Determination of the accuracy of the Global Positioning System's broadcast orbit and the WAAS-corrected orbit

Fredericton, December 17 1999

Internship project by *Bart Peeters*

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Preface

This report is written in the framework of my internship at the University of New Brunswick in Fredericton, Canada. This internship is part of my curriculum at the Faculty of Aerospace Engineering at Delft University of Technology. As a member of the Astrodynamics & Satellite Systems section, I wanted to complete it at a company that was working in this field. Professor Ambrosius introduced me to Denis Gerrits who completed his internship at UNB a year earlier. He brought me in contact with Professor Langley of the Department of Geodesy and Geomatics Engineering, who invited me to Fredericton.

At the time when I write this, almost three months have passed since work at UNB began. This report sums up the results of the research I did on the Global Positioning System satellite orbits.

I wish to express my sincere thanks to Professor Langley, for giving me the opportunity to complete this internship at UNB in Fredericton. Furthermore I thank all the students who helped me during my work, made my stay a pleasant one and have made these three months worth remembering.

Abstract

This report is written in the framework of my internship at the University of New Brunswick in Fredericton, Canada. During the three months that I worked at UNB, I tried to determine the accuracy of the broadcast orbits of the Global Positioning System (GPS) and of the orbit after applying WAAS-corrections. The Wide Area Augmentation System is currently in the test phase. That means that there are sporadic WAAS-broadcasts. Because of this there is no guarantee that the transmitted corrections are currently as good as they could be.

The GPS signal contains information about the position of the GPS satellites. This information is provided in quasi-Keplerian elements and is called the broadcast ephemeris. The broadcast ephemerides for all the satellites for the whole day are combined in a file called the 'autofile'. To reconstruct the orbits for the satellites, the Keplerian broadcast elements have to be converted to Cartesian coordinates. To do this the right ephemeris set has to be taken. This is always the latest one that is received, unless the Issue of Data ephemeris (IODE) of that set is smaller than the previous set. Always the ephemeris set with the highest IODE has to be used. An ephemeris set can be used until another ephemeris set is received with a higher IODE or when the time is between two hours before or after the Time of Clock (TOC). This method was validated against the orbit solutions of the University of Bern.

If we compare satellite position coordinates with the a precise orbit (the final and rapid orbits are provided by the International GPS Service and computed at the University of Bern), we get an estimation of the error in the broadcast orbit. These errors are for some satellites worse than for others. This can, amongst other things, be caused by problems with the control of the spacecraft itself. This is the case with satellite PRN 23 whose solar panels have to be controlled manually. The orbit of satellite PRN 6 is also much worse than the orbits of the other satellites. The reason for this is unknown.

The error in the broadcast orbit can be reduced (in theory at least) by applying WAAS-correction data. The Wide Area Augmentation System is supposed to increase the GPS accuracy, availability and integrity. Typically WAAS-orbit-corrections are provided every six minutes when a GPS satellite is in view from the service area (U.S.A. and parts of Mexico and Canada). Some initial testing has shown that the WAAS-corrections can bring the root-mean-square for all the satellites for a whole day down from 4.73 with 1.50 to 3.23 meters if only the periods that the satellites are actually in view from the service area are taken into account. The amount that the error in the broadcast orbit is corrected varies from satellite to satellite. There are even some satellites that appear to have a larger error after WAAS-correction. The reason for this is unknown. Furthermore, the errors in the WAAS-corrected orbit are less smooth than the errors in the broadcast orbit. This can give problems when the receiver's velocity is measured.

The time necessary for the computation and transmission of the WAAS-corrections generates a delay that makes it necessary to apply the ephemeris sets in a slightly different way. To prevent periods where no WAAS-data is available, switching to a new ephemeris set should only happen when the WAAS-corrections also switch to that new ephemeris set (switch Issue of Data). This requires a small change in GPS receivers, namely an ephemeris set has to be stored in memory for a certain time even after a new one is received.

List of used abbreviations

BE	broadcast ephemeris
BO	broadcast orbit
BT	broadcast Time
DGPS	Differential GPS
DOY	Day-of-Year
FO	final orbit
GEO	Geostationary Satellite
GES	Ground Earth Station
GNSS	Global navigation Satellite System
GPS	Global Positioning System
IGS	International GPS Service
IOD	Issue of Data
IODE	Issue of Data ephemeris
ITRF	International Terrestrial Reference Frame
LAAS	Local Area Augmentation System
PPS	Precise Positioning Service
RMS	root-mean-square
SA	Selective Availability
SPS	Standard Positioning Service
TOC	Time of Clock
TOE	Time of ephemeris
TTOM	Transmission Time of Message
UB	University of Bern
UNB	University of New Brunswick
USAF	United States Air Force
WAAS	Wide Area Augmentation System
WO	WAAS-corrected orbit
WRS	Wide-area ground Reference Stations

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1 Introduction

This report is written in the framework of my internship at the University of New Brunswick in Fredericton, Canada. During the three months that I worked at UNB, I tried to determine the accuracy of the broadcast orbits of the Global Positioning System (GPS) and of the orbit after applying WAAS-corrections. The Wide Area Augmentation System is currently in the test phase. That means that there are sporadic WAAS-broadcasts. Because of this there is no guarantee that the transmitted corrections are currently as good as they could be.

This section will give some information about the objective of this report and will further give an introduction to the Global Positioning System, the Wide Area Augmentation System and Nav Canada.

1.1 Objective

The objective of my research was to determine the accuracy of the GPS broadcast orbit and of the WAAS-corrected orbit and to set up a procedure to automatically generate daily accuracy statistics and post them to the World Wide Web.

1.2 GPS

“The Global Positioning System (GPS) is a space-based radionavigation system which is managed for the Government of the United States by the U.S. Air Force (USAF), the system operator. GPS was originally developed as a military force enhancement system and will continue to play this role. However, GPS has also demonstrated a significant potential to benefit the civil community in an increasingly large variety of applications. In an effort to make this beneficial service available to the greatest number of users while ensuring that the national security interests of the United States are observed, two GPS services are provided. The Precise Positioning Service (PPS) is available primarily to the military of the United States and its allies for users properly equipped with PPS receivers. The Standard Positioning Service (SPS) is designed to provide a less accurate positioning capability than PPS for civil and all other users throughout the world.” [Ref. 2]

The space segment is made up of at least twenty-four Navstar GPS satellites, which orbit 20,200 km above the earth, constantly transmitting the precise time and their position in space. The locations of the GPS satellites are known and receivers can determine their distance from a satellite by using the time it takes a radio signal to travel from the satellite to the receiver. After calculating its relative position to at least 4 satellites, a GPS receiver can calculate its position using trilateration. Certain errors creep into the process of determining the position. Selective Availability (SA) is the program implemented by the U.S. Department of Defense that makes GPS less accurate for non-military users by implementing errors on the satellite clocks. With SA in effect, the SPS positioning accuracy is 100 meters (2 d.r.m.s.). Even without SA, other errors will be encountered. The most significant of these errors is due to variations in the earth's ionosphere, which affects the propagation speed of GPS radio signals. Another source of error is caused the troposphere. Both of these errors are fairly small in comparison with the effects of SA.

The accuracy of GPS can be improved by canceling out the SA and reduce other errors with differential GPS (DGPS). A DGPS service currently under development is the Wide Area Augmentation System (WAAS).

1.3 WAAS

The GPS SPS service fails to meet the accuracy[1], availability[2] and integrity[3] requirements for high-risk navigation of, for example, aircraft. In order to meet these requirements the Wide Area Augmentation System or WAAS is being developed. WAAS is a safety-critical navigation system that augments GPS to provide a high quality of positioning information. This system will allow GPS to be used as a primary means of navigation for enroute travel and non-precision approaches in the U.S. The wide area of coverage includes the entire United States and some outlying areas such as Canada and Mexico. This is called the service area. Compatible systems are being developed to cover Canada, Europe and Japan.

WAAS is based on a network of a couple of dozen Wide-area ground Reference Stations (WRSs) spread around the service area. Each WRS is located at a known position. The WRS receives and collects data continuously from GPS satellites. The WRSs send the data to the Wide-Area Master Stations (WMSs) via a wide-area network. The WMSs calculate the error components of the GPS-received signals. The corrections are transmitted to a ground earth station (GES). The GES receives the GPS correction data from the WMS via the wide-area network and transmits the data to a geostationary satellite (GEO). The GEO receives the GPS correction data from the GES and retransmits the data to user receiver sets via the same frequency used by GPS (L1). The corrections are applied to the pseudoranges before the user calculates the GPS received position.

WAAS will improve GPS SPS accuracy to approximately 7.6 meters (95%) [Ref. 7] vertically and horizontally, improve system availability through the use of the GEOs for positioning, and provide important integrity information about the entire GPS constellation. It will give aviation users accurate positioning information to allow the use of Category I precision approaches.

1.4 Nav Canada

Nav Canada is Canada’s national provider of civil air navigation services and provides air traffic control, flight information, weather briefings, airport advisory services and electronic aids to navigation. Nav Canada has worked with the United States since 1992 to test GPS and prototype augmentation systems. The SatNav (Satellite navigation) Program Office coordinates these efforts. Their goal is to build a seamless, global, universally-used SatNav system to replace the country-wide network of more costly and less capable land-based systems.

Because GPS alone cannot meet aviation's stringent safety and reliability requirements and does not meet the accuracy criteria for precision approach, WAAS and Local Area Augmentation Systems (LAAS) are being developed to boost performance and assure constant availability of signals for en route and approach guidance.

The WAAS network will support en route through non-precision approach and, where practical and cost effective, Category I precision approach. LAAS systems will support precision approach, including Category II and Category III (autoland). These systems will be added, airport by airport, after meeting international standards expected in 2001. Nav Canada will be the provider for the WAAS-corrections for Canada. [Ref. 3]

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[1] Accuracy: the difference between the measured position at any given time and the actual or true position.
[2] Availability: the ability of a system to be used for navigation whenever it is needed by the users, and its ability to provide that service throughout the period it is needed.
[3] Integrity: the ability of a system to provide timely warnings to users or to shut itself down when it should not be used for navigation.

2 Calculating the position of the GPS satellites

Currently there are 27 active GPS satellites flying in orbits around the earth. These satellites 'know' their position and transmit this information (the broadcast ephemeris) to the users. The process of calculating the current position of the satellites is discussed in section 2.1. WAAS gives corrections to the measured GPS pseudoranges. The way the WAAS-corrections are applied is discussed in section 2.2. Section 2.3 discusses the International GPS Service final orbit. This orbit solution is very accurate and is used to measure the accuracy of the broadcast orbit and the WAAS-corrected orbit. The method of comparison of these orbits is discussed in section 2.4.

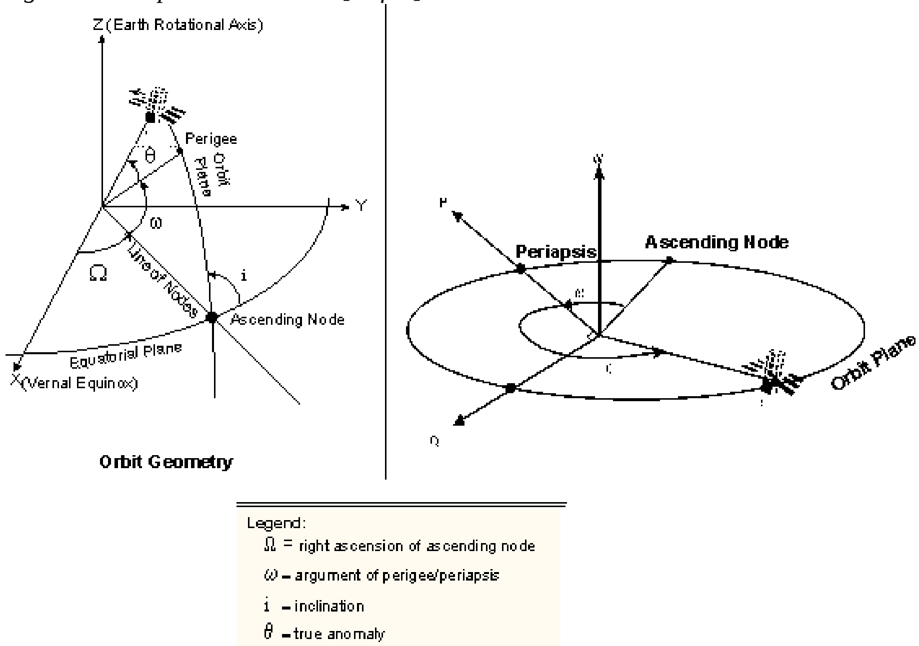
2.1 The broadcast ephemeris

The GPS signal contains information about the position of the GPS satellites, the broadcast ephemeris, in the broadcast (navigation) message. The ephemeris information is transmitted every 30 seconds. The location of the satellites is given in quasi-Keplerian elements and can be used to compute the position in Cartesian coordinates in the WGS 84 coordinate frame at any given time.

2.1.1 ephemeris parameters

In principle, to define the orbit of a satellite, a minimum set of six time-tagged numbers is required. They are called the satellite orbital elements or Keplerian elements (after Johannes Kepler [1571-1630]). These numbers define an ellipse, orient it about the earth, and place the satellite on the ellipse at a particular time. In the Keplerian model, satellites orbit in an ellipse of constant shape and orientation.

Figure 2-1. Keplerian elements [Ref. 8]



Due to disturbances in the orbit (by gravitational perturbations, solar pressure etc.) some additional elements are necessary. Table 2-1 gives the definition of all the orbital parameters used to define the orbits of the GPS satellites.

Table 2-1. ephemeris Data Definitions. [Ref. 2]

M_0	mean anomaly at reference time
Δn	mean motion difference from computed value
e	eccentricity
$(A)^{1/2}$	square root of the semi-major axis
$(\Omega)_0$	longitude of ascending node of orbit plane at weekly epoch
i_0	inclination angle at reference time
ω	argument of perigee
$\dot{\Omega}$	rate of right ascension
IDOT	rate of inclination angle
C_{uc}	amplitude of the cosine harmonic correction term to the argument of latitude
C_{us}	amplitude of the sine harmonic correction term to the argument of latitude
C_{rc}	amplitude of the cosine harmonic correction term to the orbit radius
C_{rs}	amplitude of the sine harmonic correction term to the orbit radius
C_{ic}	amplitude of the cosine harmonic correction term to the angle of inclination
C_{is}	amplitude of the sine harmonic correction term to the angle of inclination
t_{oe}	reference time ephemeris
IOD/IODE	issue of data (ephemeris)

2.1.2 Transformation of Keplerian orbit elements to Cartesian coordinates

The satellite position Cartesian coordinates at a certain time are calculated from the Keplerian broadcast ephemeris elements by applying a series of formulas. This process is shown in Table 2-2.

Table 2-2. Converting Keplerian orbit elements to a position in Cartesian coordinates. [Ref. 2]

$A = \left(\sqrt{A}\right)^2$	Semi-major axis
$n_0 = \sqrt{\dfrac{\mu}{A^3}}$	Computed mean motion - rad/sec
$t_k = t - t_{oe}*$	Time from ephemeris reference epoch
$n = n_0 + \Delta n$	Corrected mean motion
$M_k = M_0 + n t_k$	Mean anomaly
$M_k = E_k - e \sin E_k$	Kepler's equation for eccentric anomaly (may be solved by iteration) - radians
$\nu_k = \tan^{-1}\left\{\dfrac{\sin\nu_k}{\cos\nu_k}\right\} = \tan^{-1}\left\{\dfrac{\sqrt{1 - e^2}\sin E_k \;/\; (1 - e\cos E_k)}{(\cos E_k - e) \;/\; (1 - e \cos E_k)}\right\}$	True anomaly
$E_k = \cos^{-1}\left\{\dfrac{e + \cos\nu_k}{1 + e\cos\nu_k}\right\}$	Eccentric anomaly
$\Phi_k = \nu_k + \omega$	Argument of latitude
	<u>Second Harmonic Perturbations</u>
$\delta u_k = C_{us} \sin 2\Phi_k + C_{uc} \cos 2\Phi_k$	Argument of latitude correction
$\delta r_k = C_{rc} \cos 2\Phi_k + C_{rs} \sin 2\Phi_k$	Radius correction
$\delta i_k = C_{ic} \cos 2\Phi_k + C_{is} \sin 2\Phi_k$	Correction to inclination
$u_k = \Phi_k + \delta u_k$	Corrected argument of latitude
$r_k = A(1 - e\cos E_k) + \delta r_k$	Corrected radius
$i_k = i_0 + \delta i_k + (IDOT)\, t_k$	Corrected inclination
$\left.\begin{array}{l} x_k' = r_k \cos u_k \\ y_k' = r_k \sin u_k \end{array}\right\}$	Positions in orbital plane
$\Omega_k = \Omega_0 + (\dot{\Omega} - \dot{\Omega}_e)\, t_k - \dot{\Omega}_e\, t_{oe}$	Corrected longitude of ascending node
$\left.\begin{array}{l} x_k = x_k' \cos\Omega_k - y_k' \cos i_k \sin\Omega_k \\ y_k = x_k' \sin\Omega_k + y_k' \cos i_k \cos\Omega_k \\ z_k = y_k' \sin i_k \end{array}\right\}$	Earth-Centered, Earth-Fixed coordinates

* t is GPS system time at time of transmission, i.e., GPS time corrected for transit time (range/speed of light). Furthermore, t_k shall be the actual total time difference between the time t and the epoch time t_{oe}, and must account for beginning or end of week crossovers. That is, if t_k is greater than 302,400 seconds, subtract 604,800 seconds from t_k. If t_k is less than -302,400 seconds, add 604,800 seconds to t_k.

2.1.3 The RINEX navigation file

The broadcast ephemeris can be obtained from a GPS receiver or from an archive on the World Wide Web. We obtain the orbits from SOPAC[1] (Scripps orbit and Permanent Array Center). RINEX stands for Receiver Independent Exchange Format. The description of the RINEX navigation file is given in Appendix A.

The navigation files are compiled by many IGS stations throughout the world. A navigation file from such a site contains the orbital parameters for the satellites that it tracked during the day. This file therefore only holds the data for the periods that the satellites were in view at that site. This can be a problem if an attempt is made to reconstruct the orbits of all the satellites during the whole day. Therefore SOPAC assembles a file that contains the elements of all the satellites for the whole day. This file is called the 'autofile'.

The process of creating the autofile is not flawless. We have encountered the following problems:

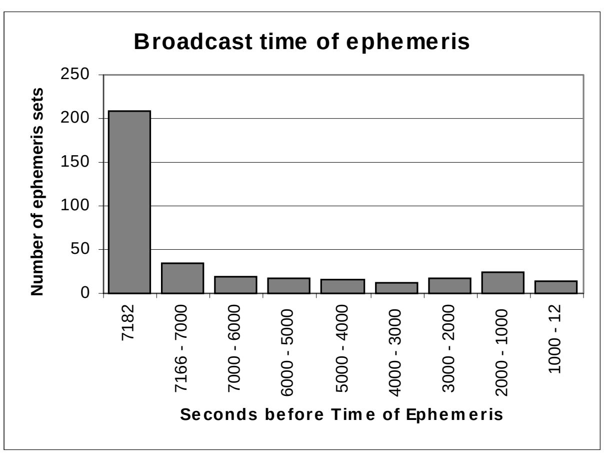
- In the autofile for the days around the week rollover (22-8-99), ephemeris sets were found to have dates from random days going back to 1980.
- Sometimes ephemeris sets are missing.
- The ephemeris for the last two hours of the day for most satellites is missing (see section 2.1.5).

Typically ephemeris sets are given in the autofile with a Time of Clock (TOC) from 00:00 till 22:00 at an interval of 2 hours. Sometimes more than one ephemeris set is given for a certain satellite for a certain TOC. The second set has a TOC of 16 seconds earlier than the "normal" one (for example 11:59:44) and has a newer Issue of Data (IOD). It is an update to the "normal" ephemeris. Typically this update has a higher accuracy than the older ephemeris set.

2.1.4 When to apply a certain ephemeris set

We consider an ephemeris set to be valid from two hours before the Time of ephemeris (TOE) until two hours after the TOE. The TOE is used as a reference time for computing the actual orbit of the satellite and to determine when the orbital elements are timing out. It should however, not be used to determine when the ephemeris set should be used for the first time! This starting point is determined by the time that the ephemeris set is transmitted for the first time (because this is almost equal to the time that it was received). This time is recorded in the RINEX navigation files and is called the Transmission Time of Message (TTOM). The TTOM is usually 7182 seconds (1:59:42) before the Time of ephemeris. Figure 2-2 shows the number of ephemerides that were transmitted on a particular day against the difference between TTOM and TOE.

Figure 2-2. The Transmission Time of Message in relation to the Time of ephemeris.

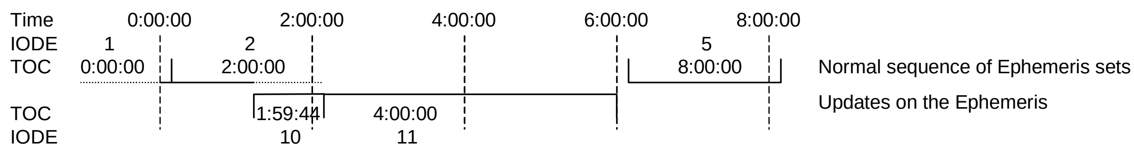


[1] http://lox.ucsd.edu/cgi-bin/complexDailyDataBrowser.cgi

2.1.5 Time out

Figure 2-3 shows an example of the use of the ephemeris sets during a typical eight-hour time interval. At 0:00:00 the ephemeris with TOC 0:00:00 is available (and has been for typically two hours). It is used until 0:00:18 (see section 2.1.4) when the ephemeris set with TOC 2:00:00 is received. An hour or so later an updated ephemeris set is received. The receiver recognizes that it is an update because the Issue of Data (IODE = 10) is not sequential to the previous one (IODE = 2). This update is used immediately until the next ephemeris set is received at 2:00:18. The next ephemeris set is received is 6:00:18 because the ephemeris with the TOC 6:00:00 is never received. Because an ephemeris set is valid from two hours before the TOC till two hours after the TOC, the set that is received last (IOD 11) is used until 6:59:59 hours. This means that there is a gap in the data for the next 18 seconds when another ephemeris set is received.

Figure 2-3. The use of ephemeris sets during a typical eight-hour time interval.



Because the navigation files give the ephemerides for the time period 0:00 < t_k < 24:00 hours, typically the last set for a satellite that appears in this file is the one for 22:00 hours. This is a problem because a certain set is normally used from two hours before this TOE until about the TOE itself (see section 2.1.4). So the last ephemeris set for the day is missing and the first one is only used for a couple of seconds untill the ephemeris with a TOE of 2:00 hours is received. This is not really a problem because the ephemeris set for 22:00 hours is valid till 24:00 hours. But when the goal is to calculate the best orbit coordinates, it is a good idea to also use the first ephemeris sets for the next day (with TOE of 0:00). If however an ephemeris update is recorded it would appear in the previous file because its TOE is 16 seconds before that of the normal TOE (i.e. 23:59:44).

2.2 WAAS messages

The WAAS signal contains a large number of different messages. All the messages are 250 bits long and are transmitted in 1 second. The messages may or may not be provided sequentially. The messages that contain the corrections for the satellite orbits are Message Types 25 (long term satellite error corrections message) and 24 (mixed fast correction/long term satellite error corrections message). Message Type 1 contains the PRN mask assignments.

2.2.1 PRN Mask Assignments Message Type 1

The PRN Mask is given in Message Type 1. It consists of 210 ordered slots, each of which indicates if data is provided for the corresponding satellite as defined in Table 2-3. A “1” indicates data is provided. A “0” that data is not provided.

Table 2-3. PRN Mask assignment [Ref. 1]

PRN Slot	Assignment
1 to 37	GPS/GPS Reserved PRN
38 to 61	GLONASS Slot Number plus 37
62 to 119	Future GNSS
120 to 138	GEO/WAAS PRN
139 to 210	Future GNSS/GEO/WAAS/Pseudolites

For example, a “1” in the fifth slot indicates data is provides for GPS PRN 5.

2.2.2 Long Term Satellite Error Corrections Message Type 25

Message Type 25 contains error estimates for slowly varying satellite ephemeris and clock errors. There are essentially two kinds of Message Type 25. Table 2-4 represents the *first half* of the corrections for the long-term satellite position and clock offset errors for two satellites, when only those corrections are needed. Table 2-5 present the first half of the Type 25 message representing corrections for the long term satellite position, velocity, clock offset and drift errors of one satellite, when velocity and drift corrections are also needed.

The first bit in the message sequence is the velocity code, indicating whether or not the message contains clock drift and velocity component estimates. If the velocity code is 0 those are not included; if it is set to 1, they are. A message with velocity code 0 contains corrections for 2 instead of 1 satellite. So Message Type 25 can contain corrections for 1, 2, 3 or 4 satellites depending on the velocity codes of the two message parts.

Table 2-4. Corrections for the long term satellite position and clock offset errors.

Parameter	Scale Factor	Effective Range	Units
Velocity Code = **0**	1	-	discrete
PRN Mask No.	1	0 - 51	-
Issue of Data	1	0 - 255	discrete
δx	0.125	± 32	meters
δy	0.125	± 32	meters
δz	0.125	± 32	meters
δa_{f0}	2^{-31}	$\pm 2^{-22}$	seconds
PRN Mask No.	1	0 - 51	-
Issue of Data	1	0 - 255	discrete
δx	0.125	± 32	meters
δy	0.125	± 32	meters
δz	0.125	± 32	meters
δa_{f0}	2^{-31}	$\pm 2^{-22}$	seconds
IODP	1	0 - 3	discrete

Table 2-5. Corrections for the long term satellite position, velocity, clock offset and drift errors.

Parameter	Scale Factor	Effective Range	Units
Velocity Code = **1**	1	-	discrete
PRN Mask No.	1	0 - 51	-
Issue of Data	1	0 - 255	discrete
δx	0.125	± 32	meters
δy	0.125	± 32	meters
δz	0.125	± 32	meters
δa_{f0}	2^{-31}	$\pm 2^{-22}$	seconds
δx rate-of-change	2^{-11}	± 0.0625	meters/sec
δy rate-of-change	2^{-11}	± 0.0625	meters/sec
δz rate-of-change	2^{-11}	± 0.0625	meters/sec
δa_{f1}	0.125	$\pm 2^{-32}$	seconds/sec
Time-of-Day Applicability t_0	0.125	0 - 86,384	seconds
IODP	1	0 - 3	discrete

2.2.3 Mixed Fast Correction/Long Term Satellite Error Corrections Message Type 24

Message Type 24 contains mixed fast correction/long term satellite error corrections. The first half of the message contains fast corrections. The second half of the message contains error corrections in the same format as Message Type 25 (see Table 2-4 and 2-5) as described in section 2.2.2.

2.2.4 WAAS corrections validation process

A Long Term WAAS correction can be applied to the appropriate satellite when the PRN of the corrections is established using Message Type 1. The corrections are only valid when the IOD of the broadcast ephemeris matches the IOD in the correction message, and only when the time interval of applicability[1] is not longer than 360 seconds.

The position error correction vector is computed as follows:

$$\begin{bmatrix} \delta x_k \\ \delta y_k \\ \delta z_k \end{bmatrix} = \begin{bmatrix} \delta x \\ \delta y \\ \delta z \end{bmatrix} + \begin{bmatrix} \delta \dot{x} \\ \delta \dot{y} \\ \delta \dot{z} \end{bmatrix} (t_k - t_0)$$

with t_k = the current time
t_0 = time of applicability (reference time)

This correction vector is added to the satellite coordinate vector $[x_k\ y_k\ z_k]^T$ that is computed according to Table 2-2. If the velocity code is set to 0, the rate-of-change vector is set to 0.

2.3 IGS orbits

The International GPS Service (IGS) collects, archives, and distributes GPS observation data sets. These observations are used by the IGS to compute other data, such as GPS satellite ephemerides and Earth rotation parameters, which are made available through the Internet[2]. The accuracies of IGS products are sufficient for the improvement and extension of the International Terrestrial Reference Frame (ITRF), for scientific satellite orbit determinations, ionosphere monitoring, and recovery of percipiTable water vapor measurements etc. To accomplish this, the IGS has a number of components: an international network of over 200 continuously operating dual-frequency GPS stations, more than a dozen regional and operational data centers, three global data centers, seven analysis centers and a number of associate or regional analysis centers. [Ref. 6]

The IGS produces three different orbit products: the Predicted, rapid and final orbits (see Table 2-6). The orbits are presented in Cartesian coordinates every 15 minutes for 24 hours. The seven final orbits for a certain week are made available via the Internet on Thursdays. This means that the longest delay in the publication of the final orbits is 20 days.

Table 2-6. Performance of the IGS orbits.

	final (FO)	rapid (RO)	Predicted (PO)
Available after	13 - 20 days	2 days	Real time
Accuracy	5 cm	10 cm	50 cm
Code	igs	igr	igp

When the health of a GPS satellite is too bad to produce a decent orbit, the satellite is left out of the orbit files.

2.4 Comparison

The IGS orbit is available at an interval of 15 minutes. The Broadcast Orbits are therefore also calculated in Cartesian coordinates every 15 minutes. The errors are computed by subtracting the X,Y,Z coordinates of

[1] Interval of applicability: the difference between the time when the message is applied and the time-of-applicability as given in the correction messages.
[2] FTP: igscb.jpl.nasa.gov

the IGS orbit from the X,Y,Z coordinates determined from the broadcast orbit. No transformations are carried out. The difference between the WGS 84 system used for the BO and ITRF used for the IGS orbits is well below 10 cm.

The 3D error is then computed as follows:

$$3D_{error\,i} = \sqrt{dx_i^{\,2} + dy_i^{\,2} + dz_i^{\,2}}$$

with dx, dy and dz the errors in the BO

This gives a set of 4 x 96 differences for every satellite during a day.

Then the root-mean-square (RMS) is calculated and the minimum and maximum values can be computed. The RMS in the X direction is defined as:

$$RMS_{x_k} = \sqrt{\frac{1}{n}\sum_{i=1}^{n} dx_i^{\,2}}$$

where k = the satellite number
n = the number of valid values for satellite k
dx_i = the error in the orbit in the X-direction

A similar formula is used for the Y and Z directions. The RMS for the 3D direction is defined as follows:

$$RMS_{3D_k} = \sqrt{\frac{1}{n}\sum_{i=1}^{n} (dx_i^{\,2} + dy_i^{\,2} + dz_i^{\,2})}$$

The overall RMS for the whole day for all the satellites can then be computed in the following way:

$$RMS_{Overall} = \sqrt{\frac{1}{s}\sum_{k=1}^{s} (RMS_{3D_k})^2}$$

where s = the number of satellites with a valid RMS

The statistics between the WAAS-corrected orbit and the IGS orbit are computed in a similar way.

3 Software

To automate the process of applying the WAAS-corrections and calculating the required statistics, I have written a set of Fortran 77 codes. The operation of the program is explained in the first paragraph. In section 3.2 some program output is discussed and the final paragraph deals with the automation of the process.

3.1 Module description

3.1.1 waas.f

The main program is called *waas.f*. This code asks the user to input the Day-Of-Year (DOY) for which the comparisons should be made. It then calls sequentially the subroutines *xyz.f, wx.f* and *stat.f*. See Table 3-1 for the program structure.

3.1.2 xyz.f

In subroutine xyz.f the navigation file (NF) for that day is read and the same is done for the NF for the next day (DOY + 1). For each time interval, in this case every 15 minutes, the subroutine *bcorb.f* is called. Where a valid ephemeris set is searched and, in case it is found, the quasi-Keplerian elements are converted to Cartesian coordinates. If a temporary flag is set (none=1) these Cartesian coordinates are written to the file *DOY.gps_xyz*. If this is not the case, zeros are written to the file and the ephemeris flag is set to not-valid (VAL=1).

3.1.3 bcorb.f

This subroutine calls another subroutine *sortp.f* which sorts the broadcast times (BT). Then this list is searched for a valid ephemeris set. An ephemeris set is valid as the broadcast time (BT) and the Time of applicability (t_0) are both earlier than the present time (t_k), but the interval of applicability (IOA) must be less than 360 seconds before the ephemeris set times out. It is also very important that the issue of data of the ephemeris (IODE) matches the IOD of the WAAS-correction. If all of these conditions are satisfied, a temporary flag is set (none=1). Then the subroutine *bceph.f* is called which converts the quasi-Keplerian broadcast elements to Cartesian coordinates.

3.1.4 sortp.f

Subroutine *sortp.f* sorts the broadcast times (BT).

3.1.5 bceph.f

Converts the quasi-Keplerian broadcast elements to Cartesian coordinates.

3.1.6 wc.f

The main program calls *wc.f*, which opens the subroutine *readwaas.f*. This subroutine puts the WAAS-correction messages in an array (MESSAGE25). For every time interval and for every satellite the file *DOY.gps_xyz* is read. MESSAGE25 is searched for a valid WAAS-correction (see section 2.2.4). It first searches for the last correction that has an earlier time of applicability (TA) than the current time (t_k). Then it checks if the IOD of that correction matches the IOD of the broadcast ephemeris (BE). If this is not the case it searches for a valid WAAS-correction that has a correct IOD. Then it checks if the broadcast time (BT) is earlier than the current time (t_k). If this is not the case it goes back in time to search for a correction that with a lower BT than t_k and a matching IOD. If it does not find a valid WAAS-correction the WAAS-correction parameters are set to zero and the ephemeris Flag (VAL) is raised by two. The WAAS-corrections are then calculated and applied to the Cartesian orbit coordinates. For time intervals where the ephemeris flag is valid for both ephemeris and WAAS-correction, the corrected orbit is written to file *DOY.waas_xyz*. If this is not the case, zeros are written to this file.

3.1.7 readwaas.f

This subroutine first reads Message Type 1, counts the zeros and writes the number of zeros that it encountered to an array (ASSIGNPRN). Then it reads Message Type 25, applies the PRN Mask (ASSIGNPRN) and sorts it by PRN. The scale factors are applied and the whole array (MESSAGE25) is written to file *DOY.waasdata*.

3.1.8 stat.f

Subroutine *stat.f* reads the IGS final orbit (FO) (or rapid orbit) and writes the Cartesian coordinates to file *DOY.igs_xyz* in a standardized format. If there is no FO available at a certain time zeros are written to the file. The ephemeris flag is set for no valid FO. Then it reads the broadcast orbit (BO) from file *DOY.gps_xyz*. If the ephemeris flag says that there is a valid ephemeris and a valid FO, the FO is subtracted from the BO. The difference is written to the file *DOY.gpsdiff*. The same thing is done with the WAAS-corrected coordinates if the EF says that there is a valid WAAS-correction, a valid ephemeris and a valid FO for this time interval.

Then the subroutine *calcrms.f* is called to calculate the RMS for the different satellites for the day for both the BO and the WO. Then the RMS for the whole day is calculated and the statistics are written to the files *DOY.gps_errors* and *DOY.waas_errors*. The subroutine *makehtml.f* is called to write the statistics to html files called *DOYgps.html* and *DOYwaa.html*.

3.1.9 calcrms.f

The root-mean-square (RMS) is calculated in this subroutine according to the formula described in section 2.4.

3.1.10 makehtml.f

This subroutine writes the statistics to html files called *DOYgps.html* and *DOYwaa.html*. It starts by reading the header of the html file from the file *headerstart.html* or *headerwaas.html*, depending on whether it is working on the BO or the WO, and writing it to the output file. Then it writes the DOY and the overall RMS for the day to the output file. Next it writes the data from the file *headerend.html* to the output file. The same goes for the file *collstart.html*. Then it writes the code to make the columns to the output file and writes the statistics at the same time at the appropriate place. A number is always written to the file with four digits. It the number is bigger than 6 or smaller than –6, it is written in red instead of black. If there is no valid data available, the values are written in white. Then the Table is closed and data from the file *footer.html* is transferred to the output file.

Table 3-1. Program structure

waas.f
- Ask DOY
  - **xyz.f**
    - read BE navigation file
    - read BE navigation file of the next day
    - do for every time interval
      - **bcorb.f**
        - **sortp.f**
          - sort ephemerides on BT
        - find valid ephemeris set
        - if there is a valid ephemeris set, flag time as valid
        - **bceph.f**
          - calculate Cartesian coordinates
    - write coordinates to file *gps_xyz*
    - in case of a not-valid-flag write 0 to file
- **wc.f**
  - **readwaas.f**
    - read Message Type 1
    - read Message Type 25
    - apply scale factors
    - write to file *waasdata*
  - read file *gps_xyz*
  - apply valid WAAS-corrections
  - if there are no valid WAAS-corrections available, flag as no-WAAS-corrections
  - write corrected coordinates to file *waas_xyz*
  - incase of no-WAAS-corrections-flag write 0 to file
- **stat.f**
  - read IGS FO
  - write FO coordinates to file *igs_xyz* in standard format
  - read BO file *gps_xyz*
  - subtract FO from BO
  - write differences to file *gpsdiff*
  - in case of no-valid-flag write 0
  - read WO file waas_xyz
  - subtract BO from WO
  - write differences to file *waasdiff*
  - in case of no-valid-flag write 0
  - **calcrms.f**
    - calculate the RMS for every satellite
  - calculate the RMS for the entire day
  - write FO statistics to file *gps_errors*
  - write WO statistics to file *waas_error*
  - **makehtml.f**
    - read header
    - write header to *html file*
    - create table and write statistics to *html file*
    - read footer
    - write footer to *html file*

Legend
DOY: Day-Of-Year
BE: Broadcast Ephemeris
BT: Broadcast Time
WAAS: Wide Area Augmentation
FO: Final Orbit
BO: Broadcast Orbit
WO: WAAS-corrected Orbit
RMS: Root Mean Square
IGS: International GPS Service

3.2 Execution control

Because the program has to compile the statistics for a day that is 2 days (rapid orbit comparison) or 20 days (final orbit comparison) before a certain date and because all the input filenames are in a different format, the execution of the program is quite tricky. The final orbit filenames are in the format igsWWWWS.sp3 (with WWWW=GPSweek and S=Day-of-Week, 0-6), the navigation files are in the format autoJJJ0.99n (with JJJ=Day-of-Year) and the WAAS-files in the format DDMMYY_TT.out (with D=Day-of-Month, M=Month, Y=Year and TT=Message Type).

The script that, amongst other things, takes care of the date conversions is called *waas.sh*. This program gets the current date and determines the date of the day it has to calculate the statistics. This date is 20 days before the current date. This ensures that an IGS final orbit is available. Then it gets the final orbit via anonymous FTP at *igscb.jpl.nasa.gov* and the navigation autofile at *lox.ucsd.edu*. The files are uncompressed and the program (*waas.a*) is run. The subroutine *xyz.f* takes the matching normal date from the autofile reads it and uses it to determine which WAAS-data file it needs. If the statistics are computed, the HTML-statistics-files are put on the WWW server running on gauss (*gauss.gge.unb.ca/grads/orbit*). Unfortunately, the WAAS-data can not be acquired automatically yet.

3.3 Automation and scheduling

The program is currently running on the Unix workstation “gauss” under Sun Solaris 5.6. Every day at 8:00 a.m. the Crontab “00 8 * * 0-6 waas.sh” executes the program *waas.sh*.

4 Sample results

The following paragraphs discuss the results of the computations for day 331 of 1999, that is Sunday 27-11-99 and GPSweek 1037 (13), day 6 of the week (IGS standaard). This day is chosen because it is the first day for where there was a total day of WAAS-correction data available.

4.1 GPS broadcast ephemeris accuracy statistics

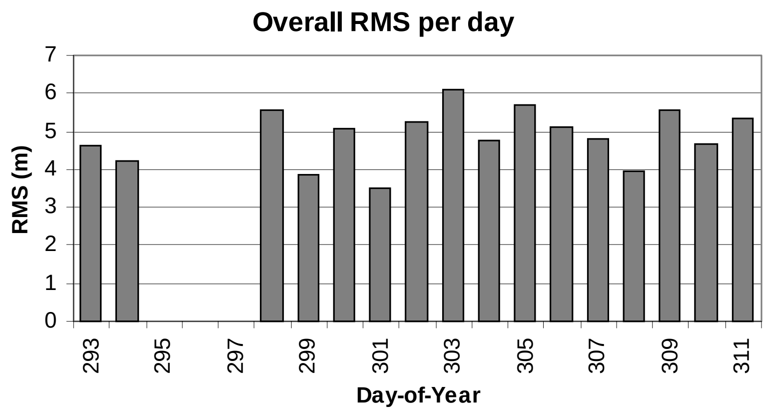
Table 4-1 shows the computed statistics for day 331. It gives the minimal and maximal errors in the X, Y and Z directions and also for the length of the 3D-vector. Further it shows the root-mean-square for those directions over the whole day. The 3D RMS for the whole day for all the satellites combined is 4.94 meters.

Table 4-1. GPS broadcast ephemeris accuracy statistics.

x				y				z				3D			
PRN	min	max	r.m.s.	PRN	min	max	r.m.s.	PRN	min	max	r.m.s.	PRN	min	max	r.m.s.
1	-1.795	2.211	1.213	1	-2.357	2.770	1.439	1	-4.092	1.697	2.144	1	0.986	4.411	2.853
2	-15.57	4.871	5.398	2	-15.79	22.63	10.88	2	-13.42	15.59	7.959	2	3.382	23.15	14.52
3	-1.360	1.741	0.891	3	-2.381	2.217	1.390	3	-0.035	2.179	1.178	3	0.656	3.002	2.028
4	-3.555	2.367	1.455	4	-3.548	5.652	2.250	4	-7.394	3.505	2.761	4	0.780	7.549	3.848
5	-2.396	4.127	1.546	5	-6.263	4.154	3.109	5	-1.220	3.539	1.713	5	1.021	7.197	3.872
6	-5.549	5.834	2.431	6	-8.427	6.766	5.020	6	-2.902	10.47	5.193	6	1.776	11.82	7.621
7	-5.540	4.883	3.193	7	-7.181	5.350	3.656	7	-3.067	6.056	2.420	7	2.349	8.942	5.424
8	-1.711	1.514	0.978	8	-2.529	1.691	1.060	8	-2.821	1.619	1.476	8	1.052	3.334	2.063
9	-2.387	3.960	1.697	9	-5.676	3.075	2.910	9	-3.971	2.527	1.753	9	1.456	6.321	3.797
10	-4.764	2.120	2.027	10	-2.781	3.508	1.702	10	-5.866	6.126	2.521	10	1.295	6.684	3.655
11				11				11				11			
12				12				12				12			
13	-2.037	2.054	1.085	13	-3.129	1.767	1.343	13	-2.562	3.064	1.708	13	1.050	3.638	2.429
14	-8.211	6.580	4.280	14	-4.992	3.755	2.673	14	-5.842	3.290	3.011	14	3.005	8.574	5.876
15	-3.202	3.588	2.292	15	-2.105	2.211	1.274	15	-2.797	0.956	0.907	15	1.098	3.762	2.775
16	-13.65	10.11	6.420	16	-11.16	1.174	2.766	16	-5.520	11.72	4.848	16	0.617	15.59	8.507
17	-3.927	5.847	2.543	17	-2.833	2.112	1.255	17	-4.731	3.633	2.619	17	0.570	6.268	3.860
18	-4.594	2.656	2.017	18	-6.191	4.291	2.703	18	-2.487	3.250	1.640	18	0.912	6.261	3.750
19	-2.776	2.979	1.681	19	-3.521	3.346	2.020	19	-2.574	3.696	1.596	19	0.864	4.451	3.075
20				20				20				20			
21	-1.175	2.205	0.626	21	-2.393	2.860	1.729	21	-2.403	1.485	0.939	21	0.347	3.283	2.064
22	-2.524	3.202	1.595	22	-3.422	3.748	2.253	22	-2.327	3.129	1.570	22	1.514	4.360	3.175
23	-4.669	2.183	1.788	23	-3.406	4.116	1.885	23	-7.903	1.769	2.576	23	0.231	9.259	3.659
24	-2.664	6.455	2.520	24	-3.076	4.980	1.646	24	-4.893	7.418	3.498	24	1.435	7.872	4.615
25	-3.645	4.595	2.073	25	-4.651	3.162	2.044	25	-4.184	2.940	1.909	25	0.496	5.152	3.482
26	-1.340	1.798	0.900	26	-2.181	1.433	0.912	26	-2.648	2.076	1.571	26	0.800	3.006	2.027
27	-4.477	6.749	3.366	27	-3.525	2.597	1.730	27	-4.808	3.462	2.802	27	1.449	7.571	4.709
28				28				28				28			
29	-4.318	1.686	1.790	29	-6.707	3.453	2.762	29	-4.868	3.993	2.319	29	0.715	6.959	4.026
30	-2.644	3.404	1.394	30	-2.944	1.942	1.260	30	-2.646	2.957	1.565	30	0.563	3.619	2.446
31	-4.442	2.719	2.292	31	-3.456	4.341	2.686	31	-3.031	5.423	2.525	31	1.282	6.742	4.341

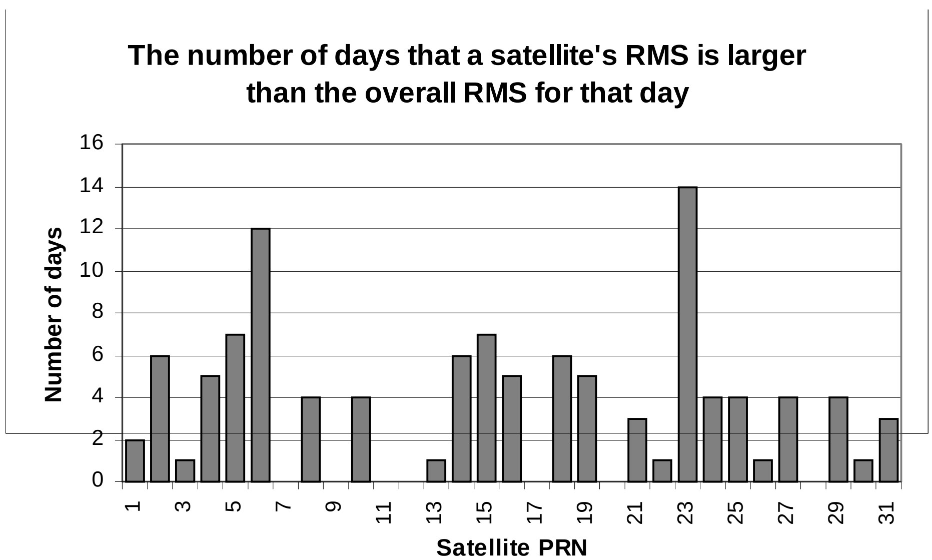
Figure 4-1 shows the overall RMS per day for a total of sixteen days. The average RMS over those days is 4.88 meters.

Figure 4-1. The overall RMS per day for 16 days.



The number of days that the RMS for a particular satellite is larger than the overall RMS is shown in Figure 4-2. It clearly shows that satellites 6 and 23 more frequently have a bad orbit than the other satellites, namely 14 and 12 times out of 16 respectively. In the case of satellite 23, this is caused by problems with its solar panels which must be adjusted manually. The cause of the bad orbits of satellite 6 is unknown.

Figure 4-2. The number of days that the satellite's RMS is larger than the overall RMS for that day.



4.2 WAAS-corrected GPS broadcast ephemeris accuracy statistics

Table 4-2 shows the statistics of the WAAS-corrected orbit of day 331. The overall RMS for this day is 4.01 meters. This is a slight improvement over the 4.94 meters of the broadcast orbit. We see that 10 of the 27 orbits improve by a meter or more, but 12 orbits are worse than what they were before correction! This is strange. WAAS may not have been operating satisfactorily on that day.

Table 4-2. WAAS-corrected GPS broadcast ephemeris accuracy statistics.

x				y				z				3D			
PRN	min	max	r.m.s.	PRN	min	max	r.m.s.	PRN	min	max	r.m.s.	PRN	min	max	r.m.s.
1	-7.650	2.343	2.370	1	-1.079	6.237	1.927	1	-3.487	4.603	1.979	1	0.239	10.64	3.640
2	-5.291	-0.073	1.975	2	-1.054	2.384	1.283	2	-3.166	0.275	1.324	2	0.618	6.258	2.702
3	-6.934	1.207	2.149	3	-7.050	1.821	1.510	3	-5.603	2.397	2.237	3	1.120	8.542	3.450
4	-12.68	10.84	4.668	4	-11.36	3.650	4.142	4	-7.663	5.347	3.896	4	1.816	17.03	7.356
5	-1.973	1.678	0.919	5	-11.31	3.153	2.637	5	-4.153	5.469	1.882	5	1.207	12.59	3.367
6	-1.558	4.455	1.698	6	-2.928	2.403	1.542	6	-4.403	2.895	2.307	6	1.310	5.372	3.253
7	-4.763	3.678	1.775	7	-6.772	1.729	2.342	7	-5.013	7.754	2.531	7	0.379	9.940	3.878
8	-1.308	1.079	0.659	8	-2.946	3.278	1.762	8	-3.903	1.569	1.614	8	1.215	4.993	2.479
9	-0.783	2.429	0.976	9	-0.621	2.981	1.663	9	-2.962	3.184	1.538	9	0.697	3.789	2.466
10	-6.796	3.301	1.909	10	-6.106	2.308	1.579	10	-3.748	0.572	1.918	10	0.751	9.154	3.133
11				11				11				11			
12				12				12				12			
13	-1.687	2.020	1.128	13	-1.680	1.511	0.734	13	-3.166	1.179	1.836	13	0.373	3.606	2.276
14	-2.425	2.226	1.234	14	-8.648	4.243	2.867	14	-3.146	10.87	2.321	14	1.633	14.10	3.890
15	-3.545	4.568	1.795	15	-15.55	5.746	4.725	15	-7.533	16.90	5.246	15	0.646	22.20	7.285
16	-3.868	1.668	1.247	16	-16.24	3.510	3.816	16	-4.533	15.87	3.970	16	0.849	22.90	5.646
17	-2.141	2.995	1.413	17	-3.905	5.939	2.056	17	-5.474	1.398	1.402	17	0.287	8.125	2.862
18	-1.829	2.414	1.139	18	-2.448	2.656	1.237	18	-3.089	1.633	1.401	18	0.946	3.353	2.188
19	-5.020	3.661	1.699	19	-1.052	4.352	1.449	19	-5.624	1.527	2.176	19	0.637	7.534	3.118
20				20				20				20			
21	-3.033	4.744	1.365	21	-2.997	2.676	1.384	21	-2.568	0.593	1.059	21	0.636	5.883	2.214
22	-7.327	2.413	2.659	22	-10.14	2.659	2.424	22	-4.772	-0.302	2.818	22	0.665	13.08	4.570
23	-7.466	1.032	1.678	23	-2.836	2.336	1.285	23	-4.644	1.911	1.869	23	0.343	7.786	2.822
24	-3.571	17.23	4.166	24	-3.217	3.430	1.851	24	-6.160	3.110	2.202	24	0.594	18.61	5.063
25	-7.907	7.942	2.938	25	-7.140	3.537	3.037	25	-6.705	3.196	3.423	25	0.234	11.60	5.438
26	-3.636	1.811	1.480	26	-6.332	2.778	2.145	26	-7.358	1.188	2.333	26	0.202	8.406	3.498
27	-3.928	2.117	1.316	27	-3.630	4.603	1.923	27	-3.981	3.954	1.880	27	0.262	7.021	2.993
28				28				28				28			
29	-18.99	2.408	4.038	29	-3.841	4.480	2.251	29	-3.909	6.558	2.234	29	0.505	20.13	5.135
30	-2.420	1.934	1.419	30	-4.273	3.249	1.672	30	-3.097	2.067	1.829	30	1.213	4.530	2.855
31	-8.905	2.708	2.140	31	-9.992	4.199	2.308	31	-11.23	1.208	2.592	31	0.789	14.35	4.077

We take now a closer look at satellite PRN 2 and PRN 25. For satellite 2 the orbit improves dramatically after applying the WAAS-corrections. Figure 4-3 shows the actual X, Y and Z coordinates for the satellite (at the top plot), the difference between the broadcast orbit and the IGS final orbit (in the middle plot) and the difference between the WAAS-corrected orbit and the final orbit coordinates (in the bottom plot). If the plot shows a zero error in the WAAS-corrected orbit (WO), it means that there were no valid WAAS-corrections available at that time. The broadcast orbit is particularly bad for this satellite for this day (see the middle plot), but after applying the WAAS-corrections the error is brought to accepTable levels. The RMS goes down from 14.52 to 2.70 meters.

Figure 4-3. The coordinates of the BO and the errors in the BO and WO for satellite 2 on day 331.

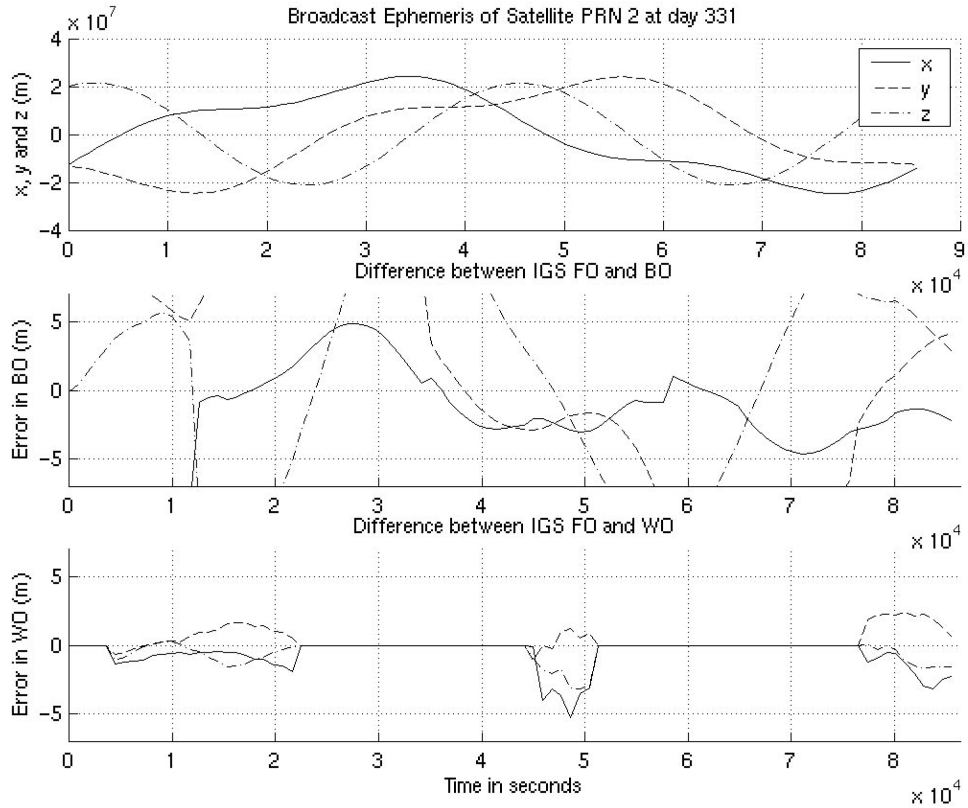
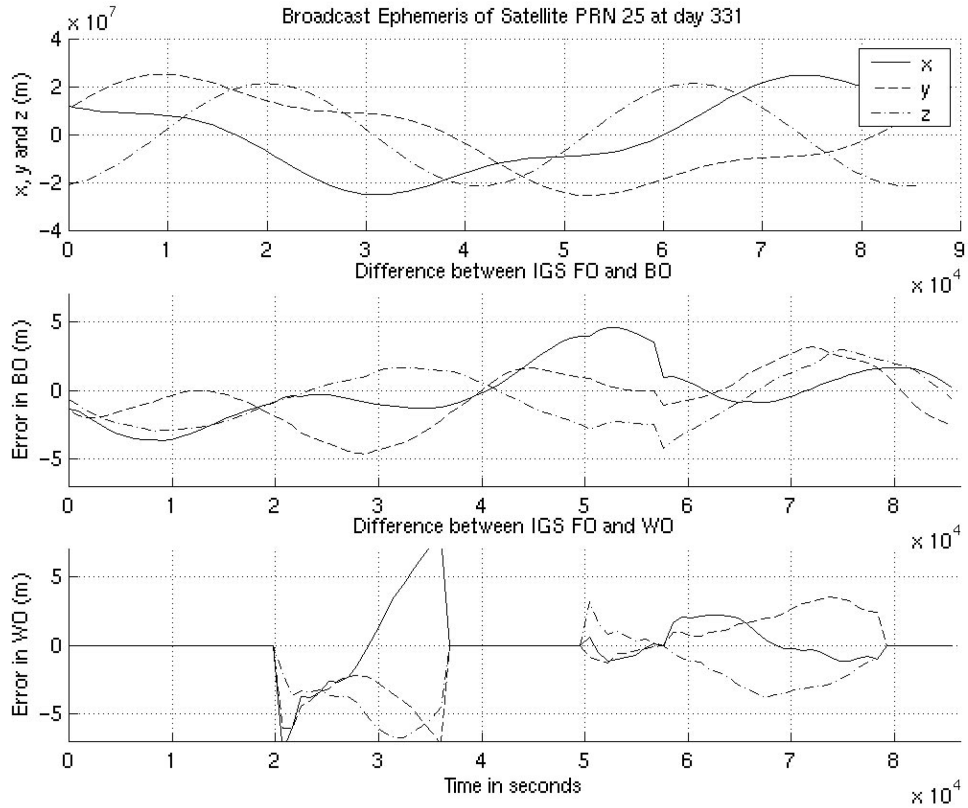


Figure 4-4 shows the orbit of satellite 25 on day 331. The BO error is at accepTable levels (the RMS is 3.48 meters), but after applying the WAAS-corrections the error increases (to an RMS of 5.43). Between 30,000 and 37,000 seconds the error drifts away to over 7 meters. Between 50,000 and 58,000 the error is largely reduced, but increases again after this period to a level of 4 meters. The error plot for all the other GPS satellites for this day can be found in Appendix D.

If we, by the way, take a closer look at the plot in the middle of Figure 4-4, we can see small bumps in the broadcast orbit-error. They occur with a frequency of two hours (7200 seconds). This is due to the switchover to a different ephemeris set. Larger, abrupt changes in the BO-error are usually created by switching to an update of the ephemeris. In that case the error reduces very quickly creating a jump. A sudden increase of the error suggests a return to the sequence of the original ephemeris sets.

Figure 4-4. The coordinates of the BO and the errors in the BO and WO for satellite 25 on day 331.



Now rises the question of the way that the WAAS-corrections are applied is valid or not. We namely assumed that all the WAAS-corrections that satisfy the earlier named characteristics (see section 2.1.4) are valid. Even if the satellite for which the corrections are valid is not in view from any position in service area (USA and parts of Canada and Mexico). This may not be right. If we therefore choose an CORS station in middle of the USA (in this case station Table Mountain in Colorado or 'tmgo') and look at the periods for which a broadcast ephemeris for a particular satellite is received, we can get an approximation of which satellites were in view over the service area at a particular time. These satellites are the only ones that appear in the navigation file of this particular station.

If we do that and apply the broadcast ephemeris sets as discussed in section 2.1.4, the overall 3D RMS for day 331 goes down to 3.23 meters (see also Table 4-3). Note that the overall RMS for the broadcast orbit for this station goes also down (to 4.73 meters, see Appendix B). This method degreases the accuracy of 10 orbits, but it improves also 10 orbits by more than a meter. This is better than the first case, but still not wholly accepTable.

Table 4-3. WAAS-corrected GPS broadcast ephemeris accuracy statistics for station 'tmgo'.

x				y				z				3D			
PRN	min	max	r.m.s.	PRN	min	max	r.m.s.	PRN	min	max	r.m.s.	PRN	min	max	r.m.s.
1	-1.004	1.143	0.812	1	-1.079	1.699	0.912	1	-3.487	0.875	1.994	1	1.322	3.623	2.338
2	-3.173	1.276	1.376	2	-0.646	2.384	1.350	2	-1.710	2.814	1.052	2	0.618	4.108	2.196
3	-5.179	1.129	1.590	3	-2.170	1.821	1.186	3	-6.638	1.741	2.569	3	1.120	8.588	3.246
4	-7.293	6.013	2.898	4	-8.437	2.741	3.087	4	-6.568	11.85	4.091	4	1.816	15.74	5.888
5	-1.973	1.678	0.981	5	-7.524	3.100	2.109	5	-3.188	2.109	1.487	5	1.413	7.744	2.761
6	-1.558	1.004	0.633	6	0.212	2.403	1.088	6	-4.077	2.681	1.961	6	1.310	4.982	2.331
7	-1.476	1.687	0.750	7	-3.038	1.275	0.981	7	-1.787	4.503	1.335	7	0.379	5.688	1.818
8	-1.308	0.828	0.615	8	-2.577	3.278	1.666	8	-2.758	1.569	1.378	8	1.136	3.779	2.248
9	-2.295	0.960	0.611	9	-3.799	2.981	1.871	9	-5.213	0.416	1.635	9	0.697	6.847	2.559
10	-2.996	3.301	1.723	10	-2.188	2.412	1.339	10	-3.748	0.361	2.032	10	0.751	4.181	2.982
11				11				11				11			
12				12				12				12			
13	-1.687	1.774	0.982	13	-1.680	1.429	0.651	13	-3.166	1.179	2.017	13	0.373	3.606	2.336
14	-2.134	2.226	1.275	14	-3.086	4.243	2.104	14	-3.146	1.586	1.581	14	1.633	4.405	2.924
15	-0.873	2.588	0.868	15	-0.297	5.566	2.067	15	-4.552	1.639	1.558	15	0.646	7.243	2.730
16	-1.194	1.517	0.809	16	-1.892	3.510	1.788	16	-3.771	2.170	1.873	16	0.849	4.722	2.713
17	-2.028	0.754	0.958	17	-1.137	5.939	1.891	17	-5.474	1.448	1.687	17	0.287	8.125	2.709
18	-1.829	2.414	1.209	18	-2.448	2.359	1.088	18	-3.089	1.633	1.499	18	0.946	3.353	2.212
19	-2.295	3.661	1.294	19	-0.899	4.353	1.798	19	-5.624	0.563	2.674	19	0.637	7.534	3.472
20				20				20				20			
21	-3.033	2.018	1.050	21	-0.564	4.583	1.406	21	-3.537	2.286	1.142	21	0.636	5.818	2.094
22	-5.985	2.413	2.310	22	-4.270	2.140	1.543	22	-4.772	-0.094	2.496	22	0.665	7.492	3.735
23	-3.003	2.601	1.456	23	-2.471	2.336	0.941	23	-4.644	6.324	2.172	23	0.343	7.271	2.779
24	-1.763	2.373	1.203	24	-3.341	2.414	1.415	24	-2.412	4.324	1.907	24	0.594	5.534	2.662
25	-1.163	11.38	3.408	25	-11.60	3.162	3.503	25	-3.819	15.69	5.386	25	0.234	22.41	7.273
26	-3.874	1.811	1.318	26	-1.815	2.778	1.428	26	-7.358	1.188	2.746	26	0.202	8.405	3.365
27	-1.413	0.558	0.664	27	-0.435	3.015	1.352	27	-3.673	1.526	1.965	27	0.356	4.785	2.476
28				28				28				28			
29	-1.084	2.408	0.853	29	-1.745	3.767	1.216	29	-3.910	2.078	1.751	29	0.505	4.601	2.296
30	-2.420	1.934	1.393	30	-1.432	3.249	1.651	30	-2.843	1.016	1.692	30	1.213	3.907	2.744
31	-8.905	2.708	2.640	31	-0.783	4.199	1.665	31	-11.23	1.208	3.128	31	1.106	14.35	4.419

So in the case that we only look at the satellites that actually were in view from the service volume, the broadcast orbit is improved by the WAAS-corrections by 1.50 meters. In the first case this improvement was only 0.83 meters. The assumption that the WAAS-corrections are only valid as they could be seen from the service area seems therefor, a valid one.

If we now again take a look at the error plot of satellite 2 (see Figure 4-5), we can see why the RMS is reduced. The period that largely contributes to the large RMS in the first case (between 45,000 and 51,000 seconds) is not present.

Note that for the times that the orbit coordinates or the errors in the orbits are zero, the satellites was not in view from station 'tmgo'.

Figure 4-5. The coordinates of the BO and the errors in the BO and WO for satellite 2 on day 331 for the periods that it was in view from station 'tmgo'.

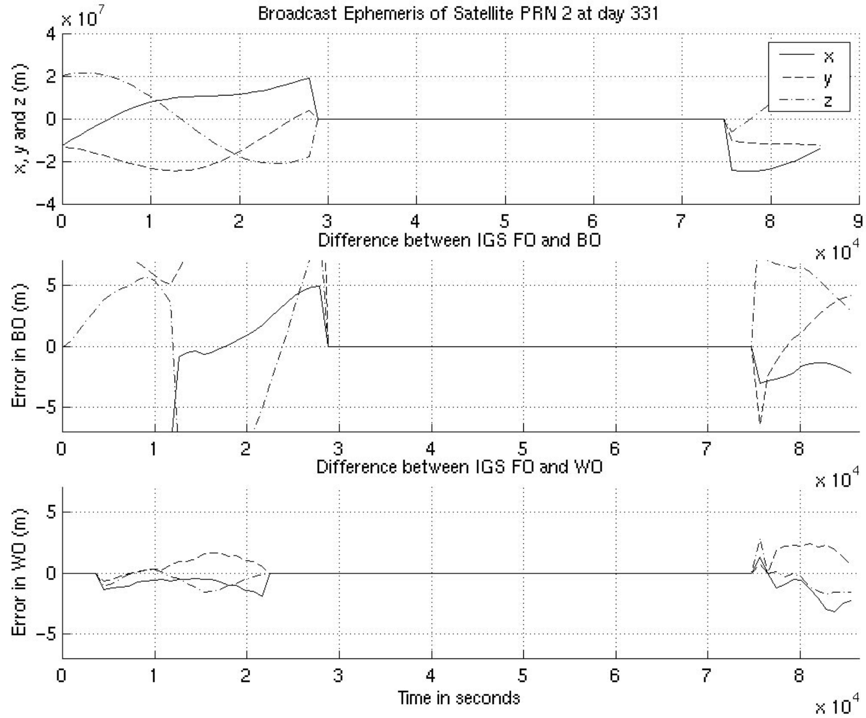
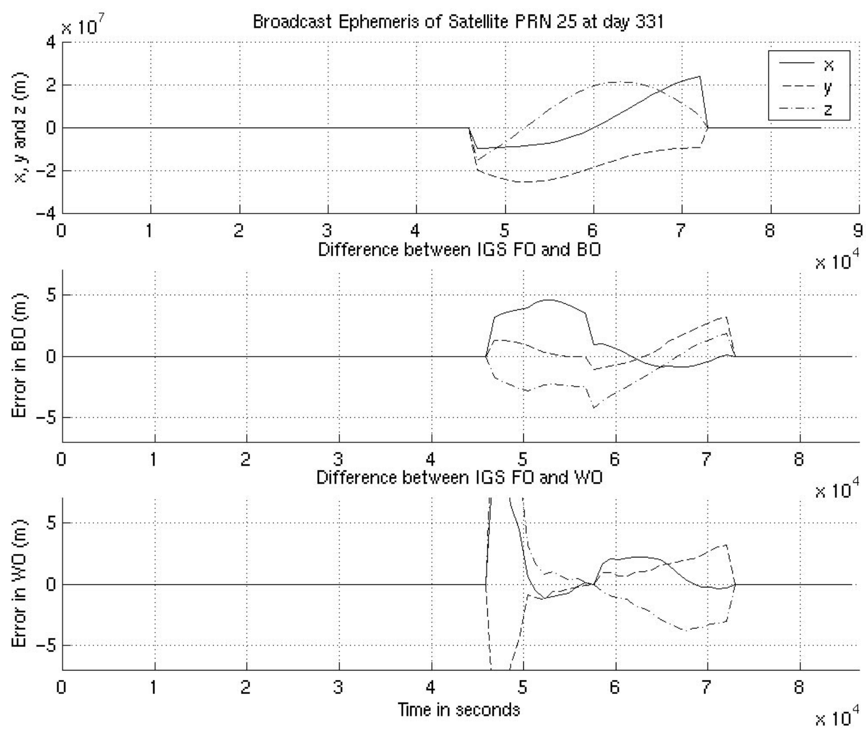


Figure 4-6. The coordinates of the BO and the errors in the BO and WO for satellite 25 on day 331 for the periods that it was in view from station 'tmgo'



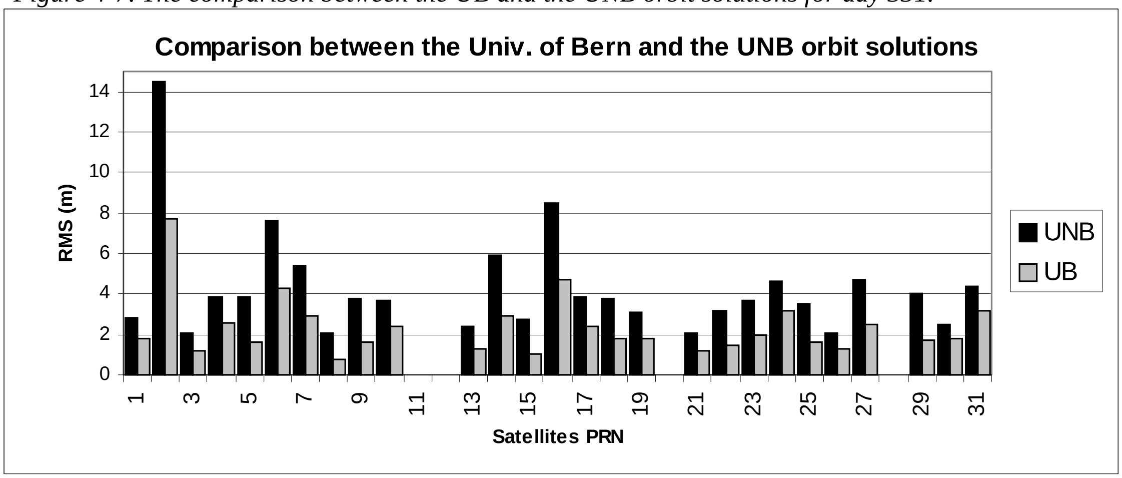
The RMS goes now down from 15.71 to 2.20 meters instead of from 14.52 to 2.70 meters. Something else can be seen for satellite 25 (Figure 4-6). The large errors occur when the satellite was not in view from this particular station. However another big error is introduced by the WAAS-corrections between 45,000 and 50,000 seconds. All this unfortunately still increases the RMS from 3.64 to 7.27 meters (this used to be from 3.48 to 5.44 meters). The error plots for the rest of the satellites for station ‘tmgo’ can be found in Appendix E. It is interesting to see that the errors in the WAAS-corrected orbits are less smooth than the errors in the broadcast orbit. This can be a problem when the receiver speed needs to be measured. The fact that some orbits are made better by the WAAS-corrections and others not is troubling because this system should increase the accuracy of GPS and not decrease it.

There is however yet another problem with the WAAS-corrections and the way that the broadcast ephemeris is applied in the traditional way (as described in section 2.1.4). Because a new ephemeris set is received with a period of at least every two hours at the same time by the user as by the WAAS Reference Stations, and because the WAAS-corrections are always transmitted with a delay there is a time gap in the WAAS-data. This means that the RMS at least every two hours jumps back from the WAAS-level (for day 331 was this 3.23 meters) to the broadcast orbit level (4.88 meters, see section 4.1). Because the time that a new ephemeris set is provided can not be predicted, this also decreases the accuracy level of system. Because the broadcast ephemeris is usually valid for a longer interval than that it is actually used for, switching to a new ephemeris set only when the WAAS-corrections do that too can solve this problem. This requires the receiver to store a newly-received ephemeris set for some time in its memory while still using the old set.

4.3 Comparison with the Bern orbit solution

At the University of Bern (UB) researchers compare the broadcast orbit to the rapid orbit after applying a seven-parameter similarity transformation. Figure 4-7 shows the RMS difference between the UB transformed broadcast orbit and the rapid orbit and the UNB results. There is a significant correlation between the two sets of orbit results. As one RMS increases, the other does too. This suggests that the method that is used for constructing the broadcast orbit (as described in this report) is a valid one.

Figure 4-7. The comparison between the UB and the UNB orbit solutions for day 331.



5 Conclusions and recommendations

5.1 Summary

The GPS signal contains information about the position of the GPS satellites. This information is provided in quasi-Keplerian elements and is called the broadcast ephemeris. The broadcast ephemerides for all the satellites for the whole day are combined in a file called the 'autofile'. To reconstruct the orbits for the satellites, the Keplerian broadcast elements have to be converted to Cartesian coordinates. To do this the right ephemeris set has to be taken. This is always the latest one that is received, unless the Issue of Data ephemeris (IODE) of that set is smaller than the previous set. Always the ephemeris set with the highest IODE has to be used. An ephemeris set can be used until another ephemeris set is received with a higher IODE or when the time is between two hours before or after the Time of Clock (TOC). This method was validated against the orbit solutions of the University of Bern.

If we compare satellite position coordinates with the a precise orbit (the final and rapid orbits are provided by the International GPS Service and computed at the University of Bern), we get an estimation of the error in the broadcast orbit. These errors are for some satellites worse than for others. This can, amongst other things, be caused by problems with the control of the spacecraft itself. This is the case with satellite PRN 23 whose solar panels have to be controlled manually. The orbit of satellite PRN 6 is also much worse than the orbits of the other satellites. The reason for this is unknown.

The error in the broadcast orbit can be reduced (in theory at least) by applying WAAS-correction data. The Wide Area Augmentation System is supposed to increase the GPS accuracy, availability and integrity. Typically WAAS-orbit-corrections are provided every six minutes when a GPS satellite is in view from the service area (U.S.A. and parts of Mexico and Canada). Some initial testing has shown that the WAAS-corrections can bring the root-mean-square for all the satellites for a whole day down from 4.73 with 1.50 to 3.23 meters if only the periods that the satellites are actually in view from the service area are taken into account. The amount that the error in the broadcast orbit is corrected varies from satellite to satellite. There are even some satellites that appear to have a larger error after WAAS-correction. The reason for this is unknown. Furthermore, the errors in the WAAS-corrected orbit are less smooth than the errors in the broadcast orbit. This can give problems when the receiver's velocity is measured.

The time necessary for the computation and transmission of the WAAS-corrections generates a delay that makes it necessary to apply the ephemeris sets in a slightly different way. To prevent periods where no WAAS-data is available, switching to a new ephemeris set should only happen when the WAAS-corrections also switch to that new ephemeris set (switch Issue of Data). This requires a small change in GPS receivers, namely an ephemeris set has to be stored in memory for a certain time even after a new one is received.

5.2 Suggestions for future work

The following list gives some suggestions for further work on the subjects that are discussed in this report:

- Apply Message Type 24.
- Make script compatible with year transitions.
- Investigate why some WAAS-corrected orbits are worse than the broadcast orbits.
- Make it possible that the script can run for an arbitrary day and not only for the present day.
- Give more information on the Internet page.
- Make the Internet page easier to use.
- Find out why satellite PRN 6 has a bad orbit.
- Investigate what kind of WAAS-corrections are provided when the satellite is not in view from the service area.
- Investigate how the WAAS-orbit corrections are predicted.

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