receiver, and GPS receiver output to user application.

There are currently two other methods available for test and evaluation of HA-NDGPS broadcasts. The first is GRIM RINEX output. GRIM records the real-time HA-NDGPS messages bit for bit in a trap file. Simultaneously (but optionally) GRIM will convert these compressed messages to user-friendly text RINEX files. While the RINEX files would be processed in post-mission mode, this approach enables all users to have a role in the test and evaluation phase.

The next method of access concerns application developers. A GRIM developer's kit is available from The XYZs of GPS. The kit provides direct and real-time access to the demodulated and decompressed broadcast message data, without the need to convert to an intermediate standardized format such as RTCM 18/19.

In summary, currently three methods are available for test and evaluation of HA-NDGPS messages.

TASK 5: REWRITE THE MODULATOR INTERFACE

Task 5 had several aspects.

Subtask 5a was to rewrite the existing modulator interface to implement a remote control capability through a TCP/IP interface. The modulator interface was rewritten so that the HA-NDGPS reference station software could be controlled from NAVCEN. At the time of this report, the complete suite of network equipment ordered by the government had not arrived, so testing of the software had to be carried out using a temporary network. The testing was fully successful.

The remote control capability allows substantial configuration control of the HA-NDGPS reference station. Most changes that currently require a visit to the site will be possible from NAVCEN. For the Hagerstown site, this will be convenient; for the Hawk Run site and planned additional sites further west, this will prove to be indispensable. These commands include software and hardware resets, broadcast measurement definitions and bit rates, and more. All commands are documented in the High Accuracy Control Program (HACP) manual; there are several dozen commands. The following command and response syntax has been excerpted from the HACP manual:

The HACP TCP/IP protocol is an NMEA-like messaging structure that is ASCII based (and is similar to that used by the GPS receivers). The general forms are:

Query

$PXYZQ,*type*[*XXXXXXXX] <CR><LF>

Response

$PXYZR,*type[,data]*[*XXXXXXXX] <CR><LF>

Command

$PXYZS,*type[,data]*[*XXXXXXXX] <CR><LF>

Notes: 1. Those items enclosed in "[" and "]" are optional.

2. <CR><LF> represent the carriage return/line feed sequence.

As a protocol rule, every command that begins with $PXYZS,*type* will have some type of response. Some commands will have a direct response with the command name in them. Others will have either a $PXYZR,ACK,type (for acknowledge), $PXYZR,NAK,*type* (for negative acknowledge), or $PXYZR,UNS,*type* (for unsupported "*type*" message).

Note: In the protocol descriptions that follow we do not show:

1) The trailing <CR><LF> sequence that follows each message.

2) The optional 32-bit CRC (in the form of *XXXXXXXX).

In this Phase II effort, the command set is extensive and allows an operator to query and command essentially all aspects of the HA-NDGPS operation. Following are a few specific examples:

What version are you?

Query: $PXYZQ,RID

Response: $PXYZR,RID,*s1,s2,s3*

GRIM, what is your status?

Query: $PXYZQ,PRG,GRIM

Responses: $PXYZR,PRG,GRIM,RUN

GRIM is currently running

$PXYZR,PRG,GRIM,NORUN

GRIM is present but not running.

$PXYZR,PRG,GRIM,STOPPING

GRIM is present, it's running, but has been commanded to stop.

$PXYZR,PRG,GRIM,ERR

Cannot find GRIM program.

Subtask 5b was to add limited commands to control GPS receiver parameters (e.g., data rate and elevation mask).

In addition to controlling the HA-NDGPS software to configure the broadcast message, changes may be required for associated GPS receiver hardware configuration. Examples of parameter that can now be commanded from NAVCEN are the elevation mask and the observation epoch spacing, as illustrated here:

What is the recording interval?

Q: **$PXYZQ,GNI,REC_INT**

R: **$PXYZR,GNI,REC_INT,*current_interval***

C: **$PXYZS,GNI,REC_INT,*new_interval***

What is the elevation mask?

Q: **$PXYZQ,GNI,EL_MASK**

R: **$PXYZR,GNI,EL_MASK,f*1***

C: **$PXYZS,GNI,EL_MASK,f*1***

Following is an example of an operator query for station coordinates, a status response, and a reset for new values:

Q: **$PXYZQ,GNI,COR_REF_POS**

R: **$PXYZR,GNI,COR_REF_POS,d*1,f1,f2,f3***

C: **$PXYZS,GNI,COR_REF_POS,d*1,f1,f2,f3***

The software developed to accomplish Task 5 includes an updated modulator interface and HACP. HACP is the primary software to handle configuration changes and distribute those changes to other software to carry out the changes

TASK 6: EVALUATE A LOW BAUD RATE MESSAGE AND PROCESSING

Task 6 had several aspects.

Subtask 6a was to collect data at reference station REMD (at 1 Hz) in Dickerson, MD, and user location MAST (also at 1 Hz) in Dover, DE. The distance between the two stations was approximately 180 km. The data were processed in RTK float mode to achieve decimeter heights and half-decimeter horizontals. The data used were full dual carrier and code observations such as those broadcast from HA-NDGPS reference stations.

The first RTK run (1 Hz; 1 Hz) was compared with a priori known truth (millimeter accuracy). The kinematics assumed in all runs were set at 1 m/s in all components, known as “velocity surprise” because it represents how much the velocity can change in one second. This level would be satisfactory for a car traveling on the highway or a hydrographic survey vessel on the Chesapeake Bay. The actual kinematics are unimportant because this is a study of errors created at the static reference site. Data were reprocessed using 5-second REMD epochs and 1-second MAST epochs.

Of interest is how the trajectory changes as a result of the thinning of the reference station data (REMD) caused by a reduction in bandwidth. For example, when the bandwidth changes from 1,000 bits per second (bps) to 200 bps, the broadcast message takes 5 times as long to arrive, and it cannot be applied for user processing until 5 seconds after the data were observed. In addition, the user must continue to use the latent data for another 4 seconds. (i.e., use the same reference station broadcast measurements, predicted forward, for 4 additional seconds.) In a typical RTK scenario, a user would use the data from 5 seconds to 9 seconds old. If a broadcast message is corrupted by background noise and needs to be discarded by the user, use of the data would continue beyond 9 seconds old, up to 14 seconds old. After a gap, the full accuracy is returned immediately.

This is considered a typical RTK scenario. Other scenarios are available to users, depending on the mission. For example, it is possible for a user to hold off processing by 5 seconds and process only time-aligned data. Another example is to process with 5 seconds of latency and set an inertial unit. In this scenario, the expectation is that the inertial unit would be more accurate than GPS.

Figure 13 shows the percentage of data collected and its availability for use. Between 0 seconds and 4 seconds, the data are broadcast to the user, who must wait nearly 5 seconds for the bit-by-bit broadcast to be completed and the data packet to be received and demodulated before it can be exploited. The user cannot use this packet until the entire packet has been received because the message in full must pass the parity check before the user can trust it. The full packet needs to be gathered and recognized, at least in the current design, before sending it to the parser and the interpreter, all before passing it to the user application. In the figure, the data collected at second 0 did not begin to be used by the user application until second 5; the user continued to use the 0-second data until 9 seconds. The figure shows a 1-second user scenario. If the user was instead a 10 Hz user, the data would be used until 9.9 seconds, more or less. By second 10, the measurements collected at second 5 have fully arrived and can now be exploited for the subsequent 5 seconds.

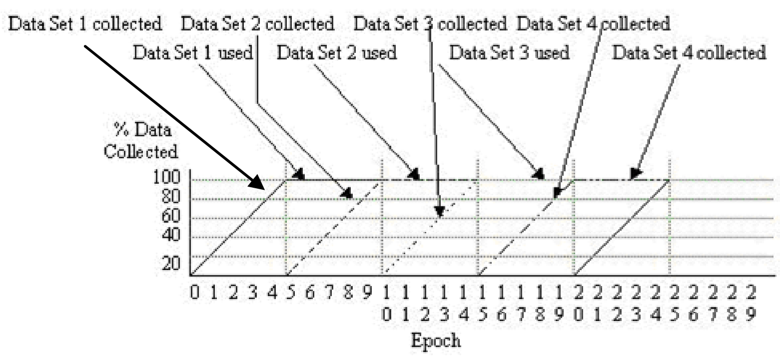


Figure 13. Percentage of data collected 0 to 10 seconds for 25 epochs.

Figure 14 shows a comparison of the RTK solution (180 km) with millimeter truth after an initial convergence period, which is not shown. The north-south and east-west components are better than 5 cm where the height is good to about 1 dm. This "1-second REMD, 1-second MAST" RTK solution is referred to throughout the Task 6 discussion, giving a basis of comparison for the lower-bandwidth (thinned) scenarios that follow. Figure 15 shows a comparison of the 1-second REMD, 1-second MAST (1,000 bps) RTK solution (180 km) with the 5-second REMD, 1-second MAST (200 bps) RTK solution.

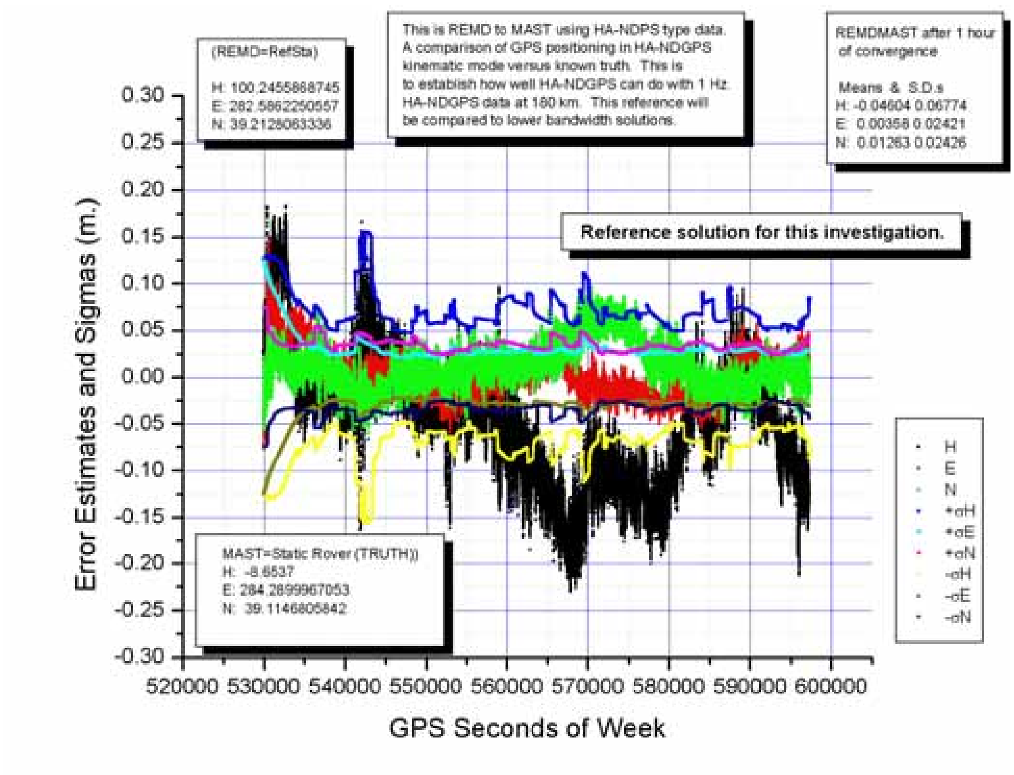


Figure 14. Expected HA-NDGPS performance at 180 km.

Figure 15 represents the change that results solely from the reduced bandwidth rather than the error penalty suffered when compared with millimeter truth. The additional error caused by the bandwidth reduction and the associated increased latencies is about 0.25 dm. Table 1 compares this 5-second scenario against millimeter truth. Comparing these statistics with the 1-second broadcast scenario in figure 14 (i.e. means plus standard deviations) shows there is no significant accuracy performance degradation when data are broadcast based on 5-second epochs. (The means and standard deviations are essentially the same.)

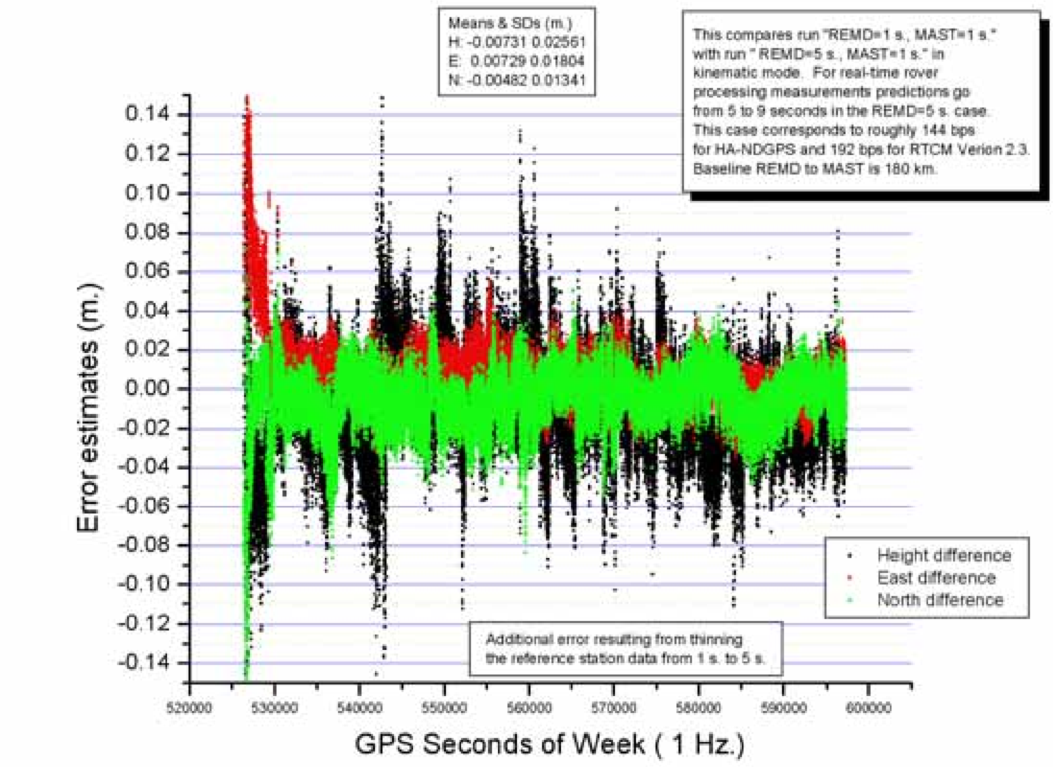


Figure 15. Comparing 5-second broadcast with 1-second broadcast from HAG1.

Table 1 indicates there is little difference between the 1-second, 1-second scenario and the 5-second, 1-second scenario when compared to millimeter truth. The means (−40 mm, −1 mm, 17 mm) are similar to those shown in figure 12 (-46 mm, 4 mm, 13 mm). The standard deviations (68 mm, 25 mm, 25 mm) are almost identical (68 mm, 24 mm, 24 mm).

Table 1. Accuracy performance of 5-second broadcast scenario.

Component	Means (mm)	Standard Deviations (mm)
Height	−40	68
East	−1	25
North	17	25

Next is the 10-second REMD, 1-second MAST scenario. Obviously the bandwidth would be halved and the latencies would be doubled. Increasing the epoch spacing clarifies how much degradation could be expected as a result of missed messages. For example, when operating a reference station at 5-second epochs, suppose a user misses an epoch. In that case, the prior received message would be used for a total of 14 seconds rather than the normal 9 seconds. This motivates the study of 10-second, 15-second, and 20-second scenarios that soon follow. Following are the results of the 10-second/1-second scenario.

Figure 16 shows the error that results from broadcasting REMD data at a 10-second rate versus a 1-second rate. The added error is still smaller than the absolute error and suggests only moderate error growth when the 5-second, 1-second scenario experiences one or two missed epochs at MAST. Clearly when there are no missed messages in the 10-second, 1-second scenario, the results are still good. Even in the 10-second scenario, some positioning users will be satisfied with processing 10-second aligned epochs roughly 10 seconds late.

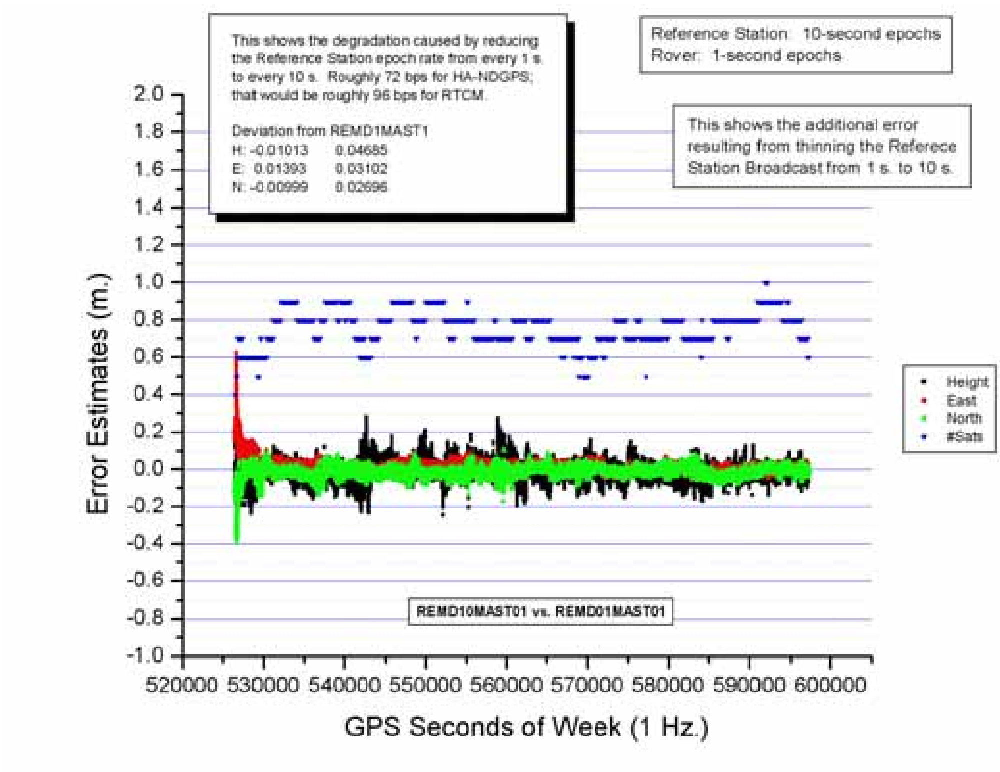


Figure 16. Comparing 10-second broadcast with 1-second broadcast from HAG1.

Table 2 shows how this 10-second, 1-second RTK scenario compares with millimeter truth. Compare these statistics with the 1-second broadcast scenario shown in figure 14 to see only a 10 percent accuracy performance degradation when data are broadcast based on 10 second epochs.

Table 2. Accuracy performance of 10-second broadcast scenario.

Component	Means (mm)	Standard Deviations (mm)
Height	−38	73
East	−6	26
North	21	29

Clearly the absolute error in the horizontals has grown from the half-dm level to the dm level. Most of this increase results from using the 10-second broadcast up to 19 seconds past user-time-aligned data.

Following is the 15-second, 1-second scenario, which suggests that while the error indeed increases, the error growth is still gradual. Figure 17 shows a comparison of the 15-second, 1-second scenario with the original 1-second, 1-second scenario. The error shown is the result caused solely by thinning the data broadcast to 15-second epochs, and it reflects the increased latencies. The absolute error associated with this case is shown in table 3. Compare these statistics with the 1-second broadcast scenario in figure 14 to see the possibility of 50-percent accuracy performance degradation when data are broadcast based on 15-second epochs.

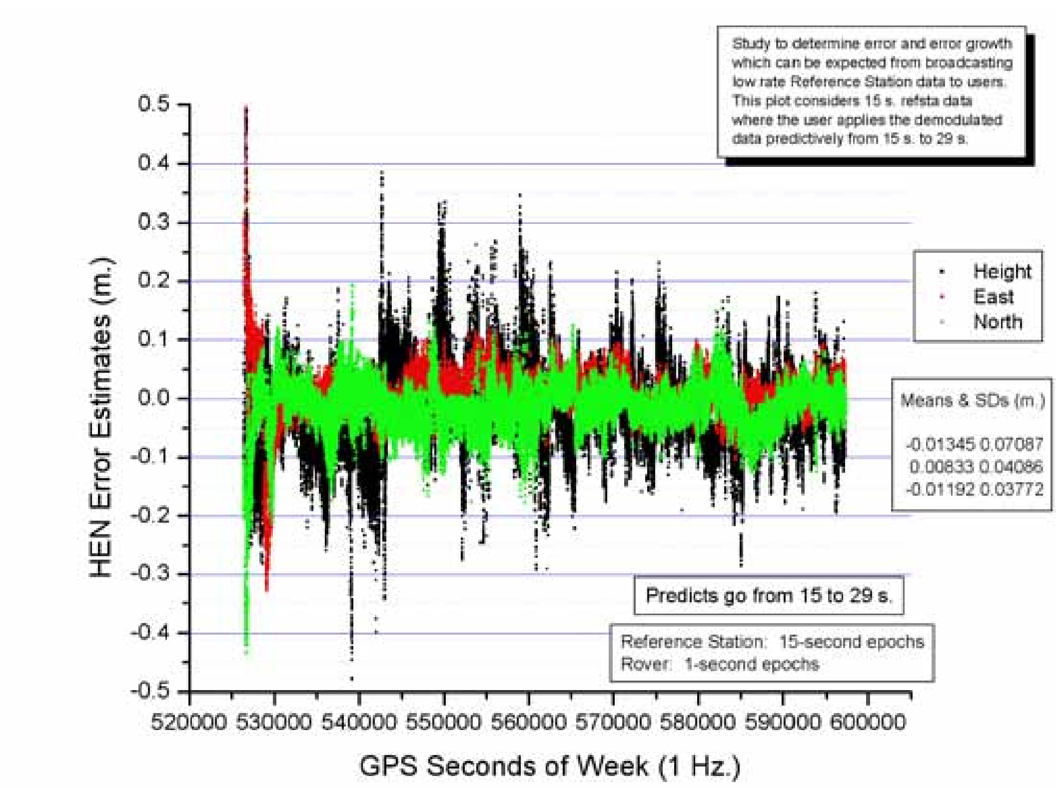


Figure 17. Comparing 15-second broadcast with 1-second broadcast from HAG1.

Table 3. Accuracy performance of 15-second broadcast scenario.

Component	Means (mm)	Standard Deviations (mm)
Height	−34	92
East	−6	36
North	22	36

Clearly the error increase is significant and undesirable. The 1 Hz rover solutions were generated using reference station data that were from 15 to 29 seconds old. Nevertheless the error growth has been gradual.

Figure 18 shows the 20-second, 1-second scenario where a typical RTK user at 180 km would begin to use the broadcast data after 20 seconds and end the use after 39 seconds. To be clear, the user would re-use a single broadcast epoch, in a predictive sense, for roughly 19 seconds (after already waiting 20 seconds to get it).

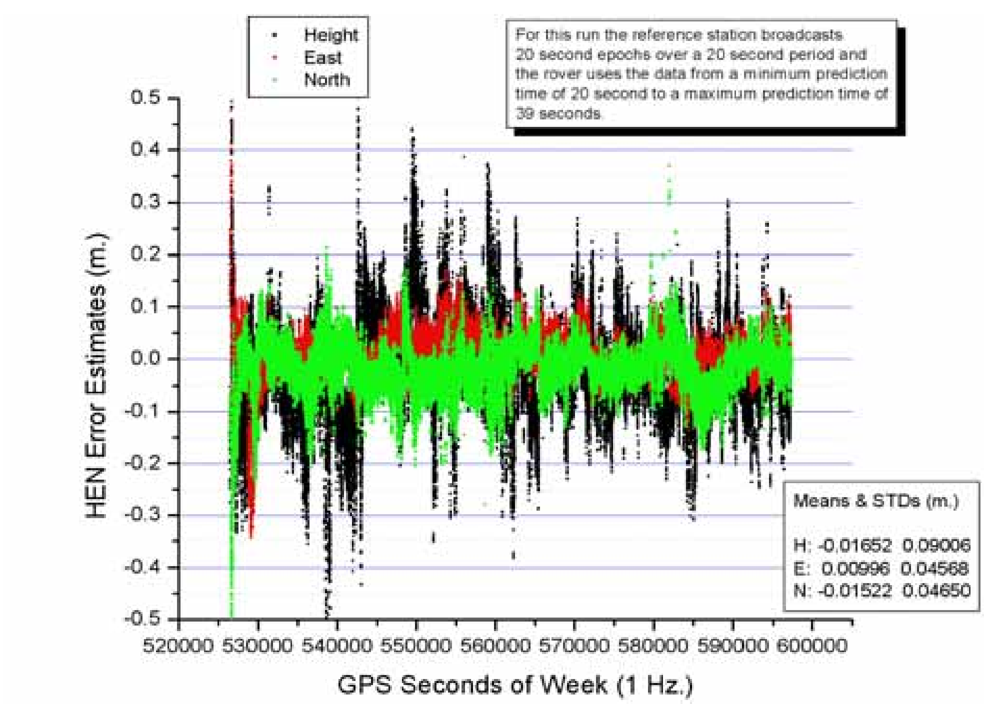


Figure 18. Comparing 20-second broadcast with 1-second broadcast from HAG1.

The horizontal error resulting from the reduced bandwidth remains less than 1 dm. Table 4 compares the results of the 20-second, 1-second scenario compared to millimeter truth.

Compare these statistics with the 1-second broadcast scenario in figure 14 to see the possibility of 100-percent accuracy performance degradation when data are broadcast based on 20-second epochs.

Table 4. Accuracy performance of 20-second broadcast scenario.

Component	Means (mm)	Standard Deviations (mm)
Height	-32	106
East	-9	40
North	26	44

These results suggest that 144 bps is minimally adequate for broadcasting dual GPS code and carrier data to a user under nominal levels of ionospheric activity, which affects the GPS signals, and nominal levels of atmospheric noise, which affects the data link. While 144 bps might be adequate to meet a simple local or private need, it would not be adequate to serve the public. First, the 144 bps rate supported 9 GPS satellites, but 12 satellites would be expected. Second, position and site name should be broadcast approximately once every 4 epochs rather that once per 60 epochs. Third, a set of smaller packets would constitute a more robust broadcast rather than the current one packet (all or nothing) message. Fourth, the addition of an integrity message would require several more bits. These four points would bring the broadcast rate to possibly 200 bps. Next, include L5 code and carrier measurements. For 12 satellites, this would require possibly 600 additional bits over 5 seconds or 120 bps, perhaps less. In addition, it might be possible to include additional information such as tropospheric zenith delay parameters, ionospheric zenith delay parameters, or precise orbit parameters, or all of these. Although the incremental bandwidths for these are difficult to estimate at this time, the following paragraph describes the first estimates.

The first estimates are 900 bits for a tropospheric delay grid or 25 bps for 3 minutes at 5-second epochs. The precise orbits might take 60 bps over 3 minutes at a 5-second rate. To repeat, these estimates cannot be accepted as conclusive. An ionospheric delay grid would be less dense, but it would require a wider range of values. A first rough estimate might be 45 bps. These estimates sum to 450 bps, assuming a 5-second broadcast. It is possible that the broadcast of precise orbits would never be required because those orbits broadcast directly from the GPS satellites are accurate to 0.25 mm per km from the reference station. This causes a random positioning error of about 6.25 cm at 250 km. Orbital improvement underway will reduce that error by a factor of about 2.5, leaving a random positioning error of about 2.5 cm at 250 km. Also, with dual data, an ionospheric delay grid serves a limited user population; therefore, it may not be required. Clearly a tropospheric delay grid has the most potential value to users.

In summary, 500 bps should be adequate to serve the public for GPS alone. If there is a decision that orbital data or ionospheric delay data do not have sufficient value, the remaining bandwidth would best be used by increasing the broadcast frequency from once every 5 seconds to as often as possible, which would be more or less once every 3 seconds.

There are smaller parent/child packet messages that have been laboratory tested, but they have not been evaluated for HA-NDGPS. To date broadcasts have been single packet where an entire epoch is broadcast in a single packet such as the RTCM-104 Type 1 message. These multipacket formats have some additional overhead, but the odds would be increased of message packets reaching distant users. Although smaller multipacket (parent/child) formats have not been exercised in the field, it is anticipated that they will be field tested in the months ahead.

In general, data gaps do not cause unusual problems. When data packets are missed, the previous packet continues to be used, much as RTCM Type 1 or Type 9 messages would continue to be used. If data packets are missed, a gradual increase in positioning error results, as demonstrated above. When the next packet arrives and passes the cyclic redundancy code (CRC) check, full accuracy returns to the user. Nevertheless, it is important that distant users experience a minimum number of missed packets.

TASK 7: COLLECT OBSERVATIONS ON ONE OR MORE HIGHWAYS IN RTK MODE TO DEMONSTRATE DRIVER ANALYSIS

Task 7 had several aspects.

Subtask 7a was to collect data for mapping one or more highway segments. Researchers traveled Route 15 north of Frederick, MD, on two separate driver analysis runs. In each run, there were eight to nine loops of 12 miles or more. Because the van could maintain the same lane, sections of roughly 4 km northbound and roughly 4 km southbound were used. Figure 19 shows a map section of U.S. Route 15 north of Frederick, MD, where the test took place.

Map used with permission from DeLorme.

Figure 19. Map segment of test site along U.S. Route 15 north of Frederick, MD.

The real-time motion plot in figure 20 shows a sample of the highway. Visible are nine passes over this section of Route 15. The blue icon shows where the van is (current track) on a rerun of the data. Figure 21 shows that the driver was able to repeat the track to within 14.5 cm root mean square (rms).

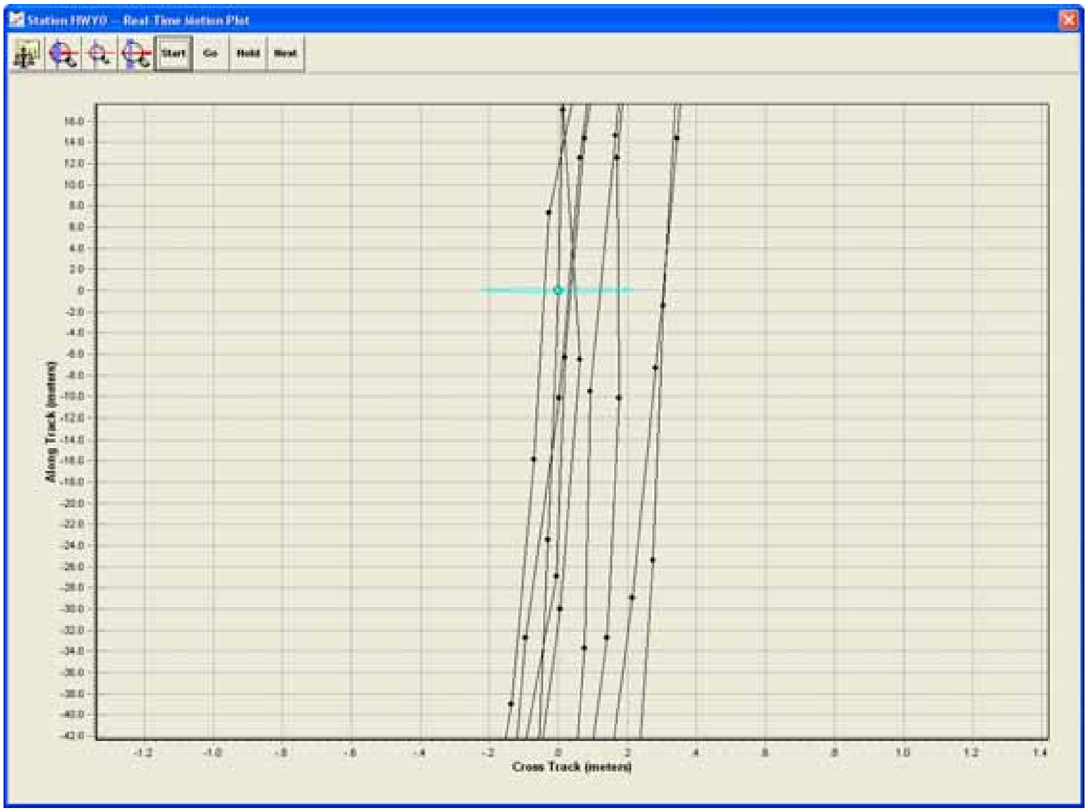


Figure 20. Display of nine tracks driven on U.S. Route 15 north of Frederick, MD.

From these runs, researchers created the road “definition” using the same program that was used to process the measurements. Figure 21 shows a small segment the roadway created manually as a visual average of the nine loops.

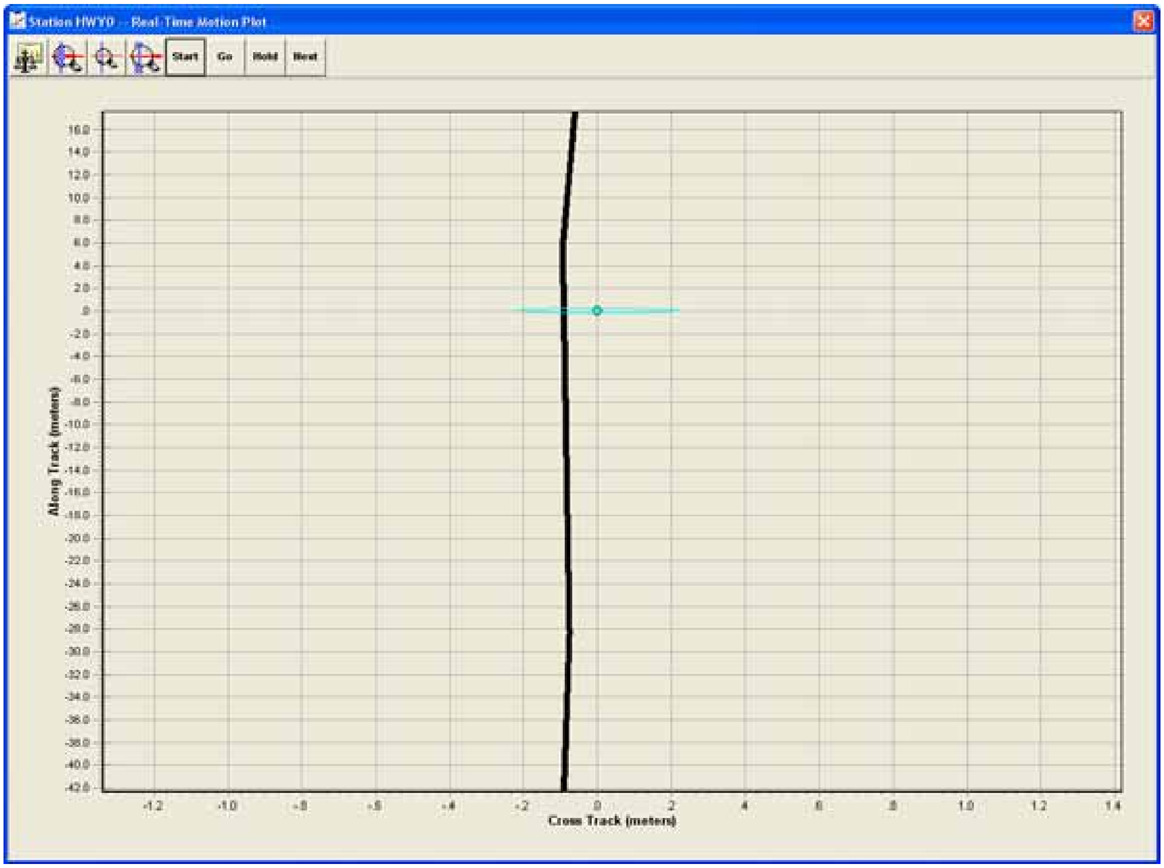


Figure 21. Display of defined "road map" created from nine tracks in Figure 20.

It is also possible to show all nine loops superimposed on the roadway.

The roadway was determined in float processing mode, and it is probably accurate at the 5-cm level after the first two loops. The positioning program could have determined the roadway precisely (1 cm) with a local reference station and subsequently operated in real time based on the Hagerstown broadcast. This was not done. For this test, the HA-NDGPS broadcast was used both to create the map and determine the driver's tracks on the same map.

Subtask 7b was to compare the driver's control of the vehicle. Figure 22 shows the driver's cross-track history related to the created road map. The figure shows the cross-track distances from the mapped road when the van was on the northbound and southbound segments of each loop. The gaps represent the portions of the loops where repetition was not possible because of a concern for traffic safety.

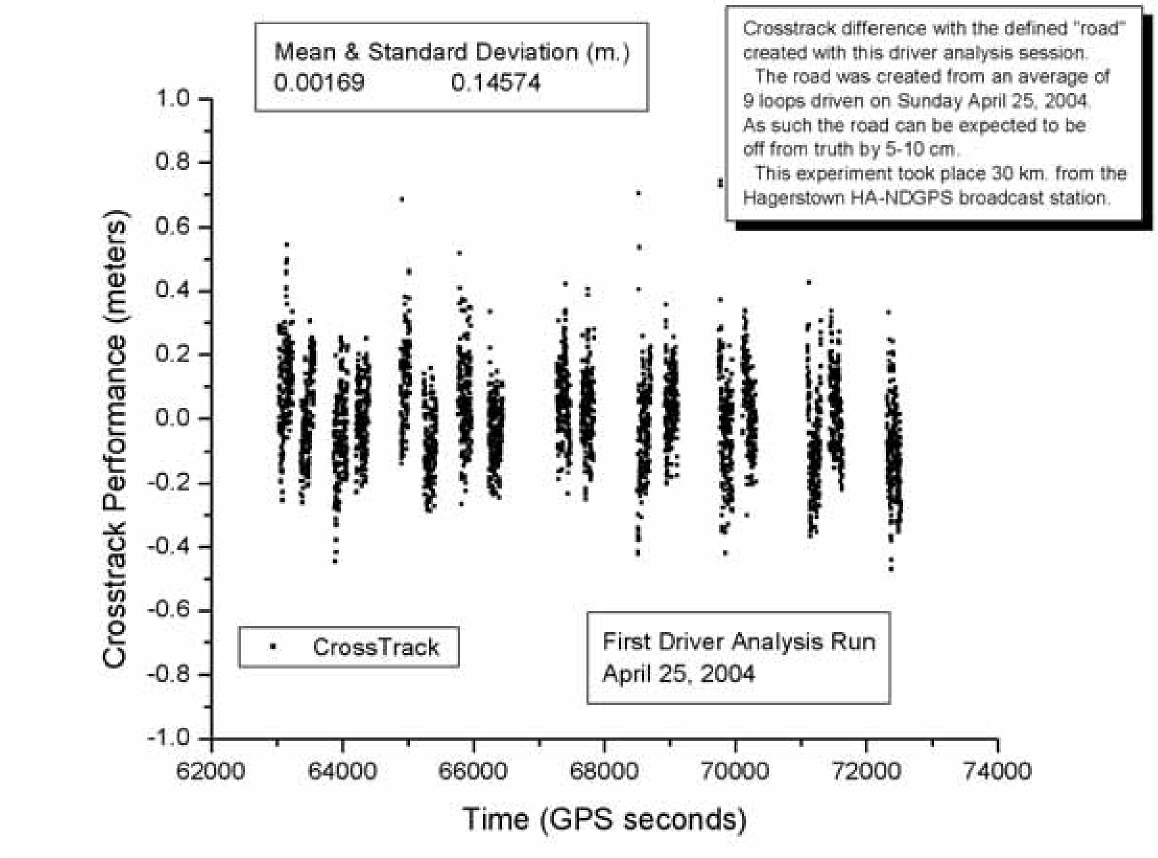


Figure 22. Representation of driver cross-track (i.e., left/right) driving variation for the 9 loops associated with figures 18 and 19.

The following method was used to compute the cross-track quantity. First the "road" was defined to be the average of the nine tracks; the average was generated visually. Because there were nine tracks, the visual procedure tended to ignore an obvious outlier. The end result of defining a road is a set of geodetic coordinates. Also, the points on the nine tracks have geodetic coordinates. The road points can be transformed to a local X-Y-Z topocentric frame where this frame is aligned with north (N), east (E), and the perpendicular to north and east, ellipsoidal height (H). Now individual points on the nine tracks could be converted to this topocentric frame and compared with the closest point in the set of road points. This was done, but the result is of little interest to compare the NEH of the tracks with NEH of the road. One more transformation computed the relative azimuth of two consecutive points on a track, then rotated the topocentric frame by this azimuth angle. This new frame is aligned along track and the closest point on the road is rotated into this new frame. While along-track and height were used to define this new frame, there is a cross-track component byproduct. In this frame the cross-track of a track point is zero and the cross-track of the nearest road point is plus or minus (i.e., left or right). This cross track component of the road with respect to the point on a track is the quantity presented in figure 22.

This route was traveled a second time with generally the same results. When the road generated from the first driver analysis run was applied to the second driver analysis run, the cross track behavior was 20 cm compared to 15 cm, an expected result. Clearly the roadway would be better defined based on many runs from different days and different satellite constellations. Obviously, it could have been determined better (i.e., 1 cm) with a local (e.g., within 5 km) reference station and centimeter RTK processing; however, this was not done.

The photo in figure 23 shows the van configuration for the Route 15 driver analysis runs. No attempt was made to place the user's local GPS antenna along the center of the van.

Figure 23. Van configuration used for driver analysis on U.S. Route 15.

TASK 8: STUDY LEVELS AND POSSIBLE NOISE REDUCTION AT THE HAGERSTOWN SITE

Task 8 had several aspects. Subtasks 8a and 8b are discussed together.

Subtask 8a was to locate a GPS antenna high above possible nearby multipath sources and compare the cleanliness of the measurements there with measurements from current NDGPS equipment. Subtask 8b was to use similar antennas, at both reference and a nearby user site, to gather observations and fix the integers to establish the level of site cleanliness.

A machine shop fabricated a pentapod apparatus to install high above the Hagerstown HA-NDGPS site to provide a signal as clear of multipath as could be done easily. This allowed researchers to compare signals with the existing NDGPS antenna locations.

Figure 24 shows a photo of the Hagerstown facility with the pentapod located on the roof and the HAG2 NDGPS GPS antenna protective dome in the background to the right.

Figure 24. The Hagerstown GWEN site with a pentapod marine antenna 4 to 5 meters above the hut to search for the cleanest signals.

At first researchers selected HAG2 to be the HA-NDGPS antenna and receiver. In this case, the antenna was a 700829 (3) Ashtech® antenna coupled with an NDGPS Z12R RS (reference station) GPS receiver. The van was instrumented with an antenna as shown in figure 25.

Figure 25. Van configuration for multipath testing at the Hagerstown GWEN site for the NDGPS 700829 (3) antenna from Ashtech to van 700829 (3) antenna from Ashtech test.

Next, researchers collected HA-NDGPS broadcast messages from HAG2 and processed the data as shown in figures 26 and 27. Initial convergence was slower than usual (figure 26); researchers interpreted this to indicate there was significant code multipath. Later in the processing, there was adequate convergence to fix the ambiguities to integers (figure 27). In that case, the results were stable; researchers interpreted this to mean the carrier multipath was not a factor and the 700829 (3) antenna from Ashtech geodetic antenna provided excellent carrier measurements.

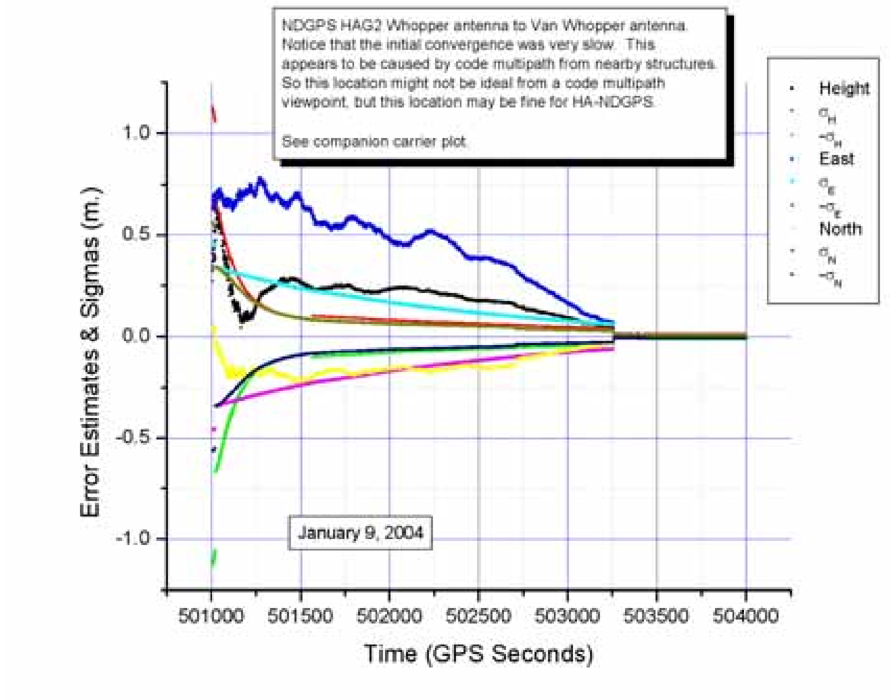


Figure 26. NDGPS 700829 (3) antenna from Ashtech to van 700829 (3) antenna from Ashtech initial convergence.

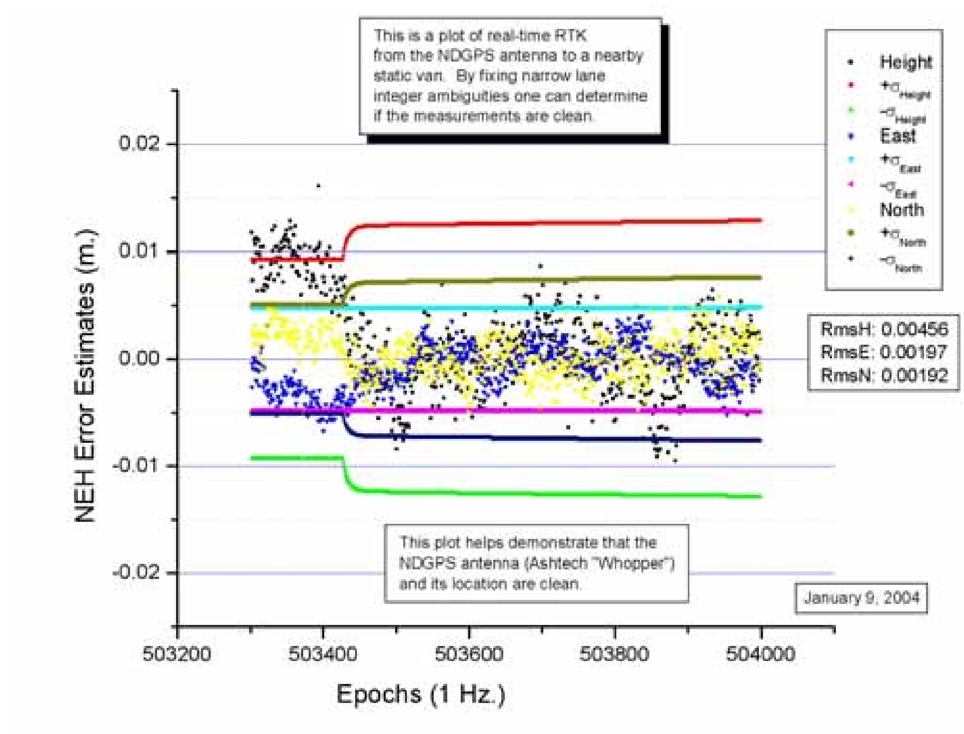


Figure 27. NDGPS 700829 (3) antenna from Ashtech to van 700829 (3) antenna from Ashtech steady state with integers fixed.

Next researchers used the Ashtech 700700 (B) marine antenna on top of the hut as the HA-NDGPS antenna plus an Ashtech Z12 Real-Time Sensor GPS receiver. The van was also configured as shown in figure 28.

Figure 28. Van configuration used for multipath testing at the Hagerstown GWEN site. In this case, HA-NDGPS marine antenna to van marine antenna is under test.

In this case, the initial convergence seemed to be nominal, as shown in figure 29. Researchers interpreted this to mean there was not as much code multipath at the marine antenna high above the hut as was experienced by the NDGPS antenna.

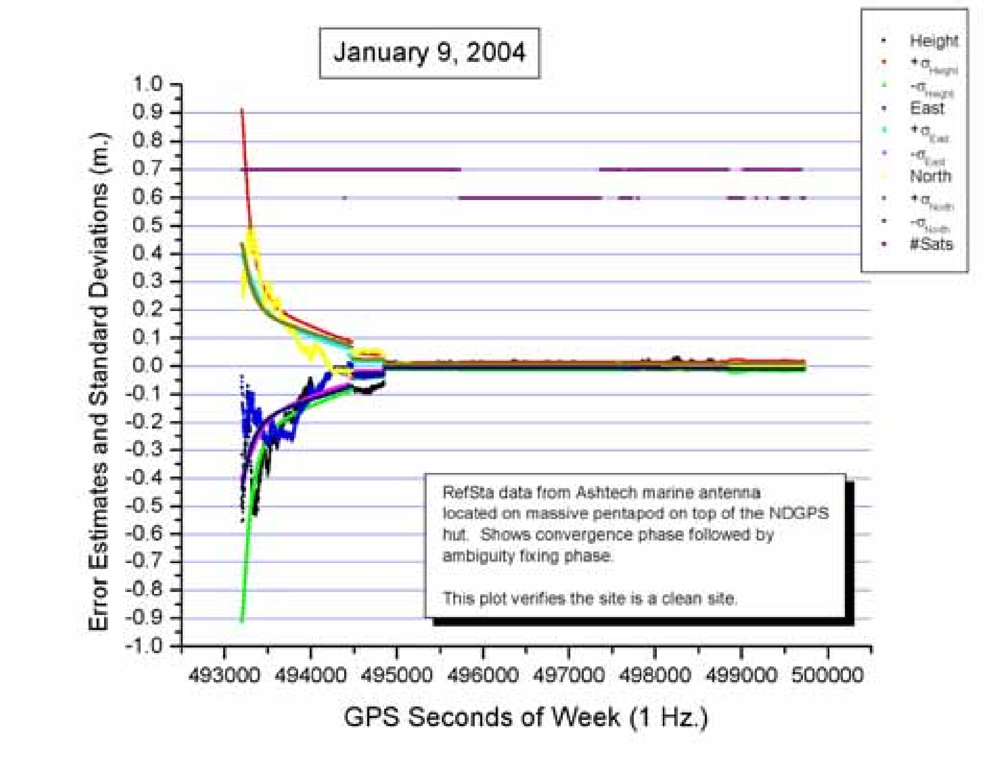


Figure 29. HA-NDGPS marine antenna to van marine antenna initial convergence.

After the results converged sufficiently to fix ambiguities to integer values, the integers were fixed, as shown in figure 30. The solution with integers fixed looked similar to the integer fixed solution using the 700829 (3) antenna from Ashtech. Researchers interpreted this to mean both sites were clean with respect to carrier multipath.

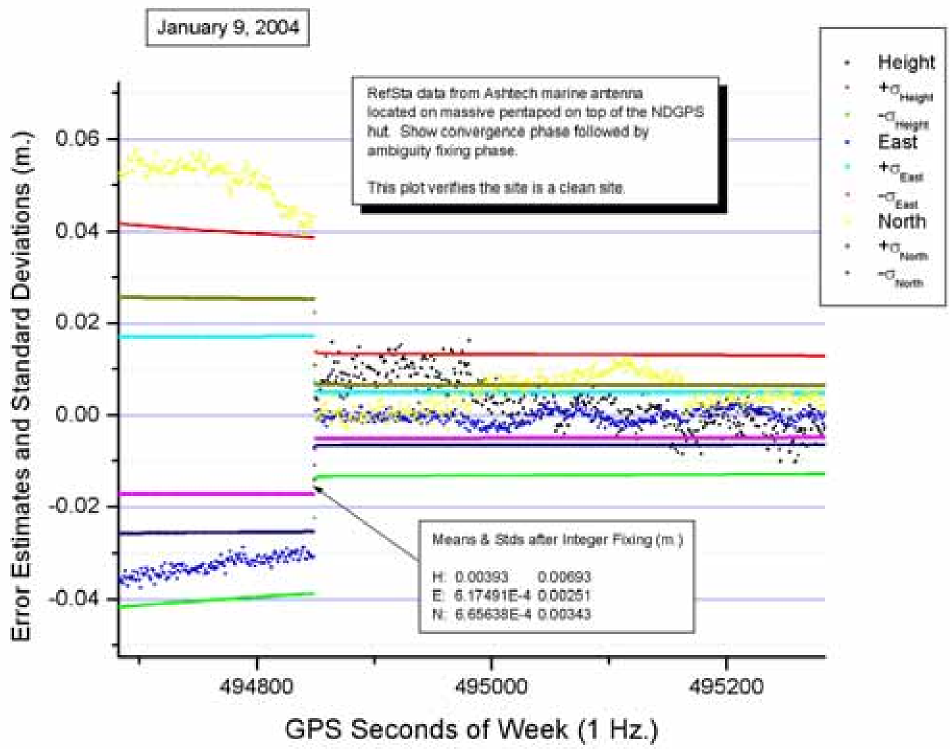


Figure 30. HA-NDGPS marine antenna to van marine antenna steady state with integers fixed.

In summary, NDGPS sites appear to have high-quality carrier observations. On the other hand, the NDGPS site code observations might have experienced significant multipath. Potentially, this is an issue if users use HA-NDGPS signals for code range navigation. It is also potentially an initialization issue for HA-NDGPS users because HA-NDGPS users will depend on the code observations during the early seconds or minutes to provide aiding to the carrier measurements.

It is significant that when NDGPS 700829 (3) antenna from Ashtech antennas are mixed with 700700 (B) marine antennas, the results are not good unless antenna modeling similar to that performed by NOAA and NGS is included.

SUMMARY

The research in this task was directed toward proving system capabilities, examining possible applications, and refining various system functions. The effort was very successful in all three areas.

Task 2—Modulator Software Rewrite and Multiple Station Solution. The new modulator software performed with greater reliability than the previous version. By supplying the modulator with data before the buffer was empty, the broadcast did not drop bits due to the nondeterministic effects of the operating system. The improvement in performance using two sites to determine the users' navigation solution gained from this relatively simple weighting implementation provides solid proof that multiple reference stations offer improved performance. More complex implementations that are currently available offer even greater benefits.

Task 3—Prebroadcast Integrity Algorithm. Development of the integrity approach offers significant insight into to the best way to implement this feature. It provides subsecond indications to the users of solution problems. Shortly thereafter, users receive an indication of the problem so they are able to apply the information and generate a navigation solution. While further work to refine the user alerts is needed, this early effort has proven successful in meeting our requirements of notifying users of satellite usability.

Task 4—RTCM Data Output. This capability allows the system to operate with almost any GPS receiver on the market today, giving users an easy way to develop applications using existing components. As new demodulators are developed, this software can be built-in to provide greater flexibility and easier implementation.

Task 5—Modulator Interface. This provides greater remote control capability, reducing the need to visit sites on a regular basis. Its implementation provides significant benefits as more geographically distant sites are installed.

Task 6—Low Baud Rate Messages. This task demonstrated the ability of the system to provide information at even lower data rates and offers insight into what the minimum data rate should be, given the parameters at the time of the test. Data rates as low as 100 bps will work, but higher data rates are needed to ensure the user received adequate and low latency information to make an accurate navigation solution.

Task 7—Highway Application. The ability to use a real-time solution to demonstrate driver behavior offers benefits, but further exploration is needed to quantify the benefits. Task 7 was intended to begin that process and did so successfully by illustrating the type of information that could be gathered and analyzed.

Task 8—Noise. Quantifying the noise at Hagerstown and demonstrating the stability of the reference stations, and insight into the effects of taller reference station towers and multipath can be further explored to reduce their effects at other sites.