Nationwide Differential Global Positioning System Test and Analysis (for HA-NDGPS)

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For

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XYZs Task Abbreviation: HA-NDGPS II

<u>PHASE II HA-NDGPS REPORT</u>

Abstract

During the years 2001 and 2002 The XYZs of GPS, Inc., FHWA, USCG, FRA, NGS, USACE, and other government organizations realized an initial demonstration HA-NDGPS system at the Hagerstown GWEN site. This demonstration phase was successful in that all the target objectives were met and exceeded. That initial effort was documented in a report by The XYZs of GPS, Inc. entitled "Support of the System Test and Analysis Program for the NDGPS Modernization Program", dated July 12, 2002.

This report documents the continuation of that effort with a new set of objectives. In general terms, the 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 system facilities and communications, and example(s).

Many persons and organizations participated in an extremely collegial fashion and all the objectives were accomplished.

Introduction

On March 14, 2003 we began Phase II of the HA-NDGPS research and development project. FHWA, USCG, and The XYZs of GPS, Inc. met to schedule, prioritize, and generally establish a plan so that XYZs could accomplish the government objectives in the most efficacious manner.

The government would secure spectrum approval, obtain demodulator receivers and antennas, provide Hagerstown, MD and Hawk Run, PA USCG NDGPS reference stations, install and operate XYZs software at these sites, and otherwise manage the HA-NDGPS project. There were several defined tasks for XYZs.

<u>Task #1</u> was meeting, communicating, and documenting. The parties maintained weekly and often daily correspondence throughout the entire year of test and evaluation, development, and documentation. Now that XYZs has completed its tasks, the remaining work for Task #1 is to write and deliver this final report. The final report has been read by FHWA and USCG personnel and edits have been suggested and most of them are reflected in this report.

<u>Task #2</u> was entitled multi-station collection, processing, and reporting. While the simultaneous collection of broadcast data from Hawk Run and Hagerstown, and processing those observations were the defining objectives, the bulk of the effort was developmental or preparatory to those objectives. The following represents the many developmental subtasks.

- **Pretest installation and configuration of a new modulator program and an updated GRIM with TCP/IP at Hagerstown and Hawk Run.**
- **Implement modulator feedback to GRIM**
- **Implement 'Restricted Active Mode' at Hagerstown and Hawk Run.**
- **Gather broadcast GPS data from Hagerstown and Hawk Run, simultaneously, and process at an in-between user site.**
- **Describe the algorithm used to combine independent solutions from Hagerstown and Hawk Run.**

<u>Task #3</u> was the development and implementation of a pre-broadcast integrity algorithm. There were three subtasks.

- **Detecting errors in the GPS constellations and its broadcasts (a demonstration)**
- **Discussion of methods of inserting integrity information into the data stream**
- **Description of possible techniques and algorithms**

<u>Task #4</u> was the development of interface software for multiple brands of GPS receivers. Only one task was defined here.

- **Convert the XYZs demodulated output format into RTCM 18/19 compatible with existing user GPS equipment. <u>Deliver source code.</u>**

<u>Task #5</u> was to rewrite the modulator interface.

- **Rewrite the existing modulator interface to implement a remote control capability via a TCP/IP Interface. <u>Deliver source code.</u>**
- **Add limited commands to control GPS receiver parameters (e.g., data rate and elevation mask). <u>Deliver source code.</u>**

<u>Task #6</u> was to evaluate a low baud rate message (e.g., 100-300 baud) and user processing based upon a HA-NDGPS data rate less than once every epoch. To clarify this, the reference station would send data once every 5 seconds, for example, while the user would observe & process his data every one second and produce 1 Hz. solutions. Real-time or post-processing would be acceptable modes for this task.

<u>Task #7</u> was to collect observations on one or more highways in RTK mode to demonstrate driver analysis. One possibility would be to map a segment of the roadway and another is to study the repeatability of driver performance so that one day a driver can be alerted when his driving performance is poor.

- **Collect data for mapping one or more highway segments.**
- **Compare the driver's control of the vehicle.**

<u>Task #8</u> considered studying noise levels and possible noise reduction at the Hagerstown site.

- **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 like antennas 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 is presented in the order of the tasks presented in this introduction. Again, Task #1 comprised meetings and status reports but now that we have completed the Phase II activities, Task #1 represents the completion and acceptance of this final report.

Task Reports

Task #1: Final Report

This final report is Task #1.

Task #2: Multi-station collection, processing, and reporting

Task 2a) Pretest installation and configuration of new modulator program and GRIM With TCP/IP at Hagerstown and Hawk Run

There were several aspects to this task. One was the need to add a second HA-NDGPS reference station. The TCP/IP feature, discussed later in Task 5 to add the remote control capability, had a role to play in this task as well. Its importance here was to eliminate the need of two modulator computer communications ports.

Another aspect of Task #2a) was to update the Hagerstown HA-NDGPS station with the latest reference station software. The main three features associated with this upgrade were eliminating the two comports mentioned above and the features described in Tasks #2b) and #2c), below.

Task 2b) Implement modulator feedback to GRIM

As originally implemented at a HA-NDGPS reference station, the GPS Receiver Interface Module (GRIM) serves two distinct functions. First, it interfaces the GPS receiver to whatever device or software 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 as the operating system did not allow immediate access to the modulator buffer. Once the modulator buffer was empty, it would send out a message to that effect; but due to 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 under-utilized 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. (It should be added that GRIM provides many other functions such as data archival, data sharing, user demodulation, etc.)

Task 2c) Implement 'Restricted Active Mode' (R.A.M.) at Hagerstown and Hawk Run

Task #5 requires TCP/IP for remote control, and includes a feature to modify Reference Station GPS receiver parameters. Additionally, the XYZs GRIM software has a 'passive' mode so that USCG GPS receiver settings cannot be accidentally changed. This R.A.M. feature gives official USCG technicians and NAVCEN operators the ability to modify a restricted set of GPS receiver parameters while not allowing others to be changed. R.A.M. has been implemented at Hagerstown and Hawk Run.

Task 2d) Gather broadcast GPS data from Hagerstown and Hawk Run, simultaneously, and process at an in-between user site.

The XYZs of GPS, Inc. and Mr. James Arnold, COTR, from the FHWA traveled to Hagerstown, MD and Hawk Run, PA to reset Hagerstown and Hawk Run and reconfigure the sites to operate at 1 Hz. and to broadcast one of the highly compressed XCOR formats. After completing this configuration change, XYZs 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. XYZs selected Orbisonia, PA, on Route 522, since it is more or less half way between HRN2 and HAG1 and 48 miles from both (Figure 1).

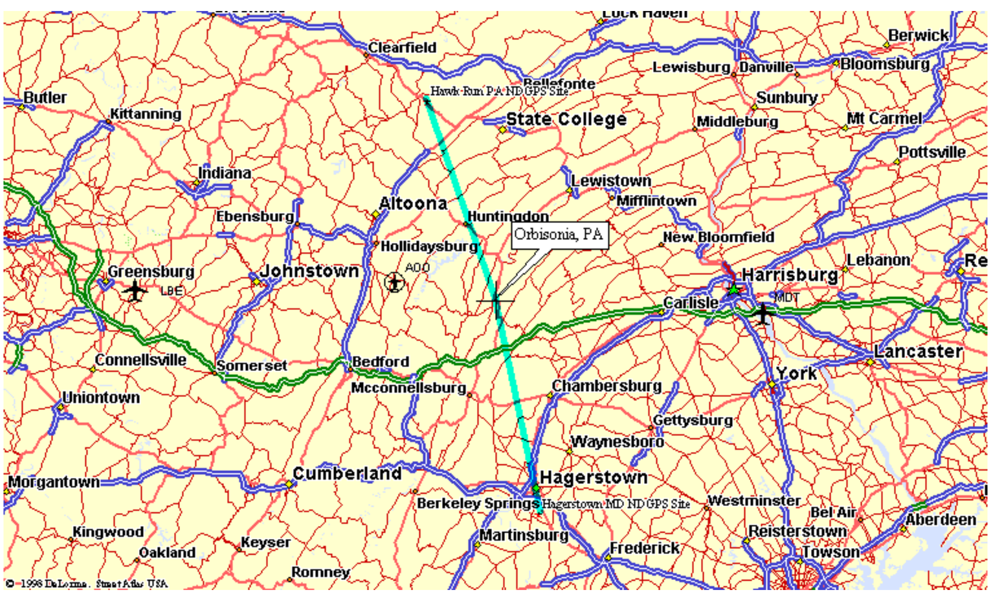

Figure 1. Map of South-Central PA showing Hawk Run, PA, Hagerstown, MD, and Orbisonia, PA. The latter is the test site which is approximately 80 km. from the RefStas.

Here XYZs demodulated HRN2 data and HAG1 data 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 and the other received demodulated data from HAG1. Both laptops ran XYZs application program DynaPos.exe in kinematic mode to achieve two separate RTK solutions for the user. It turned out that during real-time processing coordinates from HRN1 rather than HRN2 were used. Nevertheless, nearly correct baseline vector results were computed - even though the results were offset. This solution was therefore reprocessed using the correct Hawk Run coordinates. Such reprocessing does not improve the accuracy as the data used in reprocessing is exactly the same data as received in real time. This allowed the inadvertent setting to be corrected rather than collecting new data. (In other words the reprocessed results are exactly the same as would have been achieved in real time had the correct RefSta coordinates been used.)

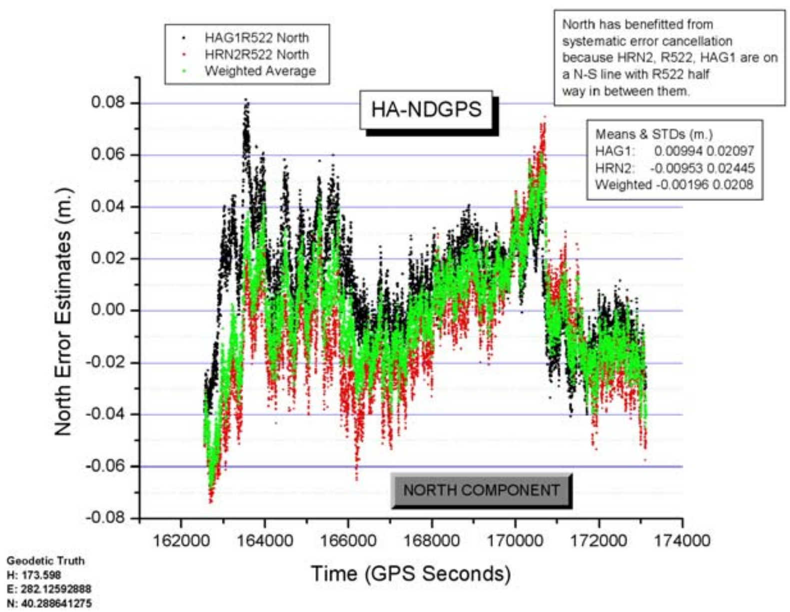

Figure 2. North component determined from HAG1 (black), from HRN2 (red), and the weighted average solution (green).

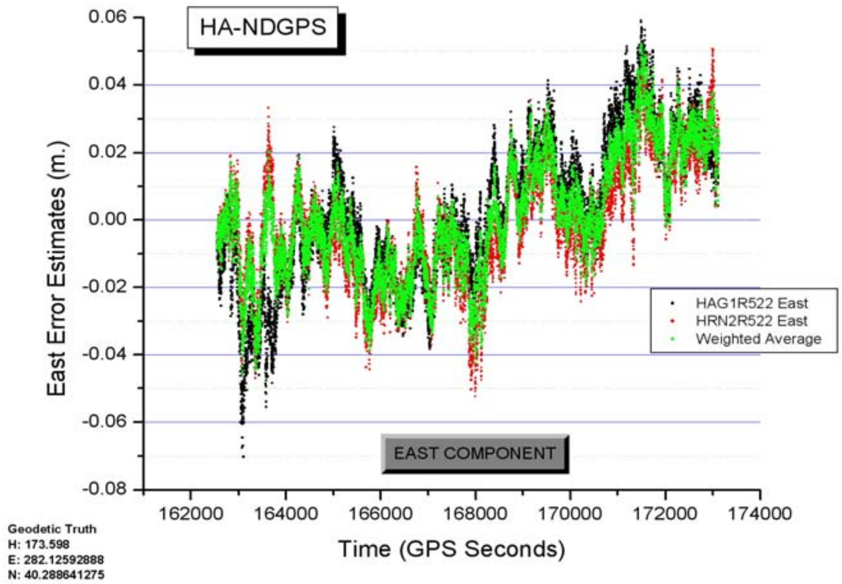

Figure 3. East component determined from HAG1 (black), from HRN2 (red), and the weighted average solution (green).

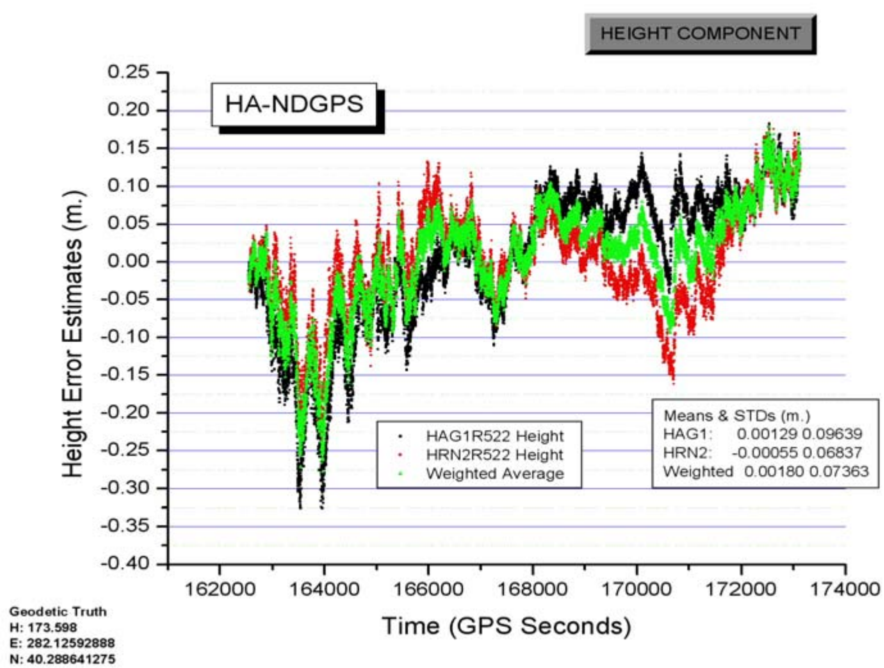

Figure 4. Height component determined from HAG1 (black), from HRN2 (red), and the weighted average solution (green).

HRN2, R522 (Orbisonia, PA), and HAG1 are along a more or less N-S line as shown in Figure 1. Thus we would expect some systematic error cancellation in the N-S component when HAG1R522 and HRN2R522 are combined in a weighted average. We would not expect much benefit in the E-W component from systematic error cancellation. 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 this day.

Let us study the Figure 2-4 plots briefly. In all cases y = 0.0 represents geodetic truth. While the data were collected at a fixed location, the measurements were nevertheless processed with medium dynamics so the Kalman filter was assuming the antenna was moving several meters every second and had no knowledge that the site was static. 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 to set up an additional local truth reference site.

The N-S component benefited from the weighted average of the two solutions. This can be seen in the N-S plot above as the weighted average solution appears to be closer to the truth. The E-W component (Fig. 3) did not appear to benefit from the combined solution; however Figures 5-7 would imply both N-S and E-W component improvement . Thus the benefit from averaging random errors might be greater than the benefit from systematic error cancellation. The height did not seem to benefit on this day either. Notice toward the end of the height plot that Hag1R522 increased while HRN2R522 decreased. This opposite behavior becomes exaggerated in passing thunderstorms and in hot humid conditions where there is a gradient; a two reference station solution can reduce this significantly. However, this particular day was warm but 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 different reference station multipath so that with enough reference stations one could hope to eliminate reference multipath. Unfortunately this does nothing to reduce user multipath so after 2 or 3 reference stations are applied the reference station multipath component already becomes insignificant. In summary there is a random error component to reduce and a systematic error component 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 which 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;

this is small 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 upon different reference stations is to benefit from systematic tropospheric delay error cancellation.

For completion we include the East-North horizontal X-Y plots in Figures 5-7, below. These plots contain the same information content as the north vs. time and east vs. time plots above, but are presented in a more traditional manner where time is not explicit. One can see the combined solution comprises the best of the two solutions in that the scatter plot is tighter for Figure 7 than for either Figure 5 or Figure 6.

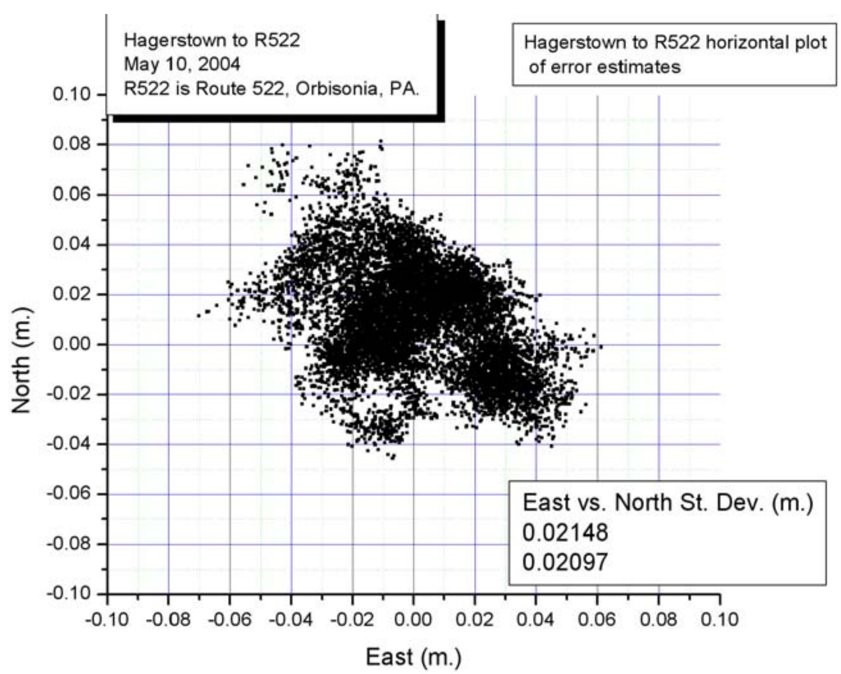

Figure 5. North component vs East component cross plot determined from HAG1

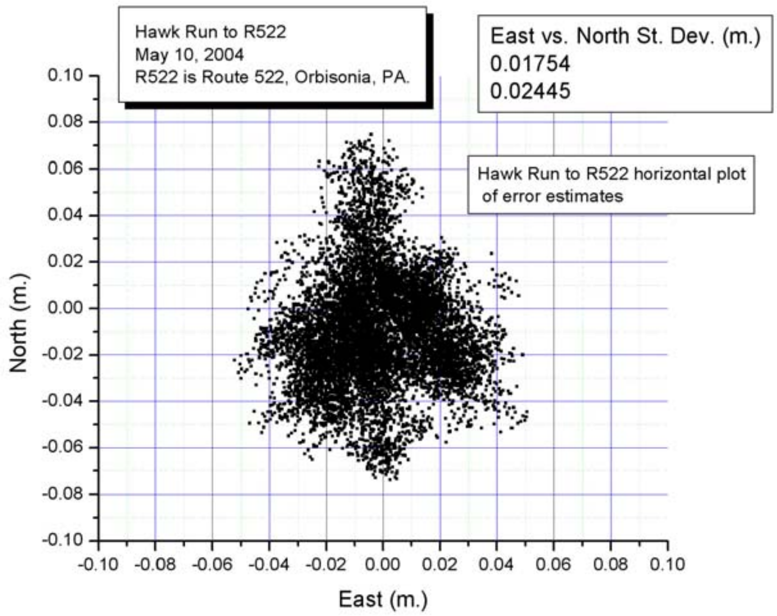

Figure 6. North component vs East component cross plot determined from HRN2

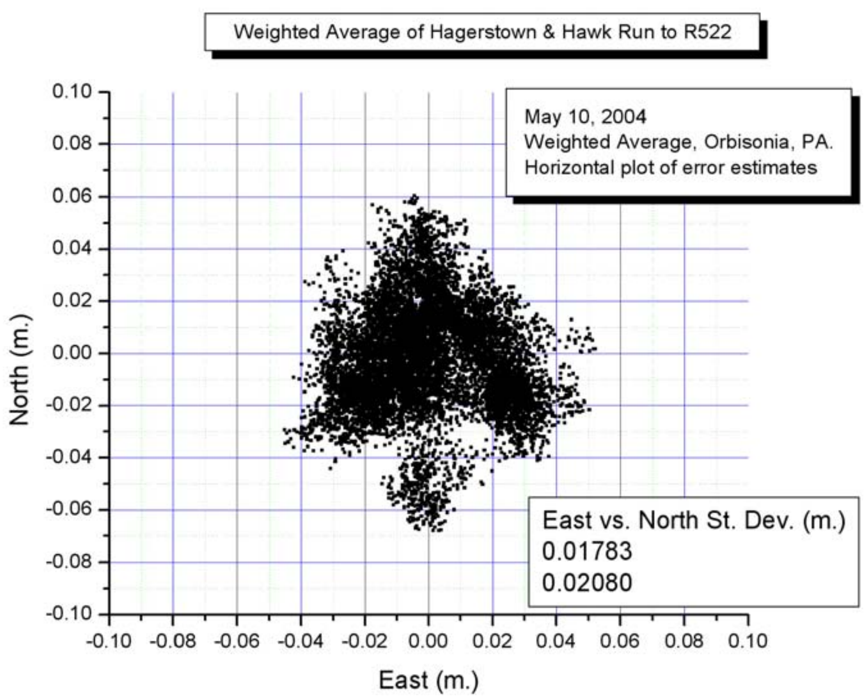

Figure 7. North component vs. East component cross plot of.HAG1 HRN2 combined.

The latter plot has somewhat better scatter properties because of the combining of the HAG1R522 and HRN2R522 plots. Under certain weather conditions the combining of multiple simultaneous solutions can have a much more dramatic improvement than experienced in this example.

Task 2e) 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 6 random variables there is an associated standard deviation (i.e., σ) output from the two Kalman filters. The graphic below describes the algorithm used to combine solutions.

$$x = \frac{\frac{x_1}{\sigma_{x_1}^2} + \frac{x_2}{\sigma_{x_2}^2}}{\frac{1}{\sigma_{x_1}^2} + \frac{1}{\sigma_{x_2}^2}} \quad y = \frac{\frac{y_1}{\sigma_{y_1}^2} + \frac{y_2}{\sigma_{y_2}^2}}{\frac{1}{\sigma_{y_1}^2} + \frac{1}{\sigma_{y_2}^2}} \quad x = \frac{\frac{z_1}{\sigma_{z_1}^2} + \frac{z_2}{\sigma_{z_2}^2}}{\frac{1}{\sigma_{z_1}^2} + \frac{1}{\sigma_{z_2}^2}}$$

This algorithm does a fair job of combining solutions and giving the better solution component more weight. (A simple alternative which could be used, but which is generally not recommended, is to simply average the solutions for all the participating reference stations. This simple solution will be reasonable so long as all the PDOPs are in reasonable agreement. However should the PDOPs differ greatly, this procedure should be avoided.) The combining of standard deviations to achieve a single standard deviation is more problematic as the correlated nature of systematic errors has not been developed. Currently we simply take the smaller of the two standard deviations. When the user combines solutions from two reference stations he gets a 13.4% reduction of random component error. This reduction of random component error continues as reference stations are added. With enough reference stations this random component reduction can be as great as 29.3%. For traditional [code] DGPS users this would be welcome as 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 – due to 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, iono error in essentially eliminated by forming iono-free combinations of measurements. This leaves tropo error as the most problematic systematic error source. Activities are underway at NOAA/NGS and USCG/C2CEN and NOAA/Boulder to develop real-time data which 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: RefSta to user distance weighting was not used in the combining algorithm and might be a consideration - depending on the Kalman filter assumptions.)

The following photo shows how the van was configured for this test. There are two demodulator antennas shown. One of them received HAG1 broadcast XCOR messages and the other one received HRN2 broadcast XCOR messages. On the driver's side in the back is the Van's local GPS antenna which was fed to a signal splitter and subsequently input to separate laptop computers. The 4th antenna, just above the driver, is unrelated to this test.

Figure 8. Van setup used for collecting data broadcast from HAG1 and HRN2, at the same time. Note one GPS marine antenna and two demodulator receiver antennas.

***Task #3:* development and implementation of a pre-broadcast integrity algorithm**

Task 3a) Detecting errors in the GPS constellations and its broadcasts (a demonstration)

The coordinates of the reference site are ostensibly known. In practice this has been a minor point of confusion during this R&D 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 whenever the configuration of the HA-NDGPS reference station is changed. While point positioning solutions are not very accurate, one can usually discriminate between reference station sides by inspecting the XYZs GRIM point solutions as part of any setup procedure. XYZs has taken this farther.

XYZs has added reference station (code) corrector-type residuals for purposes of integrity. (What is a residual? Generally a residual is the difference between something expected and something actual. As an example, one can pre-compute a GPS range, based upon a geodetic location and a satellite's location. But when the actual measurement is made it may differ by, say, a few centimeters, and that would be the residual or the left over amount or the disagreeing amount.) Large residuals indicate poor measurements, poor orbits, or incorrect geodetic coordinates, and can be caused by other problems. Small errors are a necessary but not sufficient condition for integrity. Task 3b), below, begins to address this issue. The site technician or the Control Station operator must verify that code residual errors are within specified tolerances. This effort has been completed.

As an example, compare the two graphics shown in Figure 9. In the first instance (left) the correct coordinates were used, whereas in the second instance (right) the wrong coordinates were used. The intentional error in the latter case was 100 meters in each component. Notice the large positional errors (top three lines) in the right graphic. Notice the large residuals (lower lines below white line) caused by wrong coordinates.

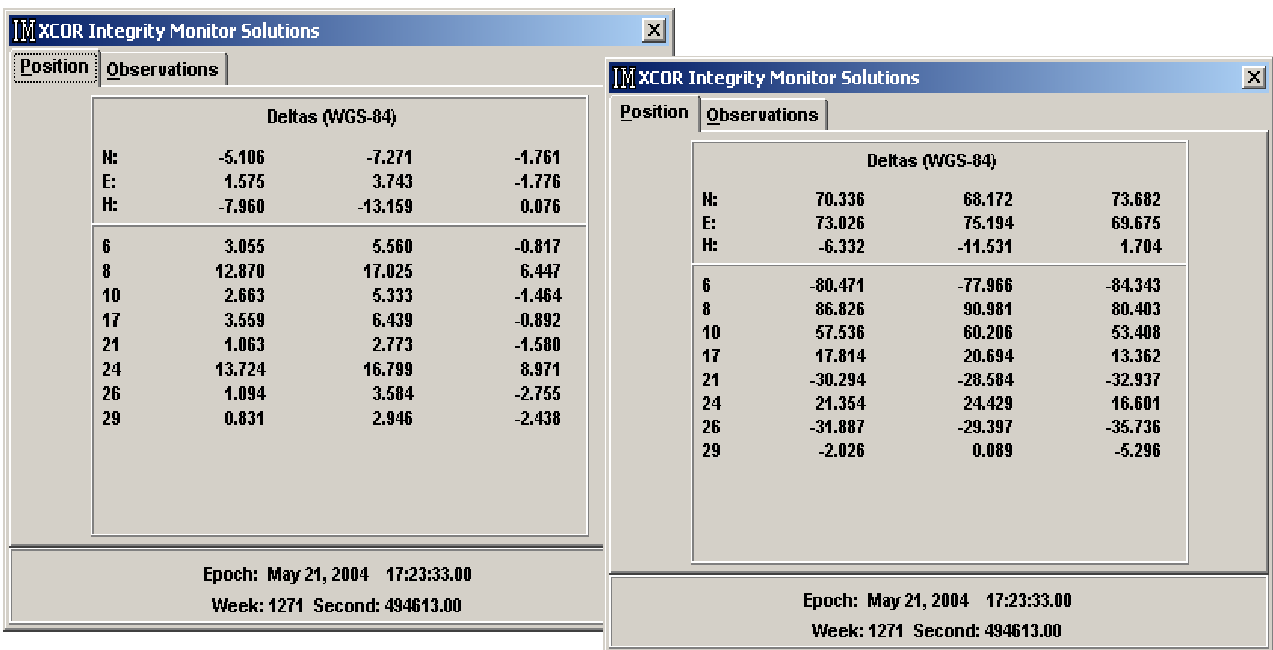

Figure 9. A first example of pre-broadcast positional integrity. On the left the correct site coordinates were used; On the right the wrong site coordinates were used;

It is obvious, from these residuals, when reference station coordinates are in error by a large amount. One could extend this idea to a differential check if data from a second NDGPS GPS receiver were used as a prelude to accepting the modulated message for transmission to users. In differential mode the code DGPS residuals would be about 1 meter just as NDGPS 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 centimeter.

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

The graphic in Figure 10 compares original data with the unpacked data at the reference station before broadcasting the data to users. This 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.

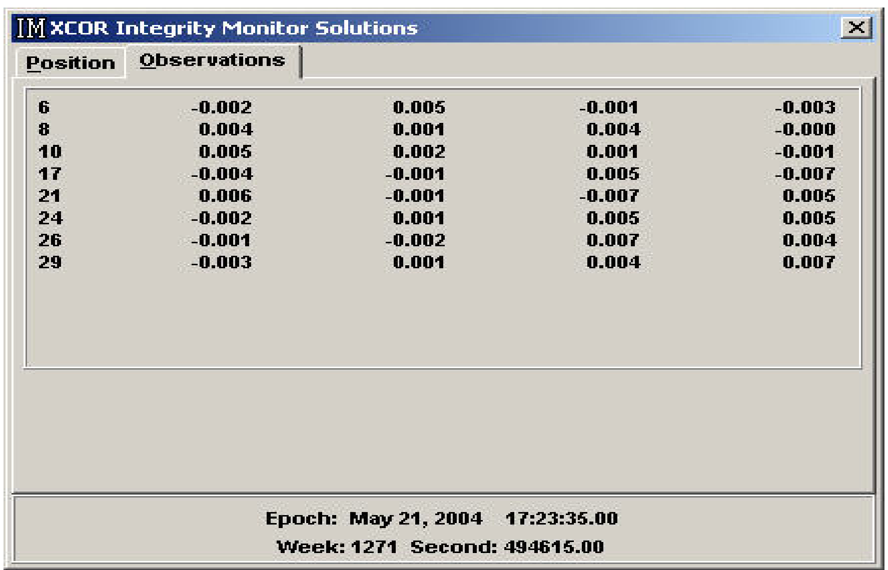

Figure 10. A first example of pre-broadcast measurement integrity. The four columns show the difference between raw measurements and what is about to be broadcast. The idea is what is important, here; not the values, per se.

Task 3b) Discussion of methods of inserting integrity information into the data stream

One method XYZs has considered for inserting integrity information into the data stream is to provide a single bit which indicates that there is an integrity message within the data stream. The location of this integrity message with the data stream would be fixed and known. The integrity message length would be variable in that there would be a message reserved for expanded integrity messages. Here are some possible messages. Four to eight bits would be required to accommodate a suite of possible messages - including some combinations.

0 – Unreliable; do not use
1 – Test & Evaluation use only
2 – Code & carrier positioning use
3 – L1 only code navigation use
4 – Multi-frequency code navigation use
5 – General code and carrier navigation use
6 – Change of site coordinates – caution

Task 3c) Suggestions of possible techniques and algorithms

Unpack messages before transmission and verify that unpacking returns the original data. Verify that one-way code residuals are small. Verify that point-positioning solutions agree with a priori known reference station coordinates. This is similar to 3a) above.

This 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 (within, say, 100 meters of the primary), then the baselines are short and individual solutions could be performed for each data type. Today 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 the correct second site coordinates would be necessary conditions or there is a problem – for example the sites may 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. Refer to Task 3a discussion on the subject of residuals.

Thus four kinds of integrity solutions have been mentioned: point positioning; code differential; carrier differential; and interferometric single-epoch solution.

Task #4: Development of interface software for multiple brands of GPS receivers

Task 4a) Convert the XYZs demodulated output format into RTCM 18/19 compatible with existing user GPS equipment

XYZs has written a new software module "HAtoRTCM.EXE" which translates the GRIM-demodulated XCOR message into messages RTCM 18 & 19. These messages are compatible with existing RTCM 18 & 19 user compatible equipment. This software source and executable are deliverables as part of this contract effort. All software associated with this task can be found on the delivery CD in the directory that follows. The user's manual, for HAtoRTCM, can be found in the same directory.

CD:\RTCM1819.RTK

The outputs of this module were studied in two different ways. In the first effort RTCM 18 & 19 messages were converted back into RINEX format and compared with the original data prior to RTCM 18 & 19 formation. These data compared correctly.

The second and more practical method of testing was to output these RTCM 18 & 19 messages, from a PC comport, into RTCM 18/19 capable user GPS equipment. XYZs used their existing Ashtech Z-Xtreme dual frequency GPS receivers for this test. The Z-Xtreme needed to be configured according to the user manual. This Z-Xtreme has an installed "Carrier Phase Differential Remote RTK" option - ideal for such a test. The Z-Xtreme RTK positioning results were output to a different RS-232 port and returned to the original PC that formulated the RTCM messages which were sent to the Z-Xtreme. The returned results were gathered using the data capture function of a terminal emulation program such as XYZs Micro-Manager Pro, XYZs Remote32, or XYZs Terminal Window program. Any commercial terminal window program could have been used to capture this data as well.

The captured data were plotted and are presented in Figure 11.

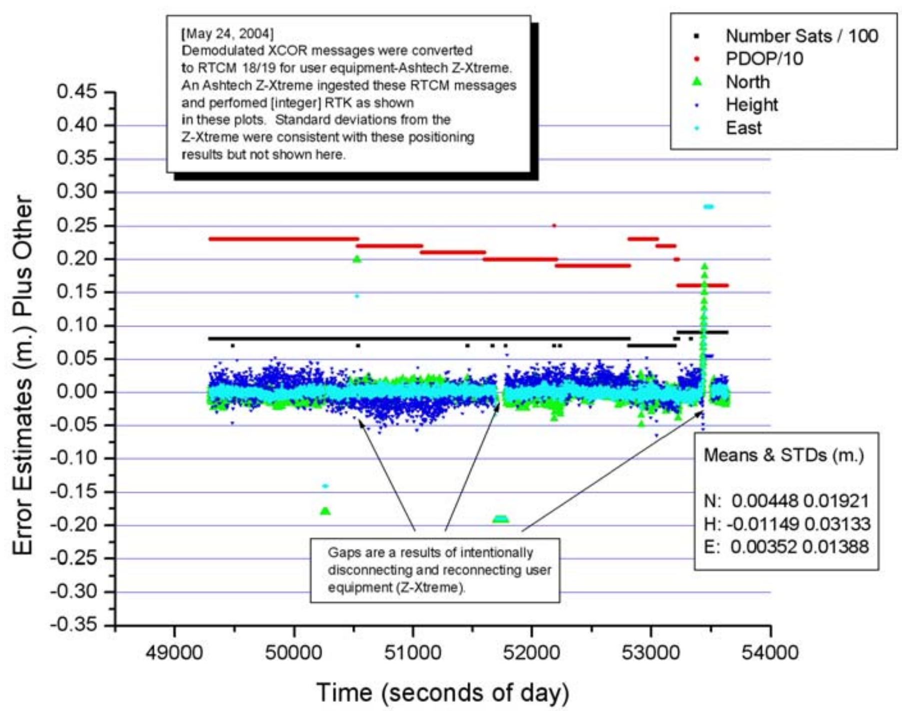

Figure 11. Demonstrated proof that GRIM to RTCM 18/19 works.

These results prove that RTCM 18 & 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 above. The number of satellites (divided by 100) and the PDOP (divided by 10) are included in the plot.

Notes: The above Task #4 discussion presents just one method of access to the HA-NDGPS signals: Demodulator receiver to GRIM; GRIM to HAtoRTCM.EXE; HAtoRTCM.EXE to user GPS receiver; GPS receiver output to whatever.

As a reminder, 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 what XYZs calls 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 XYZs. The "GRIM Developer's 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, there are currently three methods available for test and evaluation of HA-NDGPS messages.

Task #5: rewrite the modulator interface

Task 5a) Rewrite the existing modulator interface to implement a remote control capability via a TCP/IP Interface. Deliver appropriate source code.

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 which 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 much, much more. The HACP manual documents all of the commands; there are several dozens of 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, XYZs has extended the controls beyond those required. The command set is very extensive and allows the operator to query and command essentially all aspects of the HA-NDGPS operation. Following are a few specific examples. The complete set of commands can be found in the HACP manual.

What version are you?

Query: **$PXYZQ,RID**
Response: **$PXYZR,RID,s*1,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, its running, but has been commanded to stop.
$PXYZR,PRG,GRIM,ERR
Cannot find GRIM program.

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

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

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*

In addition to those required by the contract, XYZs has included several more. Here is another example where the operator queries for station coordinates, gets a status response, and later resets them to 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*

Software Delivery. The software developed to accomplish Task 5 includes an updated modulator interface and HACP. HACP stands for High Accuracy Control Program and is the primary software to handle configuration changes and distribute those changes to other software which carry out the changes. Thus, software source code for the updated modulator interface and HACP can be found on the enclosed data CD in following directory. The XYZs HACP user's manual is there as well.

CD:\HANDGPS.MODULATOR.HACP

Task #6: evaluate a low baud rate message (e.g., 100-300 baud) and processing at a data rate less than once every epoch

Task 6A2) Data were collected at reference station REMD (at 1 Hz.) in Dickerson, MD and user location MAST (also at 1 Hz.) in Dover, DE. The distance was approximately 180 km. The data were processed in RTK float mode so as to achieve dm. heights and half-dm. horizontals. The data used were full dual carrier and code observations like 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. At XYZs we call this velocity surprise; 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 as 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.
We are interested in how the trajectory changes due to the thinning of the reference station data (REMD) due to a reduction in bandwidth. When the bandwidth changes from 1000 bps to 200 bps, for example, the broadcast message takes 5 times as long to arrive and cannot be applied for user processing until 5 seconds after his data were observed as depicted in Table 1, below. In addition to that, he must continue to use the latent data for another 4 seconds. (i.e., he uses the same reference station broadcast measurements, predicted forward, for 4 additional seconds.) Thus, in a typical RTK scenario he would use the data from 5 seconds old to 9 seconds old. Should a broadcast message be corrupted by background noise, and need to be discarded by the user, his use of the data would continue beyond 9 seconds old, an out to 14 seconds old. After a gap the full accuracy is returned immediately.

This is considered a typical RTK scenario. There are other scenarios available to the user depending on his mission. It is possible, for example, for the user to hold off his processing by 5 seconds and only process time aligned data. Another scenario would be to process with 5 seconds of latency and set an inertial unit. In this scenario, one would expect the inertial unit to be more accurate than GPS.

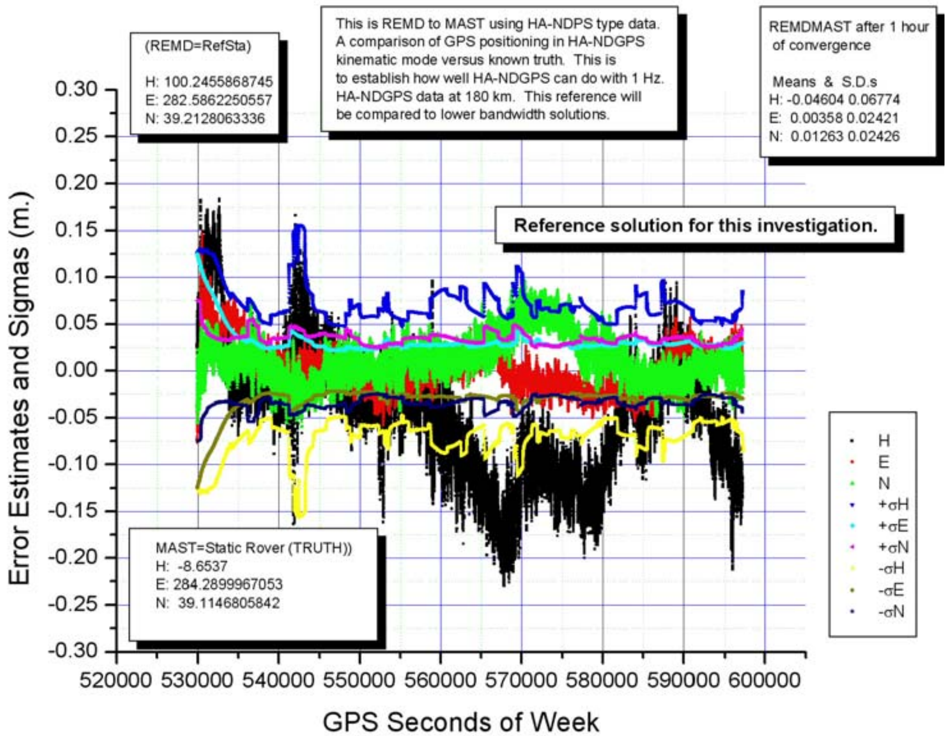

Figure 12. Expected HA-NDGPS performance at 180 km.

In Figure 12 we compare the RTK solution (180 km.) with millimeter truth after an initial convergence period – not shown. The N-S and E-W components are better than 5 cm. whereas the height is good to about 1 dm. This "1-second REMD, 1-second MAST" RTK solution will be used, throughout this Task #6 discussion, as a basis of comparison for the lower-bandwidth (thinned) cases which follow.

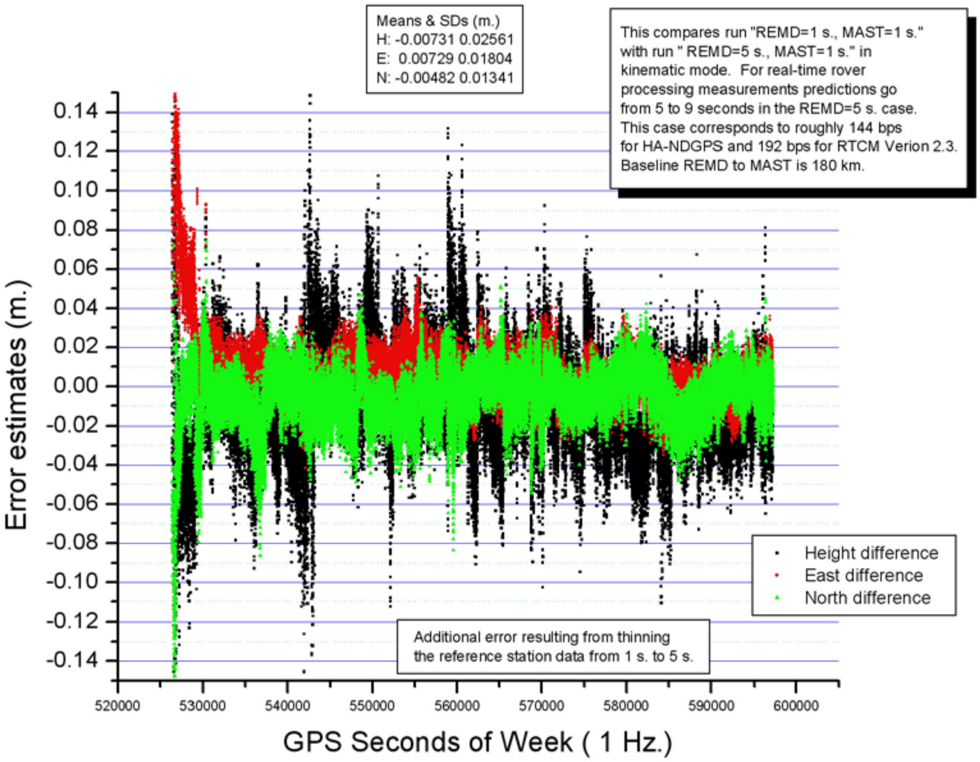

Figure 13. Comparing 5-second broadcast with 1-second broadcast from HAG1.

Table 1 attempts to describe the time line. In the 0 second column the reference station collects GPS measurements at the 0 second instant. Between 0 seconds and 4 seconds, as an example, the data are broadcast to users. These users must wait nearly 5 seconds for the bit by bit broadcast to be completed, and for the data packet to be received and demodulated, before the user can exploit it. This is depicted in the table. The user cannot make use of this packet in any way until the entire packet has been received. Why must the user wait for all the bits? The simple answer is the message in full must pass the parity check before he can trust it. The more complex answer is a full packet needs to be gathered and recognized, at least in the current design, before sending it to the parser and the interpreter – all prior to passing it on to the user application. Refer again to the table below. Note that the data collected at second 0 did not begin to be used by the user application until second 5; notice the user continued to use the second 0 data until 9 seconds. The table depicts a 1 second user scenario. If the user was 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.

0	1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7	8	9	0	1	2	3	4	5	6	7
c					**c**					**c**					**c**					**c**					**c**		
o					**o**					**o**					**o**					**o**					**o**		
l					**l**					**l**					**l**					**l**					**l**		
l					**l**					**l**					**l**					**l**					**l**		
e					**e**					**e**					**e**					**e**					**e**		
c					**c**					**c**					**c**					**c**					**c**		
t					**t**					**t**					**t**					**t**					**t**		
e					**e**					**e**					**e**					**e**					**e**		
d					**d**					**d**					**d**					**d**					**d**		
s	**s**	**s**	**s**	**s**	**s**	**s**	**s**	**s**	**s**	**s**	**s**	**s**	**s**	**s**	**s**	**s**	**s**	**s**	**s**	**s**	**s**	**s**	**s**	**s**	**s**	**s**	**s**
e	**e**	**e**	**e**	**e**	**e**	**e**	**e**	**e**	**e**	**e**	**e**	**e**	**e**	**e**	**e**	**e**	**e**	**e**	**e**	**e**	**e**	**e**	**e**	**e**	**e**	**e**	**e**
n	**n**	**n**	**n**	**n**	**n**	**n**	**n**	**n**	**n**	**n**	**n**	**n**	**n**	**n**	**n**	**n**	**n**	**n**	**n**	**n**	**n**	**n**	**n**	**n**	**n**	**n**	**n**
t	**t**	**t**	**t**	**t**	**t**	**t**	**t**	**t**	**t**	**t**	**t**	**t**	**t**	**t**	**t**	**t**	**t**	**t**	**t**	**t**	**t**	**t**	**t**	**t**	**t**	**t**	**t**
0	**0**	**0**	**0**	**0**	**5**	**5**	**5**	**5**	**5**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**
										0	**0**	**0**	**0**	**0**	**5**	**5**	**5**	**5**	**5**	**0**	**0**	**0**	**0**	**0**	**5**	**5**	**5**
					u	**u**	**u**	**u**	**u**	**u**	**u**	**u**	**u**	**u**	**u**	**u**	**u**	**u**	**u**	**u**	**u**	**u**	**u**	**u**	**u**	**u**	**u**
					s	**s**	**s**	**s**	**s**	**s**	**s**	**s**	**s**	**s**	**s**	**s**	**s**	**s**	**s**	**s**	**s**	**s**	**s**	**s**	**s**	**s**	**s**
					e	**e**	**e**	**e**	**e**	**e**	**e**	**e**	**e**	**e**	**e**	**e**	**e**	**e**	**e**	**e**	**e**	**e**	**e**	**e**	**e**	**e**	**e**
					d	**d**	**d**	**d**	**d**	**d**	**d**	**d**	**d**	**d**	**d**	**d**	**d**	**d**	**d**	**d**	**d**	**d**	**d**	**d**	**d**	**d**	**d**
					0	**0**	**0**	**0**	**0**	**5**	**5**	**5**	**5**	**5**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**2**	**2**	**2**
															0	**0**	**0**	**0**	**0**	**5**	**5**	**5**	**5**	**5**	**0**	**0**	**0**

Table 1. Depiction of measurement collection, broadcast, & usage time line for HA-NDGPS.

In Figure 13 we compare the 1-second REMD 1-second MAST (1000 bps) RTK solution (180 km.) with the 5-second REMD 1-second MAST (200 bps) RTK solution.

We would like to emphasize that this is the change which results from the reduced bandwidth rather than the error penalty one suffers when compared with millimeter truth. The additional error caused by the bandwidth reduction and the added latencies is about 1 inch or 0.25 dm.

Table 2 compares this 5-second scenario against millimeter truth.

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

Table 2. Accuracy performance of 5-second broadcast scenario. Compare these statistics with the 1-second broadcast scenario (Fig. 12) to see there is no significant accuracy performance degradation when data are broadcast based upon 5 second epochs.

The above table suggests 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, -1, 17 mm.) are similar to those shown in Figure 12 (-46, 4, 13 mm.). The standard deviations (68, 25, 25 mm.) are almost identical (68, 24, 24 mm.).

We next present the 10-second REMD/1-second MAST case. Obviously the bandwidth would be halved and the latencies would be doubled. Increasing the epoch spacing helps us understand how much degradation would 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 which soon follow. Let us next present the 10-second/1-second results.

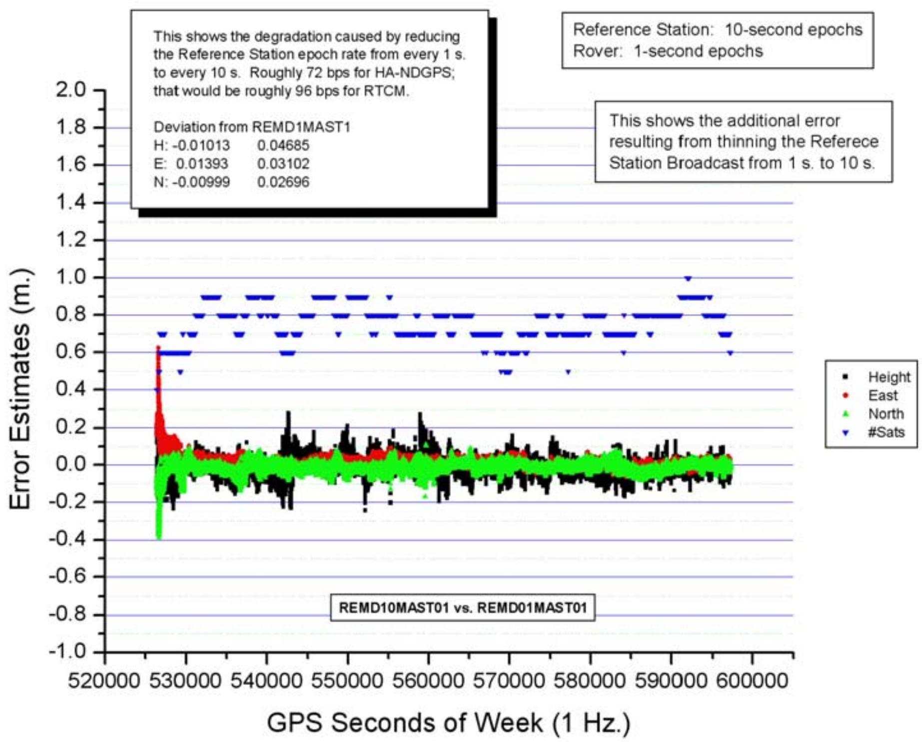

Figure 14. Comparing 10-second broadcast with 1-second broadcast from HAG1.

In Figure 14 we show the error which 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 case, the results are still very good. Please remember, even in the 10-second case some [positioning] users will be satisfied with processing 10-second aligned epochs roughly 10 seconds late.

Table 3 shows how this 10-second/1-second RTK scenario compares with millimeter truth.

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

Table 3. Accuracy performance of 10-second broadcast scenario. Compare these statistics with the 1-second broadcast scenario (Figure 12) to see there is possibly a 10% accuracy performance degradation when data are broadcast based upon 10 second epochs.

Clearly the absolute error in the horizontals has grown from the half-decimeter 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.

We present the 15-second/1-second case to suggest that while the error indeed increases, the error growth is still gradual.

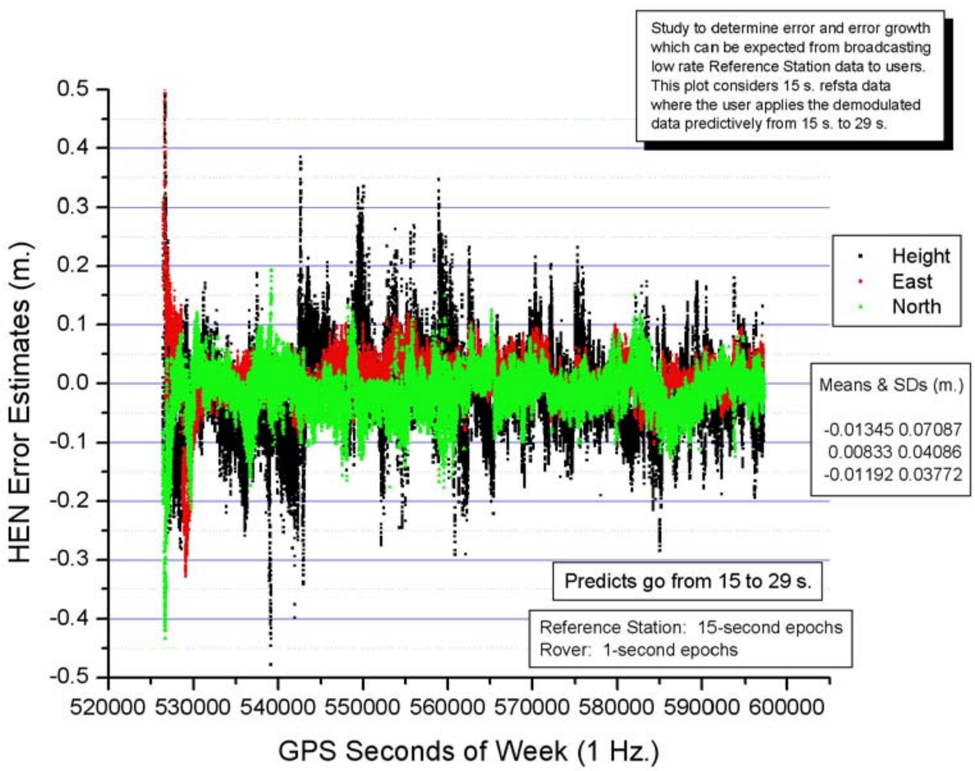

Figure 15. Comparing 15-second broadcast with 1-second broadcast from HAG1.

In Figure 15 we compare the 15-second/1-second case with the original 1-second/1-second case. The error shown is the result solely due to thinning the data broadcast to 15-second epochs and reflects the increased latencies. The absolute error associated with this case is shown in the following table.

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

Table 4. Accuracy performance of 15-second broadcast scenario. Compare these statistics with the 1-second broadcast scenario (Fig. 12) to see there is possibly a 50% accuracy performance degradation when data are broadcast based upon 15 second epochs.

Clearly the error increase is significant and undesirable. After all, 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.

Finally we present, in Figure 16, 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 would end the use of same 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).

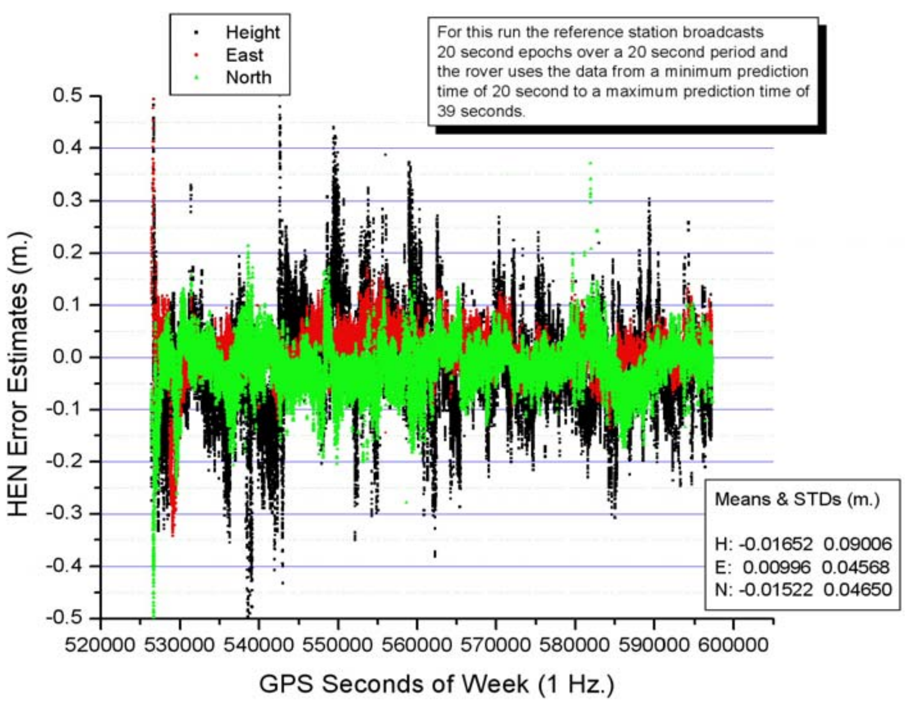

Figure 16. Comparing 20-second broadcast with 1-second broadcast from HAG1.

The horizontal error resulting from the reduced bandwidth remains under 1 dm. Table 5 compares the results of the 20-second/1-second case compare to millimeter truth.

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

Table 5. Accuracy performance of 20-second broadcast scenario. Compare these statistics with the 1-second broadcast scenario (Fig. 12) to see there is possibly a 100% accuracy performance degradation when data are broadcast based upon 20 second epochs.

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 ought to 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. Four, the addition of an integrity message would require several more bits. These four points would bring the broadcast rate to possibly <u>200</u> bps. Next we would want to include L5 code and carrier measurements. For 12 satellites this would require possibly 600 additional bits over 5 seconds or <u>120</u> bps – maybe somewhat less. In addition, one might include additional information such as tropospheric zenith delay parameters, ionospheric zenith delay parameters, and/or precise orbit parameters. While the incremental bandwidths for these are difficult to estimate, at this time, nevertheless, first estimates will be attempted in what follows.

XYZs first estimates are 900 bits for a tropospheric delay grid or <u>25</u> bps for 3 minutes at 5 second epochs. The precise orbits might take <u>60</u> 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 would require a wider range of values. A first crude estimate might be <u>45</u> bps. These estimates sum to 450 bps - assuming a 5-second broadcast. Now, it is quite possible that the broadcast of precise orbits would never be required as those 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 2.5, or so, 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 and therefore may not be required. Clearly a tropospheric delay grid has the most potential value to users.

In summary, 500 bps ought to be adequate to serve the public – for GPS alone. Should it be decided 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.

To repeat, XYZs does have smaller parent/child packet messages which have been laboratory tested but they have not been evaluated with regard to HA-NDGPS. So far XYZs broadcasts have been of a single packet variety whereby an entire epoch is broadcast in a single packet (like the RTCM-104 Type 1 message). XYZs multi-packet formats have some additional overhead, but there would be increased odds of message packets reaching distant users. Again, smaller multi-packet (parent/child) packets have not been exercised in the field; it is anticipated that they will be field tested in the months ahead.

Note: It should be mentioned that, in general, data gaps do not cause any 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. Should data packets be missed, there would be a gradual increase in positioning error - as the above has shown. When the next packet arrives and passes the 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 7a) Collect data for mapping one or more highway segments

XYZs traveled Route 15 north of Frederick MD on two separate driver analysis runs. In each run there were 8-9 loops of 12 miles or more. Sections, roughly 4 km. going north, and roughly 4 km. going south, were studied - since the van was able to maintain the same lane in those highway stretches. A map taken from MapQuest is shown in Figure 17.

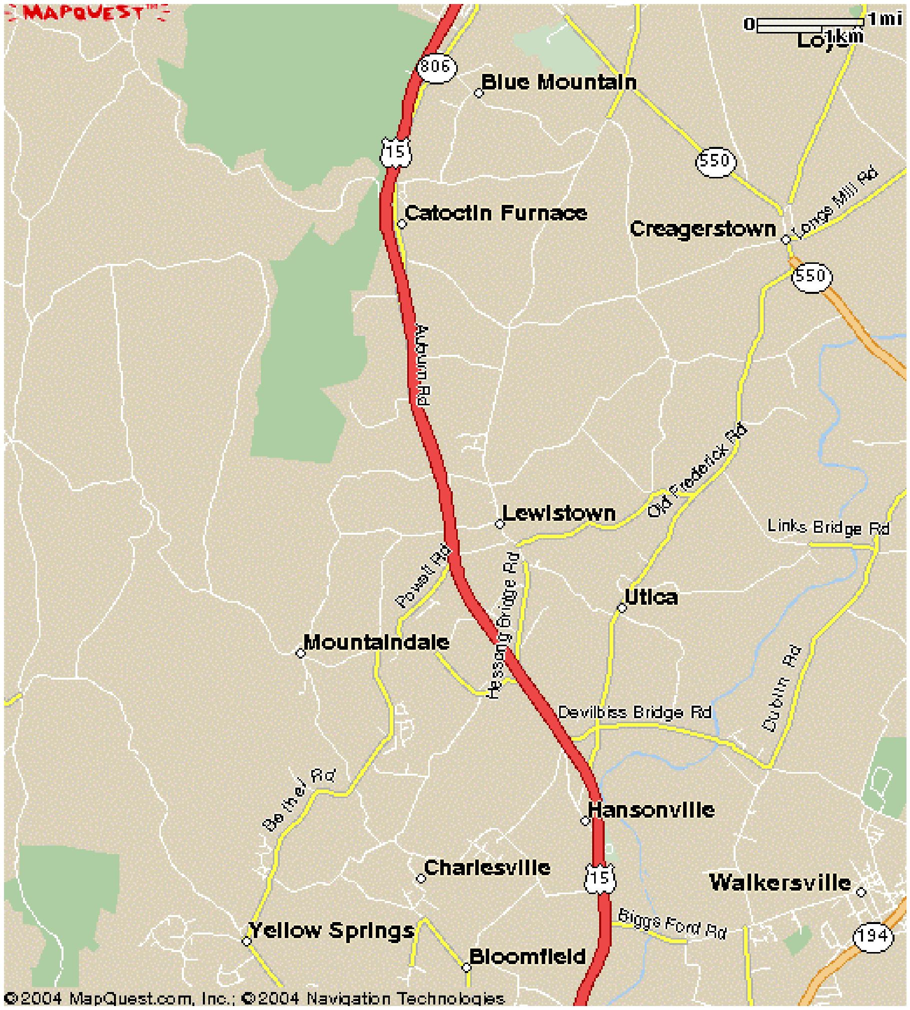

Figure 17. U.S. Route 15 north of Frederick, MD.

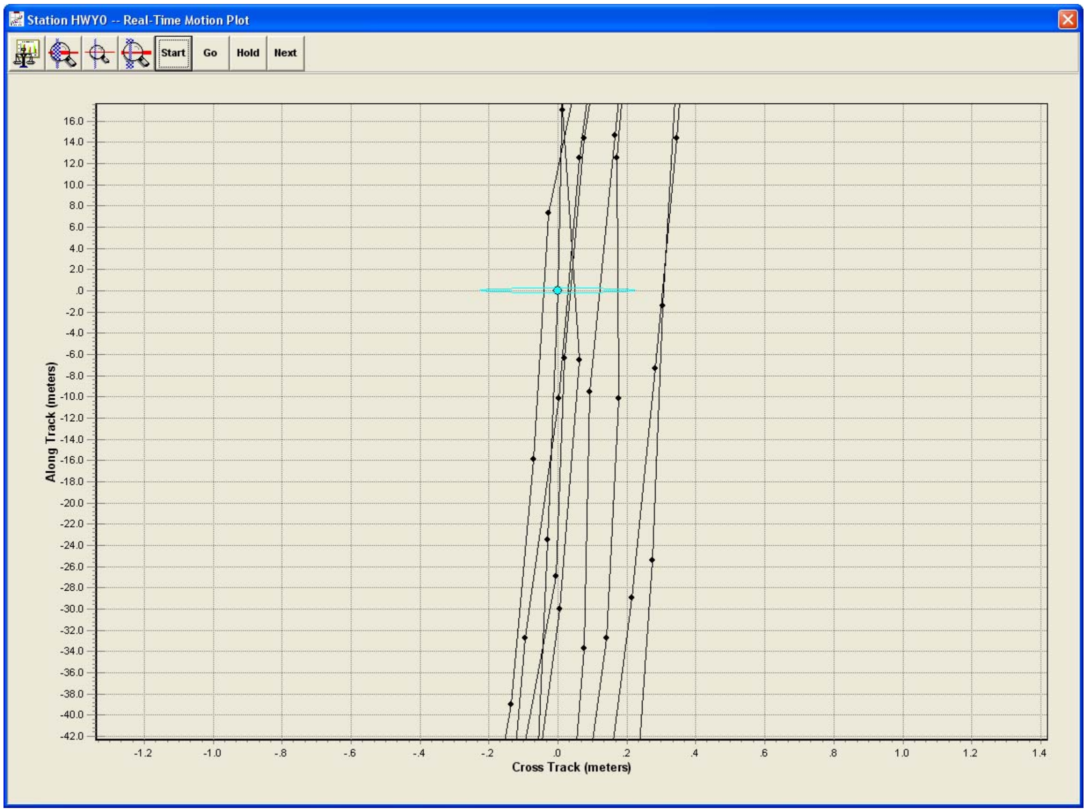

Figure 18. Display of 9 tracks driven on U.S. Route 15 north of Frederick, MD.

The Real-Time motion plot in Figure 18 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. As will be seen below, the driver was able to repeat his track within 14.5 cm (rms).

From these runs we created the “definition” of the road using the same program that was used to process the measurements (XYZs DynaPos.exe). Below is small segment the roadway created manually as a visual average of the 9 loops.

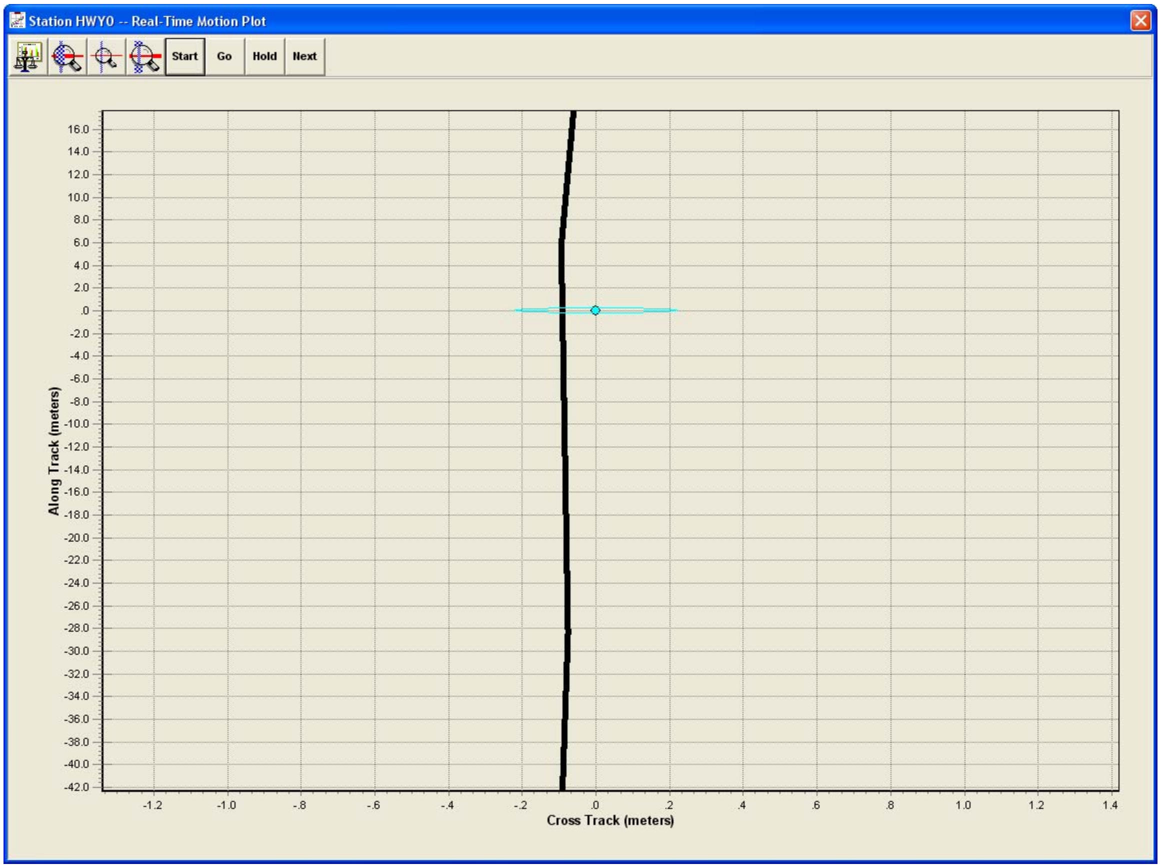

Figure 19. Display of defined “road map” created from 9 tracks in Figure 18.

It is also possible to show all 9 loops superimposed upon the roadway.

Bear in mind that the roadway was determined in float processing mode and is probably accurate at the 5-centimeter level after the first couple of loops. XYZs DynaPos.exe could have determined the roadway precisely (1 cm.) with a local reference station and subsequently operated in real time based upon Hagerstown broadcast. This was not done. For this effort, the HA-NDGPS broadcast was used both to create the map and to determine driver’s tracks upon the same map.

Task 7b) **Compare the driver’s control of the vehicle**

Next I present the driver’s cross-track history with respect to the created road map.

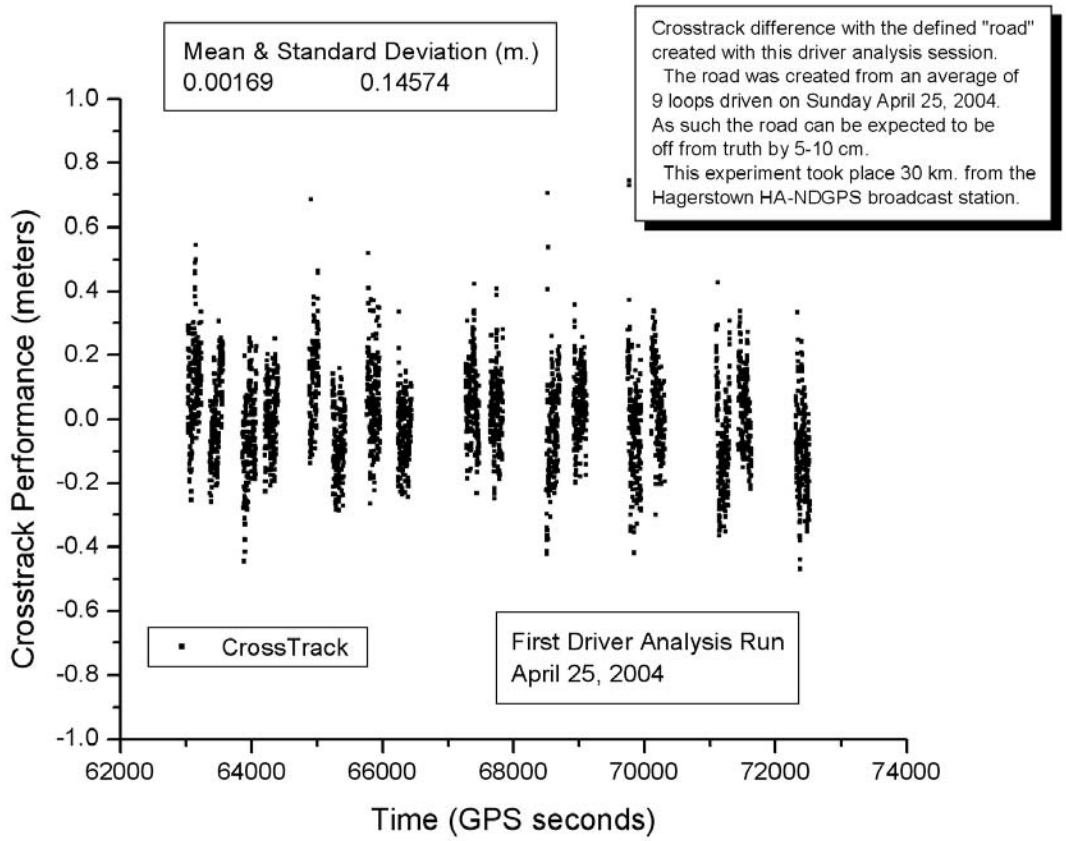

Figure 20. Presentation of driver cross-track (i.e., left/right) driving variation for the 9 loops associated with Figures 16 and 17.

In Figure 20 are the cross-track distances from the mapped road when the van was on the north-bound and south-bound segments of each loop. The gaps represent the portions of the loops where repetition was not possible due to traffic safety.

How was the cross-track quantity computed? First the "road" was defined to be the average of the 9 tracks; the average was generated visually. Since there were 9 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 9 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, east, and the perpendicular to north and east, ellipsoidal height. Now individual points on the 9 tracks could be converted to this topocentric frame and compared with the closest point in the set of road points. This is done but the result is not too interesting since we are not interested in comparing the NEH of the tracks with NEH of the road. So we make one more transformation. We compute the relative azimuth of two consecutive points on a track. We then rotate 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 have been 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 20.*

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. This would be expected. Clearly the roadway would be better defined based upon 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 21 shows how the van was configured for the Route 15 driver analysis runs. Please notice there was no attempt to place the user's local GPS antenna along the center of the van.

Figure 21. Van configuration used for driver analysis on U.S. Route 15.

Task #8: Studying levels and possible noise reduction at the Hagerstown site.

Task 8a) Locate GPS antenna high above possible nearby multipath sources and compare the cleanliness of the measurements there with measurements from current NDGPS equipment.

Task 8b) Use like antennas, at both reference and a nearby user site, to gather observations and fix the integers to establish the level of site cleanliness.

For Task 8, 8a) and 8b) will be discussed together.

XYZs had its machine shop fabricate a pentapod apparatus to install high above the Hagerstown HA-NDGPS GWEN site so as to be as clear of signal multipath as could be done easily. This allowed XYZs to compare signals with the existing NDGPS antenna locations.

Figure 22 is a photo of the Hagerstown facility with the XYZs pentapod located on the roof and the HAG2 NDGPS GPS antenna protective dome in the background to the right.

Figure 22. Photo of the Hagerstown GWEN site. In the back is the HAG2 site. On top of the hut is a pentapod with a marine antenna placed 4-5 meters above the hut in the search for cleanest signals. The HAG1 site was behind the camera. The 299 foot mast is several hundred feet to the right.

At first we selected HAG2 to be the HA-NDGPS antenna and receiver. In this case the antenna was a 700829 (3) “Whopper” antenna from Ashtech coupled with an NDGPS Z12R RS (reference station) GPS receiver. We instrumented the XYZs van with a like antenna as can be seen in Figure 23.

Figure 23. Van configuration used for multipath testing at the Hagerstown GWEN site. In this case NDGPS Whopper to van Whopper is under test.

Next we collected HA-NDGPS broadcast messages from HAG2 and processed the data as shown in Figures 24 and 25. Initial convergence was slower than usual (Figure 24) and we interpreted this to indicate there was significant code multipath. Later in the processing there was adequate convergence to fix the ambiguities to integers (Figure 25). In this case the results were extremely stable. We interpreted this to mean the carrier multipath was not a factor and the Whopper geodetic antenna provided excellent carrier measurements.

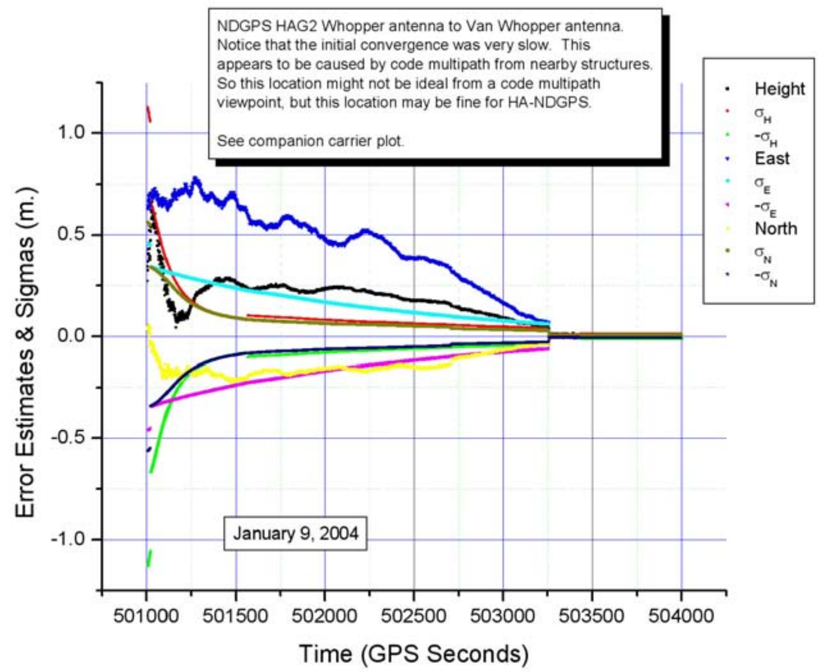

Figure 24. NDGPS "Whopper" antenna to van "Whopper" antenna initial convergence.

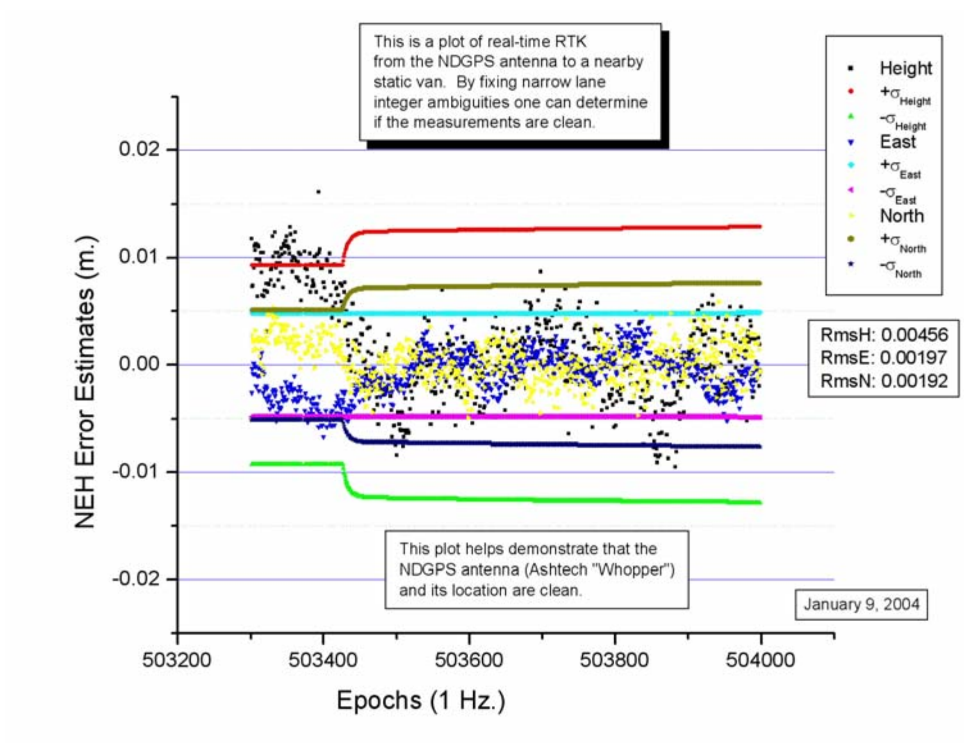

Figure 25. NDGPS Whopper antenna to van Whopper antenna steady state with integers fixed.

Next we used the Ashtech 700700 (B) marine antenna on top of the hut as the HA-NDGPS antenna along with an Ashtech Z12 Real-Time Sensor GPS receiver. The van was also configured identically as shown in the Figure 26 photo.

Figure 26. 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 the Figure 27. We interpret 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.

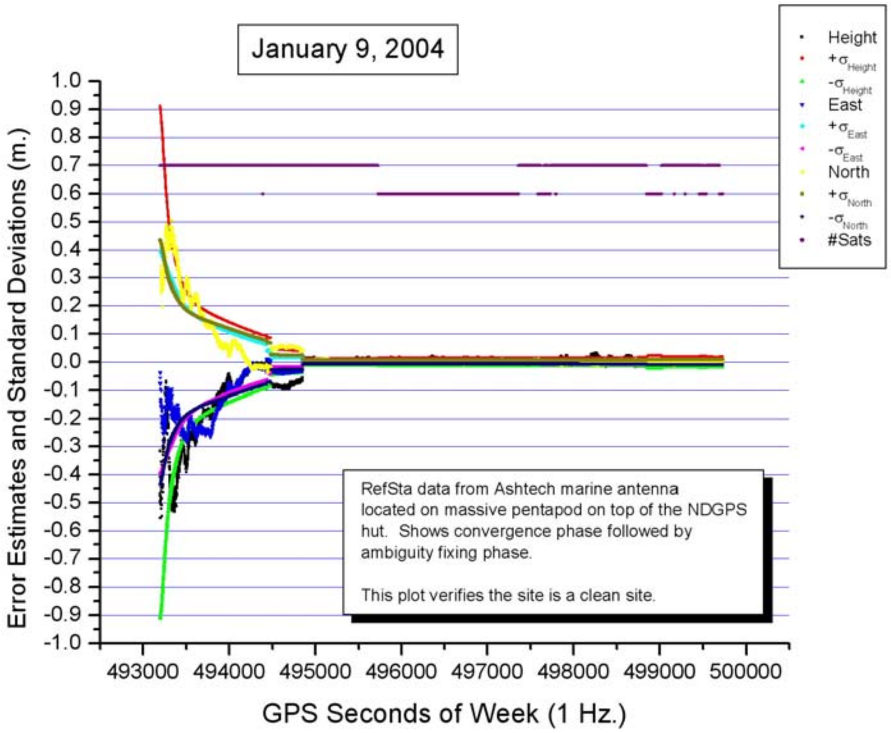

Figure 27. HA-NDGPS marine antenna to van marine antenna initial convergence.

After the results converged sufficiently to fix ambiguities to integer values, the integers were fixed as shown in Figure 28. The solution with integers fixed looked similar to the integer fixed solution using the Whopper. We interpret this to mean both sites are clean with respect to carrier multipath.

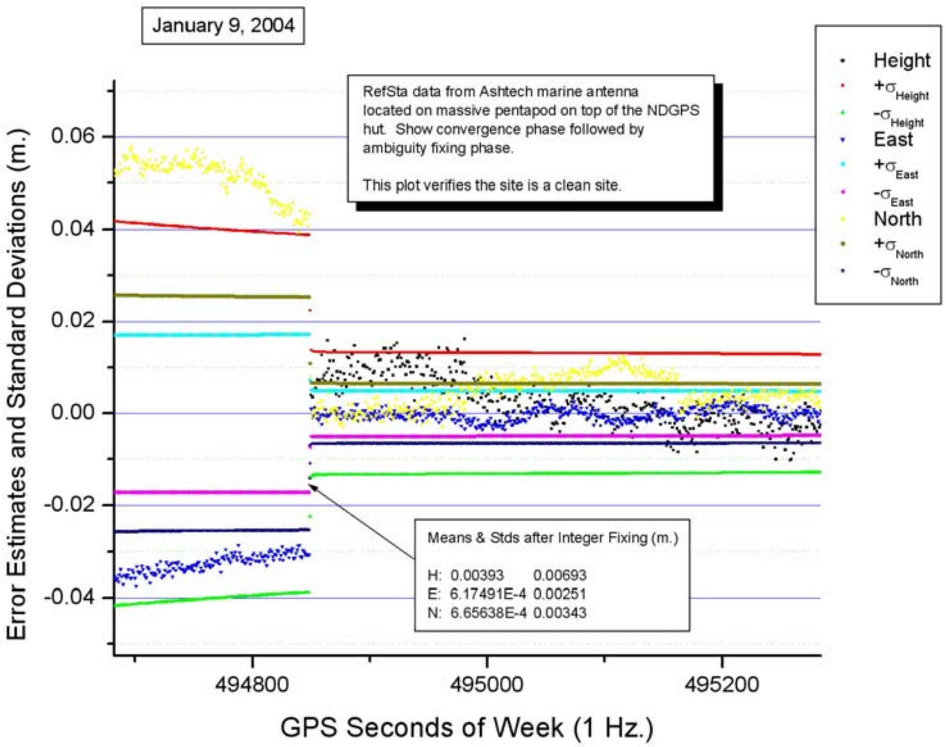

Figure 28. HA-NDGPS marine antenna to van marine antenna steady state with integers fixed.

In summary, NDGPS sites appear to have very high quality carrier observations. On the other hand, the NDGPS site code observations might have experienced significant multipath. This is potentially 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.

(Separately, it needs to be noted that when NDGPS Whopper antennas are mixed with 700700 (B) marine antennas the results will not be very good unless antenna modeling such as is performed by NOAA/NGS is included.)

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