WAAS NETWORK TIME PERFORMANCE USING WRS DATA

Cheryl Griffith, Stephen Peck, Peter Diamond, *Raytheon*

Abstract

Raytheon Systems Company is currently designing the algorithms of the FAA's Wide Area Augmentation System (WAAS). This paper will briefly overview the WAAS network time (WNT) algorithms and their integration into the overall system.

The WAAS system is required to provide users with orbit, clock, and ionosphere corrections for single-frequency measurements of the GPS signal. The clock corrections will be made in the WAAS network time (WNT) reference scale. This reference scale is required to track the GPS time scale, while at the same time providing the users with the translation to UTC. Other internal requirements are placed on the WNT bias and frequency jumps from the accuracy demanded in the WAAS fast corrections.

The WAAS architecture requires that WNT be computed at multiple WAAS master stations (WMS) using potentially differing sets of measurements from potentially differing sets of receivers and clocks. This design must provide the user a seamless transition when switching from one WMS's WNT realization to another.

This paper expands on two previous papers, one presented at ION GPS-97 using simulated clock data as input, and the other presented at the 1999 Technical Meeting using receiver data from the National Satellite Testbed (NSTB) and preliminary WAAS data. We included some introductory sections from previous papers here for completeness. Here, we will present the performance results of the WNT algorithm using GPS clock and receiver data from WAAS Reference Station (WRS) using the standalone WNT algorithm with the WAAS prototype software. We will also show some recent WNT algorithm results from the operational WAAS software, indicating that the WNT design should meet the aforementioned requirements, taking into account possible WAAS WMS switches.

Two tests are performed. The first test shows how well WNT for a single WMS network agrees with estimated GPS. We will check this in the operational, as well as in the standalone/prototype, WAAS software. The second test will check the coordinated WNT algorithm. Using two different subsets (taken from a single WRS thread to simulate two WMS networks) of the WRS sites, we demonstrate that coordinated WNT as computed at the two different networks closely agree (on WNT), thereby ensuring a seamless transition from one WMS network to another. We will also show how WNT differs in the operational system between two actual WMSs.

INTRODUCTION

Raytheon Systems Company is currently developing the Wide-Area Augmentation System (WAAS) under contract with the Federal Aviation Administration (FAA). WAAS is a GPS-based navigation system that is intended to become the primary navigational aid for commercial aviation during all phases of flight-from enroute through Category I precision approach. This system will make use of a network of WAAS reference stations (WRS) distributed throughout the US National Airspace System.

These reference stations will collect pseudorange measurements and send them to WAAS master stations (WMS). The master stations will process the data to provide correctional information for each GPS satellite. This correction information will include as separate components the GPS ephemeris errors, satellite clock bias and ionospheric estimation data. The corrections will be sent to the users by means of a Geosynchronous Earth Orbit (GEO) satellite using a signal and data format designed by RTCA [4].

WAAS is first expected to provide supplemental radio navigation, and eventually to become the primary system of navigation. The system will add the following features to the current GPS system: a GEO ranging function that will improve availability and reliability; differential GPS corrections that will improve accuracy; and integrity monitoring that will provide and enhance safety.

All the aforementioned corrections need to be calculated at a given epoch referenced to a time standard. Obtaining these corrections requires the determination of the satellite's position using range measurements. In turn, utilizing ranging measurements requires the determination of the clock biases of the system, namely, the satellites and the ground stations clocks with respect to a standard---ideally GPS time. Unfortunately, not all the system clock biases can be solved simultaneously because they represent an underdetermined linear system. Furthermore, they cannot be directly referenced to GPS because the GPS master time is not directly obtainable. To constrain the solution, an extra constraint needs to be added. In its simplest form, this constraint will be equivalent to holding one clock bias "fixed," hence referencing all other clock solutions to this one. This "reference clock" becomes the network time (or, in our case, WAAS network time), and all corrections are referenced to it. Note that this constraint is not necessarily confined to be a single clock; a linear combination of network (and perhaps satellites) clocks —as it will be the case in the implementation presented here —can be utilized. This degree of freedom allows one to coordinate the network time with any other standard such as GPS or UTC.

1.1 WNT REQUIREMENTS

Requirements on WNT can be classified as external and internal. The external requirements are the WNT algorithm-specified requirements while the internal requirements come about as the result of other WAAS algorithm requirements.

The WNT reference scale is required to track the GPS time scale and also provide users with a means of obtaining UTC. WNT is required to agree with GPS to within ±50 nanoseconds. At the same time, the WNT to UTC offset must be provided to the user, with the offset message being accurate to 20 nanoseconds, although this will not be addressed in this paper.

There are also internal or derived requirements to provide a user corrections with sufficient accuracy to meet the precision approach navigation accuracy. The user uses the fast corrections to extrapolate to its current time using the range-rate correction [4]. To meet system specifications, this correction must be accurate to approximately one nanosecond (1-sigma). To achieve this accuracy, jumps in the WNT bias should be less than 1 nanosecond, and jumps in the WNT frequency should be less than 2E-10.

1.2 MOTIVATION FOR EXTERNAL REQUIREMENTS

The reader may be prompted to ask the purpose of these external requirements. If all the clocks in the WAAS system were referenced to a stable time standard, why should this time be required to keep close to GPS time? WAAS alone would indeed function just fine as long as all the clocks are synchronized. The problem arises when the user wishes to combine solutions from WAAS-monitored GPS satellites to those which are not WAAS-monitored. This can only be accomplished if WNT agrees closely with GPS time. An example of this is when the user wishes to apply the Receiver Autonomous Integrity Monitoring (RAIM) Algorithm, which requires signals from 6 satellites (which may or may not be monitored by WAAS at the time).

The requirement for WNT offset to UTC time to be less than 20 nsec exists so that a WAAS user with access to WNT can use this offset to make the translation to UTC. This requirement was not analyzed in this paper.

2. ALGORITHM DESIGN

The following description of the WNT Algorithm has been summarized from [2].

2.1 WAAS SYSTEM ARCHITECTURE

A brief description of the WAAS System has been included to aid in the understanding of the WNT algorithm design. Please see Figure 1.

Range signals from the GPS space vehicles (SV) and the WAAS GEO satellites are received at the WAAS reference stations (WRS). There are 25 WRS for the initial (Phase 1) WAAS. Each WRS consists of three independents sets of WAAS reference equipment (WRE). These WRE each have an all-in-view dual frequency GPS receiver with its own cesium clock. Measurements from all WRE at all WRS are sent to each WAAS master station (WMS), of which there are two in Phase 1 WAAS.

Each WMS has two corrections processors (C1 and C2 in Figure 1) and two safety monitors. Each corrections processor chooses one distinct WRE input from which corrections are calculated. This is done for each WRS that has at least two working WRE. These include all WAAS corrections (GPS and GEO orbits, clocks, and the L1 frequency ionosphere vertical delays at the ionosphere grid points). This correction processor also includes the WNT algorithm that defines the time scale to which clock corrections are referenced.

The safety monitors each compare the output of each correction processor to verify the output is in reasonably close agreement, then individually form the WAAS message for uplink using the verified data from the master correction processor (C1). The two safety monitors check their respective output for an exact match. If the output matches, the message is passed to the ground uplink station (GUS) for uplink to the GEO satellite, which is rebroadcast to the user via bent pipe transponder. The GUS also has a receiver tied to a cesium clock to maintain the uplink signal to look as if it originated from the GEO satellite.

2.1.1 CORRECTION PROCESSOR WNT ALGORITHM

Figure 2 depicts the WNT algorithm. Please see [2] and [3] for a more detailed description of the WNT algorithm. The Correction Processor box shows the individual parts of the algorithm which reside within each correction processor (C_1 and C_2 in Figure 1). These parts consist of the measurement collection at the WRS sites and the clock bias and monitoring function in the 'Process input data' capability (PID). PID selects measurements from one WRE per WMS and screens out all bad clocks. The initial "raw" WNT_i time scale is an average of all the "good" input WRE clocks for WMS_i.

Next, the receiver measurements are then are sent to the orbit determination (OD) and clock filters which, in particular, compute the biases of all SV clocks relative to WNT_i (the localized WNT time scale of correction processor i). These clock bias computations are accurate to within a nanosecond. This output is used to determine a piecewise linear steering function to keep WNT_i synchronized to GPS time. The WNT_i time scale is then steered to GPS time by a twice daily clock steering command; this steered WNT_i is called localized WNT_i. Additionally, localized WNT_i is given a one time adjustment for the bias offset between "raw" WNT_i and GPS after the first five minutes upon initial startup. For the twelve hours, "raw" WNT_i and localized WNT_i differ only by this bias adjustment.

The final part is a WMS to WMS time scale synchronization between each WMS master correction processor (processor one (C_1) is designated the master processor). The C_1 processor differs from the C_2 processor in that only the C_1 processor synchronizes its localized WNT with the other WMS master correction processor. This design ensures that both WMSs have synchronized WNT and, hence, allows for smooth operation if the WMS to WMS communication link is lost.

Since only the master corrections processor coordinates with the other WMS, each corrections processor has a possibly different WNT time scale (based on distinct sets of clocks in Raytheon baseline design). The safety monitor checks the output from each corrections processor to verify the outputs against each other. A WNT bias offset (WNT_{iC1} to WNT_{iC2}) would produce a systematic disagreement in SV clock corrections from the two processors. Thus, a bias check will be implemented in the safety monitor to account for this effect (see the lower section of Figure 2.) It will also report the detected WNT_{iC1} to WNT_{iC2} bias to operations and maintenance for assessment of WNT performance.

3. ANALYSIS

The goal of the analysis was to see how the WNT algorithm performs with WAAS receiver clocks. Previously, the WNT algorithm performance has been evaluated with simulated clock data [3] and NSTB receiver clock data [1]. At the time previous papers were written, WRS clock data output from the WAAS orbit determination and clock filter was not yet available.

Some modifications had to be made to the clock data from the WAAS integrated prototype code (IPC) to make it more like the WAAS operational code. One such adjustment accounts for the fact that the IPC continually "loosely" steers the receiver clocks toward GPS, where in the operational WAAS system, the receiver clocks are allowed to drift freely after an initial adjustment to GPS is made upon startup. Thus, this loose steering was removed in postprocessing. Additionally, the filter in the WAAS IPC solves for the receiver and satellite clock biases with respect to one reference clock, an adjustment was made to shift the reference from one clock to raw WNT. These clock data were then processed through a stand-alone WAAS Network Time algorithm. The WNT results from the operational WAAS code come directly from the program itself with no modifications.

3.1 THE WAAS RECEIVER ARCHITECTURE

Kalman filter output of the WRE and satellite clock biases with respect to a reference clock was provided by the WAAS IPC. The WRE clocks, along with their corresponding filter states (FS), used in our analysis of the prototype software consisted of the twenty-four thread A Novatel receivers listed in Table 1. The receivers at remaining WRS location, Cold Bay, Alaska, were not included because the precise location of these receivers was not yet available.

3.2 WMS COORDINATION

The function of WMS coordination is to synchronize the WNT_{iC1} solutions from each WMS. Currently, since there are just two WMS, i ranges from 1 to 2. The two WMS transmit their SV clock solutions with respect to WNT_{iC1} every five minutes. The offsets between the clocks are estimated using a 2 state Kalman filter with the two states being clock bias and frequency offsets. The measurement data for the filter are the offsets between the localized WNT and the WNT average. The inputs are the frequency steering commands.

For our study (using the WAAS IPC) we took subsets of 17 receivers from a set of 20 receivers (see below) and ran the WNT algorithm on these subset datasets to simulate different WMS networks. The output of these datasets provided the input required for the Kalman filter, which yields the changes in bias and frequency to coordinate WNT between the two networks.

3.3 THE DATA SET

Our data set for the WAAS IPC consisted of a 5-day continuous run from the week of January 8 through 12, 1999. The receivers ZJU1, ZKC1, ZLC1, ZSU1, and CDB1 were not present in this particular data set. Data for evaluating the WAAS operational code consist of the latest November 1999 Signal in Space (SIS) ten-day run of the code available.

4. RESULTS

The results are as follows:

4.1 CLOCK STEERING PERFORMANCE (WAAS IPC)

The upper chart of Figure 3 depicts the steering of (WNT - estimated GPS) to zero for a period of 5 days. The entire dataset was used minus the 5 receivers as described in 3.3. Note, true GPS time is not known here, only each satellite's estimation of GPS time from the broadcast ephemeris. (WNT - GPS) is denoted by the thick (blue) line in both charts. The lighter (green) line running through the center shows the linear fit of (WNT – GPS) from the previous steering period. This line includes an initial bias fit which is applied after the first five minutes. The lower chart in Figure 3 depicts unsteered ("raw" WNT - GPS). Recall that raw WNT is the average of all good receiver clocks. The abbreviation Nsec in the y-axis stands for nanoseconds.

The two horizontal lines in the upper chart are give us the 50 nanosecond neighborhood around zero. As can be seen, the steering algorithm does a pretty good job of keeping WNT within 50 nsec of GPS time.

GPS satellite PRN 15 has Selective Availability turned off, and thus its broadcast ephemeris would provide the best estimate of GPS time. Figure 4 singles out the steering performance for PRN 15. Zeros indicate when the satellite is out of view. In this case, the difference between the two time standards is less than 50 nanoseconds the entire five days.

4.2 WMS CLOCK COORDINATION BETWEEN PROCESSORS (WAAS IPC)

WNT steering to GPS was computed for two subsets of the dataset of twenty receivers described in 3.2. The two subsets or networks consisted of two sets of seventeen receiver clocks where three clocks were different. Network "A" had receiver clocks HNL1, ZFW1, and ZMA1 removed. Network "B" had receiver clocks ZAB1, ZHU1, and ZME1 removed. The WNT coordination algorithm (see 2.1.1.) does an excellent job of coordinating the two network's computation of WNT to one time. Figure 5 depicts the difference in WNT for coordinated and uncoordinated WNT. As to be hoped for, the line which stays near zero, is the difference between coordinated WNT.

Figure 6 is a zoom of the same chart with the y-axis expanded. The difference in coordinated WNT hovers around .25 nsec for the entire period, easily meeting one of the algorithm's external requirements that WNT bias jumps (between WMS) be less than 1 nanosecond. Thus, the coordination algorithm will ensure robustness, and provide a mechanism to coordinate with international WAAS-like systems.

4.3 WNT CLOCK STEERING PERFORMANCE (WAAS OPERATIONAL CODE)

Slightly different metrics are used in the WAAS operational code to measure the WNT algorithm performance. Output from the operational code is in the form of recording "keys." These keys must exist, or be created, and then activated. The keys related to WNT Steering performance are the WNT-to-GPS biases and frequency offsets as computed from the linear fit data. The average of the WNT-GPS deltas is also computed. Table 2 lists these values from one of our most recent runs. The values are recorded every 12 hours when a new linear fit is computed. As can be seen, the bias values are under 15 meters (50 nsec) and do not drift to above 15 meters during the twelve-hour period. The performance here is better than in the IPC because there are more stringent requirements on an SV before it is allowed to be part of the WNT ensemble. The stand-alone WNT tool which works on the IPC output includes clock data from all the satellites which are in view.

4.4 WNT BETWEEN PROCESSORS (WAAS OPERATIONAL CODE)

There are no recording keys to directly tell us the difference between coordinated WNT at two WMS. We do, however, have two different types of recording files that give us a pretty good idea. One file is the differences in satellite fast corrections (in meters) exchanged every five minutes at each WMS. The other file is the bias and frequency offset as calculated from the WMS to WMS coordination filter (which usesthesefast correction delta data as input. Please see Section 3.2.). Table 3 is a small example of this first recording file. Fast correction differences by satellites between WMS are listed for a good and bad day. The wnt sync bias and drift are the outputs of the coordination filter. The fs offset and drift are the actual coordination corrections being applied to keep continuity. Even for the bad day, if we use the worst case delta bias of –4.373326m and apply the coordination offset value of 2.307116, we would get a bias between fast corrections of 0.2832m which is still less than 1 nanosecond.

Table 4 gives WNT bias and frequency offset states as estimated by the coordination filter for November 15, 1999. You may also notice that the estimate at time 0:00 is the same as the "good day" example given in Table 3. In this case, the system has been up and running without interruption for several days. As the orbit determination and other filters stabilize, the difference between WNT for the two master correction processors dramatically decreases. The bias eventually settles down to less than 30 cm (1 nsec). The reason for this very small difference as compared to the performance results in the IPC (see 4.2) is because we purposely choose three clocks to differ in both subnetworks. If all is functioning perfectly, both master corrections processors should be receiving the same clock data, and hence, localized WNT should be near the same. Coordinated WNT should only be needed when there is a problem with data dropout between networks.

5. CONCLUSIONS

The WNT algorithm results with the WRE clocks run through the WAAS IPC show that the WNT to est. GPS bias is within 50 nsec. the majority of the time. In the WAAS operational code, the results are better, WNT stays within 50 nsec of GPS all the time. The stricter requirements for a clock's inclusion in the WNT ensemble is responsible for this improvement.

Results also show that the more challenging requirement of maintaining WNT within 1 nsec. between WMS is readily met even when three clocks differ. Results from the operational system indicate the coordinated WNT is not even necessary when the WAAS in operating in its nominal state.

The current WAAS system is designed to provide a mechanism to coordinate between other WAAS-like systems as WADGPS grows internationally. This will ensure nearly seamless WAAS uplink transitions between WMS, as well as time transfer between users who receive their WAAS corrections from different GEO satellites.

Future analysis will include continuing to evaluate the WNT algorithm as the WAAS system moves beyond phase 1. WMS-WMS coordination will also be analyzed with as the network grows. The current WAAS system contains only 25 WRS for phase 1, but will increase to 50 or more stations in later phases. Also, there may be coordination between other international WAAS-like systems.

6. ACKNOWLEDGMENTS

The authors would like to thank the FAA for their support of this effort. This analysis was performed under the FAA WAAS contract. Thanks also to Tim Schempp at Raytheon for his support and assistance in obtaining clock data.

The contents of this material reflect the views of the authors. Neither the Federal Aviation Administration nor the Department of Transportation makes any warranty or guarantee, or promise, expressed or implied, concerning the content or accuracy of the views expressed herein.

7. REFERENCES

[1] Griffith, C., Peck, S.,*et al.*, "WAAS Network Time Performance with Site Data," *Proc. of ION 1999 Nat'l Tech. Meeting*, San Diego, CA, Jan. 25-27, 1999, pp. 839-846.

[2] Peck, S., "WAAS Network Time (WNT) Algorithm," Raytheon Systems Company, ENB 1.5.17, Nov. 1996.

[3] Peck, S., Griffith, C.,*et al.*, "WAAS Network Time Performance and Validation Results," *Proc. of ION GPS-97*, Kansas City, KA, Sept. 16-19, 1997, pp. 1123-1131.

[4] Minimum Operational Performance Standards for Global Positioning System/Wide Area Augmentation System Airborne Equipment, RTCA Document No. RTCA/DO-229A, RTCA, Inc., June 8, 1998, pp. 54 & App. A.

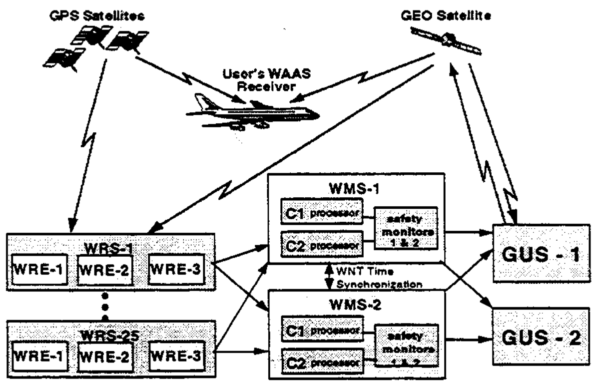

Figure 1: WAAS System

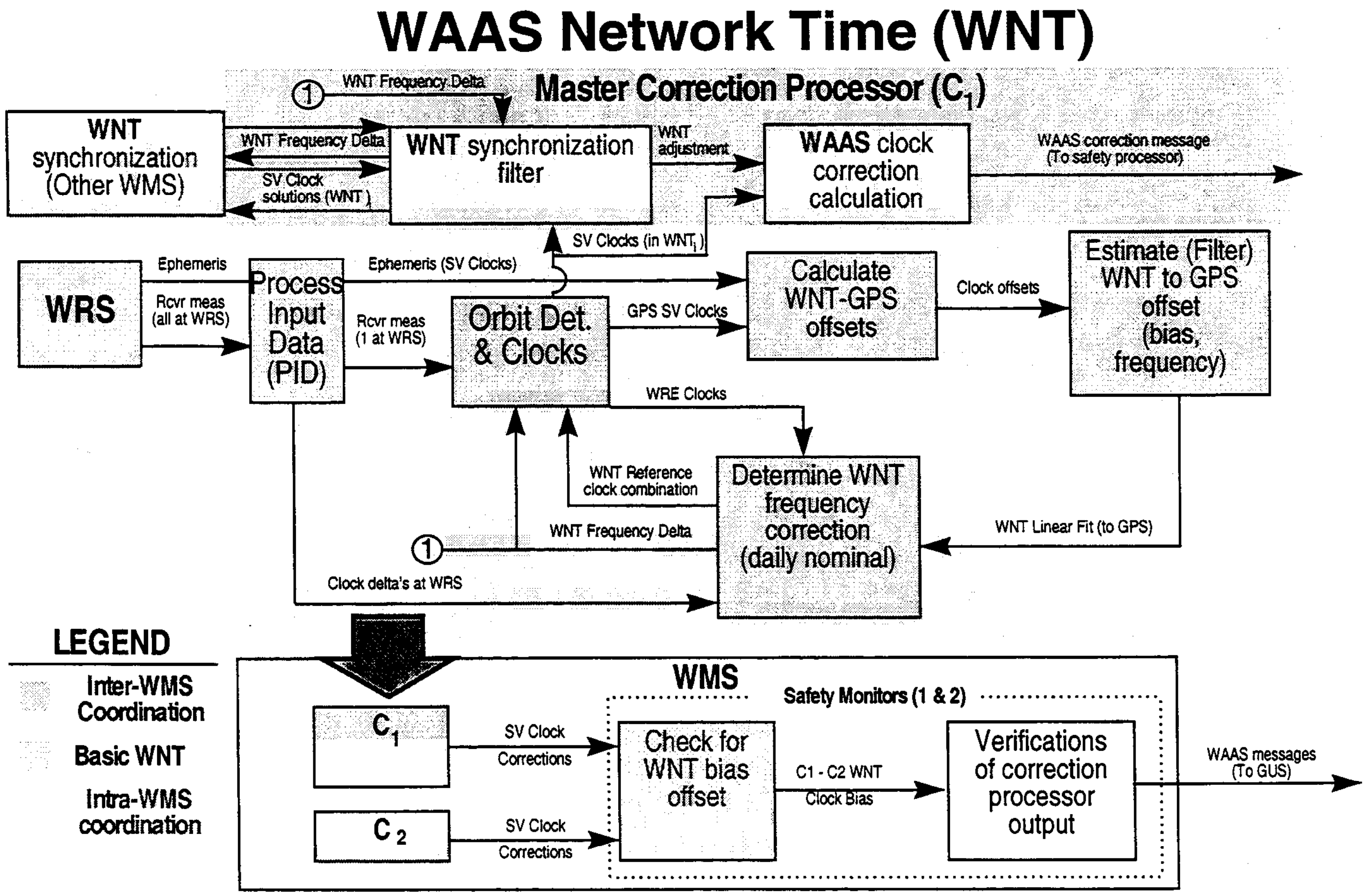

Figure 2: WAAS Network Time (WNT)

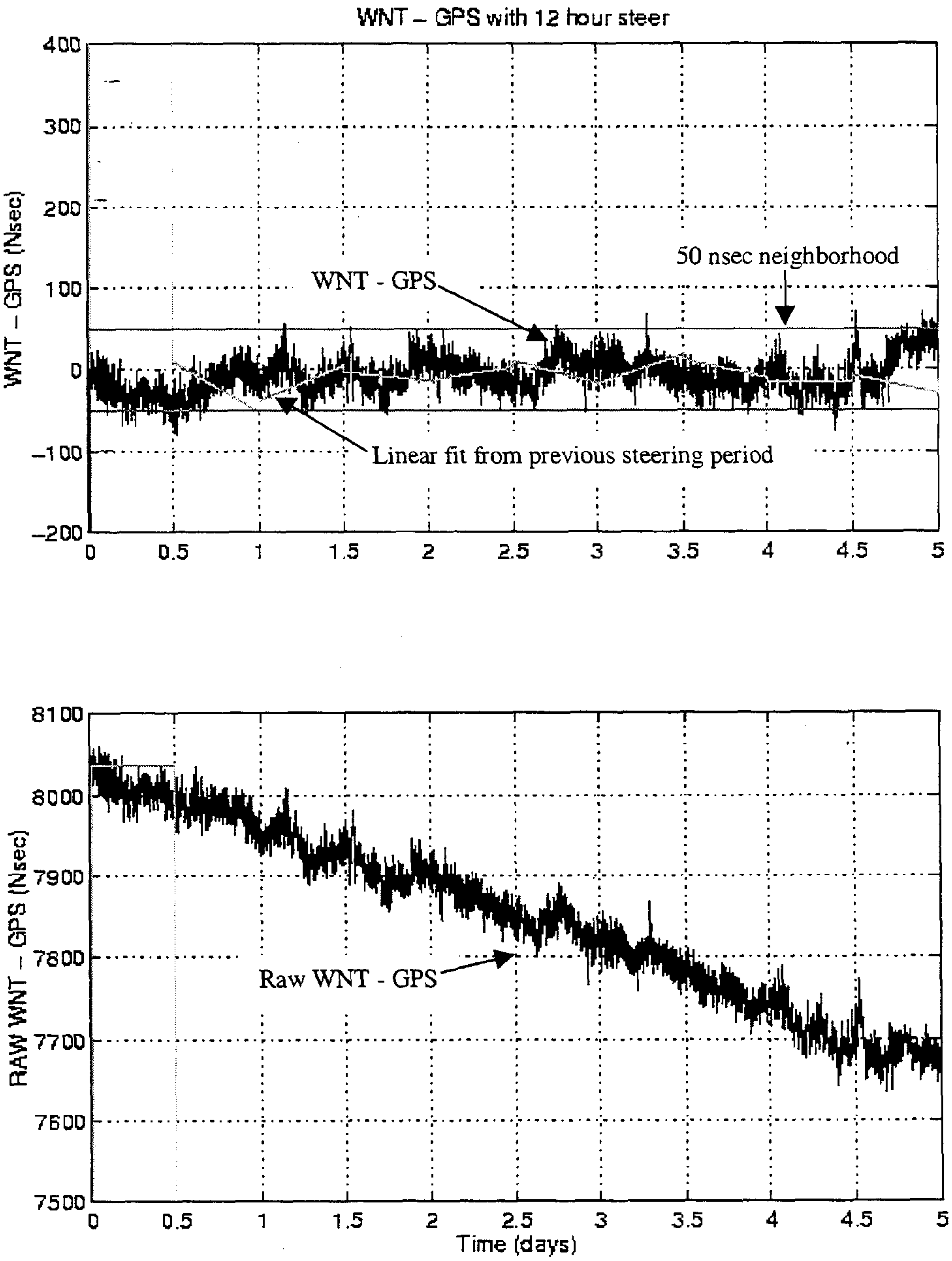

Figure 3: WNT Clock Steering to GPS

FS	GIPSY ID	NAME	TYPE	ID
00	HNL1	"Oahu, HA"	NovWAAS	7aa0
01	ZAB1	"Albuquerque, NM"	NovWAAS	70a0
02	ZAU1	"Chicago, IL"	NovWAAS	75a0
03	ZBW1	"Boston, MA"	NovWAAS	65a0
04	ZDC1	"Washington, DC"	NovWAAS	69a0
05	ZFW1	"Fort Worth, TX"	NovWAAS	71a0
06	ZHU1	"Houston, TX"	NovWAAS	6aa0
07	ZKC1	"Kansas City, KA"	NovWAAS	76a0
08	ZLA1	"Los Angeles, CA"	NovWAAS	6da0
09	ZLC1	"Salt Lake City, UT"	NovWAAS	73a0
10	ZMA1	"Miami, FL"	NovWAAS	6ca0
11	ZME1	"Memphis, TN"	NovWAAS	77a0
12	ZMP1	"Minneapolis, MN "	NovWAAS	68a0
13	ZNY1	"New York, NY"	NovWAAS	78a0
14	ZOA1	"Oakland, CA"	NovWAAS	6ae0
15	ZOB1	"Cleveland, OH"	NovWAAS	66a0
16	ZSE1	"Seattle, WA"	NovWAAS	67a0
17	ZSU1	"San Juan, PR"	NovWAAS	7ba0
18	ZTL1	"Atlanta, GA"	NovWAAS	74a0
19	JNU1	"Juneau, AL"	NovWAAS	7ca0
20	ZJX1	"Jacksonville, Wy"	NovWAAS	6ba0
21	ZAN1	"Anchorage, AL"	NovWAAS	79a0
22	ZDV1	"Denver, CO"	NovWAAS	72a0
23*	BIL1	"Billings, MO"	NovWAAS	6fa0

*Reference

Table 1: WRE Sites used in Analysis

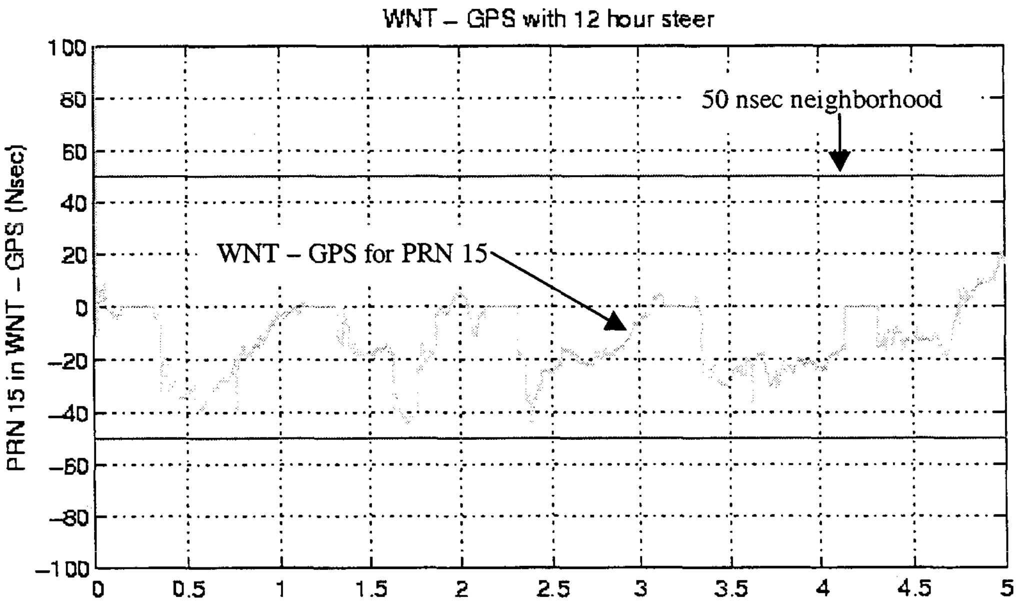

Figure 4: WNT Clock Steering for PRN 15

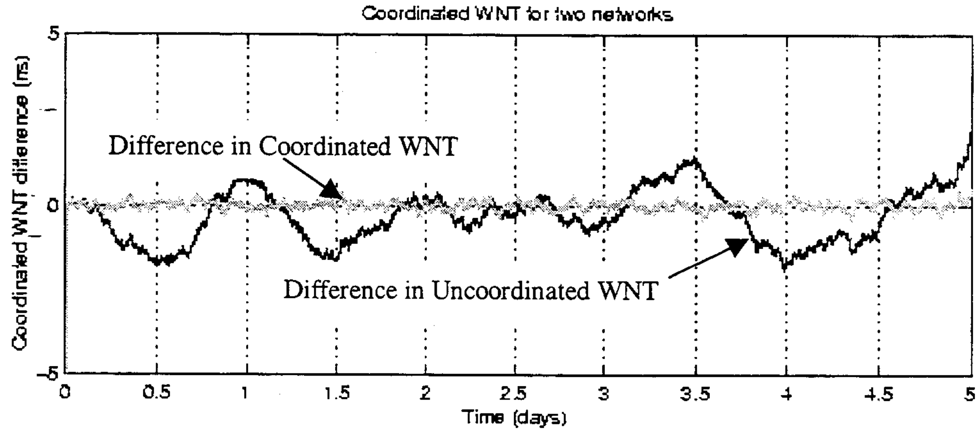

Figure 5: Difference in Coordinated WNT

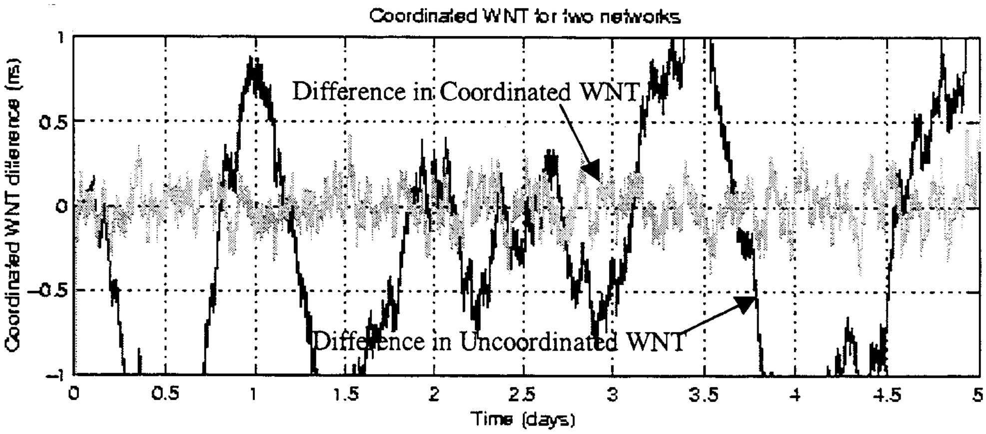

Figure 6: Difference in Coordinated WNT (Zoom)

WMS	Date	Time	Steering Bias (m)	Frequency (m/s)	Average Deltas (m)
ZDC_CP1	11/12/99	11:59	-6.72	-0.00	-3.57
ZDC_CP1	11/12/99	23:59	1.11	0.00	-3.07
ZDC_CP1	11/13/99	11:59	-4.05	-0.00	-1.48
ZDC_CP1	11/13/99	23:59	-2.16	0.00	-3.01
ZDC_CP1	11/14/99	11:59	1.18	0.00	-0.25
ZDC_CP1	11/14/99	23:59	-0.02	-0.00	0.06
ZDC_CP1	11/15/99	11:59	-1.0011	-0.00003247	-0.30969
ZDC_CP1	11/15/99	23:59	1.7189	0.00009841	-0.39404

Table 2: WNT Steering Performance in Operational Code

```
Good Day:
SCWT: sync delta bias = -2.078781
SCWT: sync delta bias = -2.024821
SCWT: sync delta bias = -2.016531
SCWT: sync delta bias = -2.009378
SCWT: sync delta bias = -2.008604
SCWT: sync delta bias = -1.998265
SCWT: sync delta bias = -1.986177
SCWT: sync delta bias = -1.972953
SCWT: sync delta bias = -1.944234
SCWT: sync delta bias = -1.937220
SCWT: sync delta bias = -1.933999
SCWT: wnt sync bias -0.996286 drift 0.000020 fs offset -0.995954 fs drift 0.000017
SCWT: wnt sync num in 11 num left 11, median = -1.998265
Bad Day:
SCWT: sync delta bias = -4.897449
SCWT: sync delta bias = -4.728961
SCWT: sync delta bias = -4.725888
SCWT: sync delta bias = -4.692512
SCWT: sync delta bias = -4.665009
SCWT: sync delta bias = -4.638439
SCWT: sync delta bias = -4.585548
SCWT: sync delta bias = -4.547804
SCWT: sync delta bias = -4.504793
SCWT: sync delta bias = -4.396825
SCWT: sync delta bias = -4.373326
SCWT: wnt sync bias -2.306279 drift 0.000025 fs offset -2.307116 fs drift 0.000025
SCWT: wnt sync num in 11 num left 11, median = -4.638439
```

Table 3: Fast Correction Difference Recording File Example

Time	WNT Bias State (m)	WNT Freq. State (m/s)	Time	WNT Bias State (m)	WNT Freq. State (m/s)
0:00	-0.9962	0.00003143	13:00	-0.4318	-0.00000431
1:00	-0.9423	0.00000532	14:00	-0.4384	0.00000717
2:00	-0.9006	0.00000776	15:00	-0.3835	0.00001606
3:00	-0.8707	0.00001248	16:00	-0.4095	0.00000560
4:00	-0.8036	0.00002388	17:00	-0.3296	0.00001794
5:00	-0.7444	0.00002282	18:00	-0.3352	0.00001649
6:00	-0.7586	0.00001972	19:00	-0.3245	-0.00001626
7:00	-0.6825	0.00002506	20:00	-0.3229	0.00000870
8:00	-0.6088	-0.00004811	21:00	-0.2913	0.00001824
9:00	-0.5459	-0.00001567	22:00	-0.2839	0.00000516
10:00	-0.4896	0.00000800	23:00	-0.2685	0.00000687
11:00	-0.4751	-0.00006502	23:20	-0.2612	-0.00000157
12:00	-0.4577	0.00000850	00:35	-0.0000	0.00000000

Table 4: WNT difference between two WMS (Operational Code)