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High Accuracy Nationwide Differential Global Positioning System Merging Concepts and Techniques from the Past and Present

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This paper describes the development and of the High Accuracy Nationwide Differential Global Positioning System (NDGPS), which augments GPS, providing a 10 centimeter positioning accuracy in real time. As a low frequency broadcast using the groundwave technique to broadcast corrections to users on the surface, the broadcast overcomes obstructions commonly limiting use of satellite based services. It was developed to meet the demands of surface based safety related transportation services in both the maritime and land based modes including the Intelligent Transportation System. HA-NDGPS is intended to support a wide range of current and future positioning and navigation requirements for federal, state and local government agencies. Some of the current and future needs of the private sector may also be satisfied, but this is not the primary purpose of the system. Dual coverage will improve system availability from 99.7%-99.9%, meeting the accuracy, integrity, and availability requirements of many safety applications.

1. Introduction.

The High Accuracy Nationwide Differential Global Positioning System (HA-NDGPS) project was established to assess the implementation feasibility for improving the accuracy of the NDGPS service, using the existing infrastructure, to meet the requirements of additional applications without decreasing availability and integrity and still meeting the needs of existing users. Partner agencies include:

Federal Highway Administration
US Coast Guard
Federal Railroad Administration
US Army Corps of Engineers
National Geodetic Survey
Forecast Systems Laboratory
Interagency GPS Executive Board

1.1. Goals.

The project had three major goals. These were to examine ways to enable 3-D dynamic positioning at the centimeter level throughout the US, coexist with existing infrastructure, and minimize deployment costs.

1.2. Project Development.

The project was divided into three broad phases. The first phase emphasized development and integration. Some of the milestones addressed included:

- Develop Modulator and Data Link Receivers
- Interface System Modules
- Broadcast Characterization and Optimization
- Single Site Concept Demonstration

Phase II emphasized pushing the limits and trying applications that could be enabled with the greater

accuracy and integrity provided by HA-NDGPS. It emphasized:

- Pre-Broadcast Integrity Algorithm Development
- Multiple Site/Baseline Concept Demonstration
- Ionosphere/Troposphere Prediction
- Application Development

In Phase III, project development into a fielded system is the focus. Some of the areas addressed include:

- Development of Agency Responsibilities
- Integrate Into Existing and Future NDGPS Sites and Control Stations
- Finalize Site Software
- Integrity
- Compression
- Troposphere and Ionosphere Models
- Finalize and Validate
- Develop Compression

2. System Description.

The HA-NDGPS concept broadcasts all code and carrier phase observables for L1 and L2, for up to 12 GPS satellites each second. The system has the capability to include L2C, L5, and other satellite constellations (i.e. Galileo) as they become available, also each second.

2.1. Broadcast Description

The modulation is raised cosine minimum shift keyed, synchronized to GPS. This makes for a very efficient broadcast that can support a multitude of uses.

2.1.1. Data.

The data to be broadcast includes GPS Satellite observables (both code and carrier), data for a tropospheric model, data for an ionospheric model, precise orbit data, and integrity. It can also accommodate observables for other navigation satellite constellations (Galileo, GLONASS, etc), and augmentation systems if they are deemed capable of providing sufficient data to make them useful.

2.1.2. Data Rate

The data rate used to date is 1000 bits per second. This allows for the transmission of all GPS observables in 1-second epochs from 12 GPS satellites. As additional data is added, this is reduced. For example, adding Galileo to the data set would reduce the GPS observables to once every two seconds. Since there is no reason to provide Galileo data every other second, it could be provided every fifth second with GPS observables four out of five seconds. When Galileo becomes available or decisions made on the use of GLONASS, appropriate analysis will be completed to identify the appropriate amount of data that is needed for these other navigation constellations. It may also be possible to increase the data rate at some broadcast locations due to extended coverage and increase signal reliability at longer ranges.

2.1.3. Synchronization.

Both the data and the carrier are synchronized to GPS. In the event GPS fails, synchronization will be maintained with an internal facility atomic clock. Synchronization was done initially to improve the data link reliability at the edge of the coverage area. It provides a moderate processing gain. While this is still the primary goal, it is important to note that carrier synchronization of both the HA-NDGPS and the NDGPS creates a new capability. The dual broadcast from the facility can serve as a ranging signal independent of GPS. The accuracy has not been determined but, depending on the modulator and the transmitter characterization and the distance to the broadcast facilities, the accuracy, in free space, could be better than 1 meter.

2.1.4. Frequency.

The frequency band identified for the broadcast is 435 kHz to 495 kHz. This is a relatively little used portion of the spectrum and is currently allocated for Maritime Mobile on a primary basis and Aeronautical Radionavigation on a Secondary basis. There is no Maritime Mobile operations in the US and little Aeronautical Radionavigation usage. There are certain frequencies that should not be used. 455 kHz is a prime intermediate frequency (IF) used by many inexpensive radios. By their very nature, they are

susceptible to interference. While the HA-NDGPS service can legally use this frequency, staying away from it reduces the potential for interference to these devices. Additionally, NAVTEX uses 490 kHz for local broadcast in other than English and, while not used in the US, broadcast on 490 KHz has the potential to impact foreign users. Thus, we will not use 490 kHz. This leaves more than 50kHz available across the US. By reusing frequencies and spacing adjacent facilities no closer than 3 kHz, sufficient spectrum will be available.

2.2. Proof of Concept Deployments.

Three prototype systems have been deployed to date. These are located at Hagerstown, MD, Hawk Run, PA, and Topeka KS. Plans are to install one more at St. Mary's WV as soon as the site is established. The site locations are highlighted in Figure 1.



Figure 1. Site locations

2.2.1. Broadcast Configuration.

Figure 2 shows the configuration for the broadcast of the HA-NDGPS data. The existing GPS Reference Station (RS) is connected to the rack mount personal computer (PC) via an unused bi-directional RS-232 port. The RS is instructed to generate observables at 1-second epochs and this data is then analyzed in the PC to ensure it meets specific criteria for integrity. The data is then compressed and modulated in the PC and sent to the transmitter where the signal power is increased up to 3 KW and fed to the antenna for broadcast. Note that the data is stored within the PC for later use if needed.

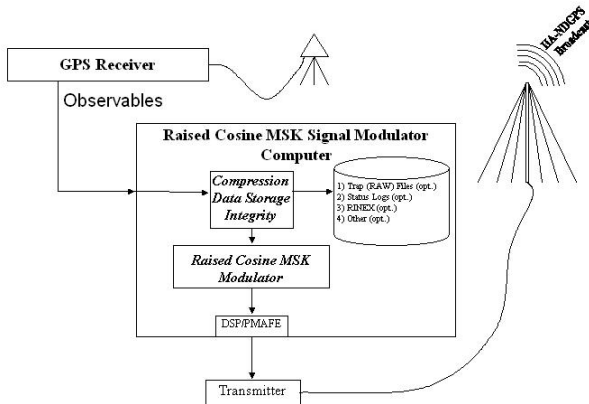


Figure 2. Site Configuration

2.2.2. Site Modifications.

Figure 3 is a block diagram of what equipment was added to the NDGPS facility to support the prototype HA-NDGPS broadcast. The equipment added includes a rack mount PC, a transmitter, and a diplexer. The rack mount PC includes a data formatter and modulator card (Figure 4) as well as the data compression and modulation software. Additional cabling includes the RS-232 connection between the RS and the PC, a cable taking the 1 PPS signal from the receiver to the PC, the low power RF cable between the PC and the transmitter, and some 400 feet of LDF-450 between the transmitter and the diplexer.

Two different transmitters have been used. The first was a 1500W unit from Nautel, Inc. This was chosen to meet signal stability and power output requirements. The additional transmitters are 3000W units, again from Nautel, Inc.

The diplexer was designed by Morgan Burroughs and Associates and built by the Saxton Highway Electronics Lab. Figure 5 shows three of the six panels of the diplexer after it was mounted inside the ATU hut at the base of the broadcast tower. Note that the large inductor is approximately 4 feet tall. This gives some idea of the size of the unit.

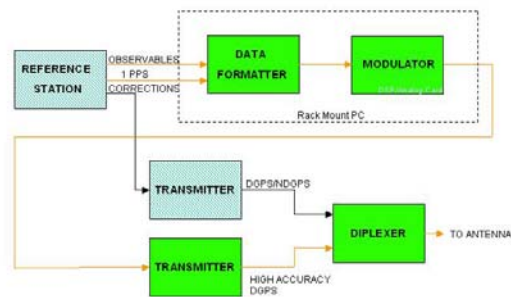


Figure 3. Site Block Diagram



Figure 4. Data Formatter and Modulator Cards



Figure 5. Diplexer

2.3. End User Prototype Configuration.

The end user configuration is just as straight forward as the broadcast configuration. The signal is received and demodulated. The demodulator supplies a

data stream to the laptop PC. Within the PC, the data is decompressed, stored, and provided to an application residing on the same PC. The example shown combines the demodulated and decompressed observables with GPS data to calculate a solution. In the test configurations we use, all data is stored to the hard drive in the computers so that it can be played back later.

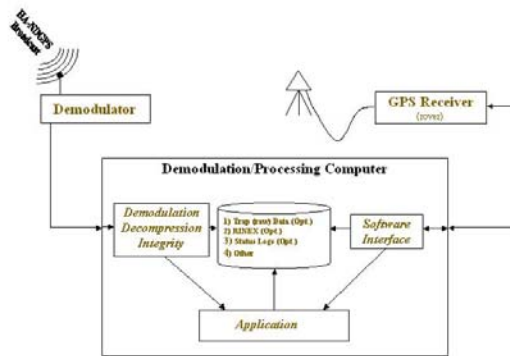


Figure 6. End User Equipment Block Diagram

3.0 Deployment Configuration.

3.1. Broadcast Facility

3.1.1. Hardware Configuration.

Figure 7 is a block diagram of the proposed broadcast facility as it would be in a fully updated and recapitalized NDGPS broadcast facility. Note that the additions to the baseline provided by the Coast Guard include a PC, atomic clock, transmitter, RS232 Ethernet converter, coupler, diplexer, computers and low power RF cables, and a roughly 400 foot long RF cable from the amplifier to the coupler. It is important to note that the diplexer design did not take into account that a coupler would be installed and vice versa. Thus, it is possible to design portions of the diplexer into the couplers, reducing costs, space, and potential equipment failures.

3.1.1.1 Transmitter.

During discussions with transmitter manufactures, it has been determined that it may be possible to combine the two amplifiers into a single unit with common modules. There are questions concerning the cost and reliability of such a unit. The additional cost, if any, may be offset by the reduced cost of shelters for established broadcast sites.

3.1.1.2. Atomic Clocks

The atomic clocks that assist in maintaining a backup navigation capability are directly linking one GPS receiver with two reference stations. This is not

likely to be the final configuration but is provided here for simplification. When the final design is complete, it may be possible to provide the time synchronization through the network devices, but care must be taken to ensure no unknown delays occur.

3.1.1.3. GPS Receivers

The GPS receivers identified in the block diagram are L1/L2 units. It is expected that this will be upgraded to include L5 and Galileo as these signals and systems become available. If at all possible, these should be procured early in the deployment program in order to maximize the usefulness of the system. Since much of the control of these receivers is performed in software, the software can be upgraded via the frame relay network connection.

3.1.1.4. Computer

The PC contains not only software to interface to the various GPS receivers, but also the modulator card and its associated software. The modulator card for HA-NDGPS could, potentially, reside in the same computer as the legacy modulator. In the diagram shown here it was drawn as a separate computer due to the limited space within the currently identified computer. The Coast Guard has already procured several of these computers and, unfortunately, they do not have sufficient space to support two modulator cards. Two potential configurations could be employed. The first would have four computers for each site, using the supplies already procured. The second could have two computers per site, using a newly procured computer with sufficient space for two modulators.

3.1.1.5. MSK Receiver

The MSK receiver is a multi-channel device use to monitor the local broadcast, both legacy and HA-NDGPS. It could be used to monitor adjacent sites as well, providing status information to the Network Control Station if communication with the adjacent site is lost.

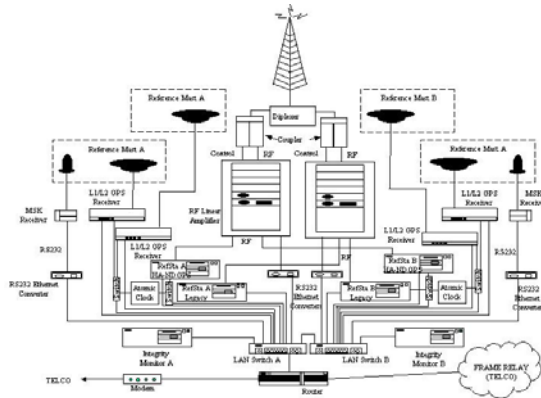


Figure 7. Proposed Broadcast Facility Block Diagram

3.1.2. Software.

There are three main software programs within the HA-NDGPS systems; (1) a program to interface with the GPS receiver and compress the observables, (2) a program to modulate the compressed observables onto the 450kHz carrier, and (3) an overall control program.

3.1.2.1. GPS Receiver and Reference Station.

Communications between the GPS receiver and the Reference Station PC, be it HA-NDGPS or legacy, is over the Ethernet link. In the existing configuration interface software from Trimble is used to pull data from the GPS receiver and format it for the modulator. This software, GPS Receiver Interface Module (GRIM), is available off-the-shelf and can be used for both the HA-NDGPS system and the legacy system. GRIM offers several compression schemes as well as data storage options, each selectable by the user.

3.1.2.2. Modulator

The software for the modulator has gone through several iterations from the initial development program. It is now finalized and an easy to use graphical user interface (GUI) has been developed. It can be used to select the modulation frequency and data rates, among other options.

3.1.2.3. Control Software

Both GRIM and the modulator program can be controlled, or initiated, by the High Accuracy Control Program (HACP). In the event power is lost to the computer, HACP provides the initiation routine to enable both GRIM and the modulator program without a control operator needing to intervene.

3.1.3. Additional Information to the End User

3.1.3.1. Integrity.

Integrity has not been fully defined at this point. Currently we examine the residuals and if they fall outside a predetermined bound, the data from the satellite that causes that out of bound condition is eliminated from the data stream to the modulator before it is broadcast. This provides a near instantaneous integrity function. Further work will be completed to define what the user is told about the removed data and to demodulate the data after it leaves the modulator to ensure its accuracy. The capability will also be added to monitor the actual broadcast to look for gross failures. This information will be provided to the user at the next epoch. Additionally, a panel will be convened to examine the software to ensure it adequately addresses all the concerns a safety of life system should address.

3.1.3.2. Atmospheric Models

The Forecast System Laboratory (FSL) has been under contract to develop predictive models for the ionosphere and the troposphere. The tropospheric model is undergoing validation testing and the ionospheric model should be entering that phase shortly. Trimble has been contracted to add these to the existing HA-NDGPS data stream. It is intended to trickle this data out over several minutes, but provide enough data every few seconds to allow users to improve their navigation solution.

The method for supplying this data to the broadcast site has not been determined and is the subject of further work. Currently, it is envisioned the tropospheric and ionospheric data will be provided to the National Control Station (NCS) and the model will be run there. The output from the model will then be parsed to the individual broadcasts sites. Once received at the sites, it will be encoded, compressed, and provided to the end user through the broadcast.

3.1.3.3. Precise Orbits.

The usefulness of precise orbits broadcast from the reference stations has been debated for some time. With the Improved Clock and Ephemeris from the GPS constellation there has been some doubt that it is necessary. It is expected that the precise orbits, broadcast from the reference stations, will be useful and current plans call for including it in the data stream. The source of the precise orbits will be determined in the near future.

3.2. End User Equipment

The current demodulator used for test scenarios is a single channel modified DNAV-212 from Raven Industries. While these units are adequate for testing, additional capability will be needed to make full use of the broadcast. The end goal for the

development and engineering phase demodulator/receiver is to have at least four independent channels (six will provide additional capability long term, but four is sufficient to prove the current concepts) that can be tuned to either the legacy service or the HA-NDGPS service in such a way as to select all legacy channels, all HA-NDGPS channels, or some combination of the two. The demodulators will also be capable of synchronizing to GPS in order to pull the weaker signals out of the noise at the edge of the coverage area, effectively increasing the range of the broadcast.

The output of the demodulator can be selectable at this time. Vendors will be able to create their own data since they will have access to either the observables (in the case of the HA-NDGPS broadcast) or the data routinely sent over the NDGPS service. Thus, the output can be a RTCM type 9 message, RTCM type 18/19, or a vendor proprietary format. The test units will provide either the observables or the RTCM type 18/19 messages, along with integrity and troposphere and ionosphere model data as they become available.

4. Work To Be Completed.

Several efforts need to be completed in the near term. Several of these were identified above include integrity, atmospheric modeling, and precise orbits. During this same time frame, development of a standardization package for the end user data shall be developed for coordination with RTCM or another standards organization, implementation designs, and identification of NCS upgrades.

4.1. Phased Approach.

One of the strengths of the approach used in the development of the HA-NDGPS program has been the addition of capabilities over time. For example, inclusion of a rack mount PC running GRIM in the reference station allows the collection and dissemination of the GPS observables to NGS immediately. With slight modifications, this will also allow the site to collect site status information and hold it if commercial communications are lost. The data can then be provided to the NCS once communications are restored. This approach allows us to incrementally field HA-NDGPS where site conditions will not allow a full implementation immediately, but also allow the implementation of additional capability (i.e. ephemeris) as the data becomes available.

4.2. Additional Work to be Completed

4.2.1. Requirements Definition

This is the first item that will be completed since much of the additional work depends on the basic

requirements placed on the system. The top-level requirements have been identified and built to in the prototype systems. Additional descriptive language will be used to provide guidance to implementers and identify functional requirements. It is important to note here that how something is done is very different from what capability needs to be included. Thus, the requirements definition will focus on capability first and address how as a derived requirement.

4.2.2. Signal Specification

Many aspects of this have been defined, tested, and documented, but needs to be placed in a signal specification document. Since this is one of the earliest products needed, it will also be one of the earliest deliverables.

4.2.3. Automatic Control and Data Logging

The USCG has discussed this over the years and the recent events along the Gulf of Mexico have heightened the need for a quick solution. A multi-pronged approach is proposed here.

First, collect all the observables at 1-second epochs and send them to NGS, along with integrity data as it becomes available. There appear to be two ways of doing this.

One way, which we shall call approach 1, appears easiest, would convert the data from RS232 to Ethernet and monitor/control it with a separate PC in the equipment hut running GRIM. GRIM would be there to ensure that after a reset the particular port we are interested in is reset to the appropriate data rate as well as store the data and forward it at a later time if communications to the site are lost.

The other way, which we shall call approach 2, while more complicated, may offer a longer-term solution. This can be accomplished quickly by, again, installing a rack mount PC and adding a second virtual data link to the site to provide data back to NAVCEN and NGS. During times when commercial communications are lost, the data can be stored locally at the site and forwarded once communications are restored.

The second part of this is to tap into the existing RSIM data and log it at the end of each epoch of GPS data. If communications is lost, the data can be stored until communications is restored or, in the case of a HA-NDGPS modification, it may be possible to include it at the end of the broadcast.

The third and final prong of this work would provide two-way communications to the NDGPS facility. In the event of commercial communications loss, the data can be sent, by exception, to one of the control stations by an alternate communications link, perhaps satellite. The station can also be controlled and

if additional data is needed that has been recorded, the site can be instructed to provide that data.

4.2.4. Equipment Specification

Much of the equipment that has gone into the HA-NDGPS prototype installations has had specifications developed for it. Much of this work should be transferable to the deployable installations. Thus, this work will focus on documenting equipment specifications that have already been developed and identifying equipment and documenting its specifications prior to full-scale deployment.

4.2.5. Receive Data Standard.

The approach decided upon was to use an off the shelf compression, modulation, and control program. This package is collectively called the broadcast software. Each of these can be purchased or licensed in sufficient quantity and at a low enough price that it does not appear to be reasonable for the Government to develop one independently. Add in the cost of maintaining the code, and the benefits to purchasing off the shelf software increases substantially. Since this will be a safety system, care must be exercised to ensure it meets the required level of acceptability. Thus, portions of the software have been negotiated to be opened to review by a panel established by the Federal Government.

Given that the broadcast software is proprietary, concerns about the decompression/demodulation software (referred to as the user software) could arise. This raises the concern that the user software would be proprietary. The developer has agreed to make the user software available as an open standard and assist with providing it to a standards group.

4.2.6. Atmospheric Models

The two models that are being developed, one for the troposphere and one for the ionosphere, have been in development for several years. Much of the work that remains is speeding up their prediction capability (in the case of the ionosphere model) and validating them. Incorporation of both models into the broadcast software has begun. Techniques to move information on both the troposphere and ionosphere to and from the reference stations need to be detailed and their impact on the overall system need to be defined.

4.2.7. Integrity

The current integrity function examines the residuals in the carrier data and, if they are outside a predefined envelope, the data from the satellite is removed from the data stream prior to modulation. Additional integrity will be added including using the

observables with a second receiver to verify solutions are where they are supposed to be.

As the integrity function develops, an Integrity Panel made up of Government and Private Sector experts will be convened to ensure the integrity defined meets the requirements established by potential users.

5. Summary

Combining old concepts with new technology, we have created a service that exceeds the expectations of most users. Accuracy is better than 10 cm horizontal 95%, integrity is instantaneous, and availability is above 99.9% in the defined coverage area.

The prototype systems have been functioning for several years and have provided a test bed for controlled development. Users are being defined and their requirements built into the system. Some work remains to be completed to document the system and finalize it for full deployment, but that is straight forward and can be accomplished quickly.