Broadcast Ionospheric Model Accuracy and the Effect of Neglecting Ionospheric Effects on C/A Code Measurements on a 500 km Baseline

By David MacDonald
Waypoint Consulting
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Intro

The ionosphere can be defined as the area approximately 90 to 1000 kilometers above the Earth's surface. The ionosphere contains free electrons, which have the effect of slowing down GPS code measurements relative to the speed that they would travel in free space. The ionospheric delay must be either measured (possible with dual frequency data) or estimated using one (of several) models (e.g. broadcast iono model).

This report is divided in two parts. The first part attempts to quantify the accuracy of the predicted ionospheric model, which is available on the GPS navigation message. There are more accurate models available (i.e. from the IGS), however they are not considered here. The second part gauges the error introduced on C/A measurements if ionospheric effects are neglected on a 500 km baseline.

It is widely known that ionospheric effects are strong at auroral (65-75^{o} geomagnetic latitude) regions. For this reason two stations were chosen in Alaska for this test (at near auroral latitudes). Both test were performed on a day for which the ionosphere was relatively calm (March 27, 2002), and on a day that an ionospheric storm was observed (April 19, 2002).

Section 1 – Accuracy of the Broadcast Ionospheric Model

Procedure

As the effect of the ionosphere is frequency dependent, an ionospheric correction can be calculated given simultaneous measurements of L1 and L2. This calculated correction is then used as the benchmark when evaluating the accuracy of the broadcast model. Naturally, the accuracy of this calculated ionospheric correction must first be gauged.

To test the calculated ionospheric correction, data was taken from the IGS stations CARR and CARH, which are only about 3 m apart. Ionospheric corrections were independently calculated on an epoch-by-epoch basis for two satellites at both locations. As the ionospheric error at these two stations should be theoretically identical for a given satellite, the corrections were differenced and plotted. The level at which these plots disagreed was taken as the noise level of this experiment.

Next, the broadcast ionospheric correction and the measured ionospheric correction are compared for four satellites on two different days. The Alaskan IGS stations CLGO and KEN1 are used in this test.

Test 1 - Accuracy of the Computed Ionospheric Correction

The ionospheric delay is calculated three ways. Firstly, the delay can be measured from the two code measurements (C/A or P1 and P2) however this measurement is subject to a large amount of noise (approximately ±1 m) as the code measurements themselves are subject to this level of noise. The noise level on the code measurements will vary depending on the elevation mask as it becomes more pronounced on low elevation satellites. Signals from low elevation satellites travel comparatively longer through the atmosphere, resulting in weak P1 and P2 signals (due to the codeless or semi-codeless techniques required to recover the P-code due to anti-spoofing). A result of this is larger code correlation errors, which results in increased pseudorange error for low elevation satellites.

Secondly, these code-derived ionospheric corrections can be low-pass filtered to produce a correction that is less noisy (approximately ± 0.5 m). Lastly, phase measurements on both frequencies can be used to produce a smooth, precise ionospheric correction.

Despite the high precision of the carrier-derived ionospheric correction, there is a difficulty inherent in using GPS phase measurements. This is because an integer ambiguity must be resolved. These ambiguities are resolved to an accuracy of 20-30 cm, as shown below. Accurately resolving the integer ambiguities depends on maintaining continuous lock (of L1 and L2) on a satellite for extended periods of time.

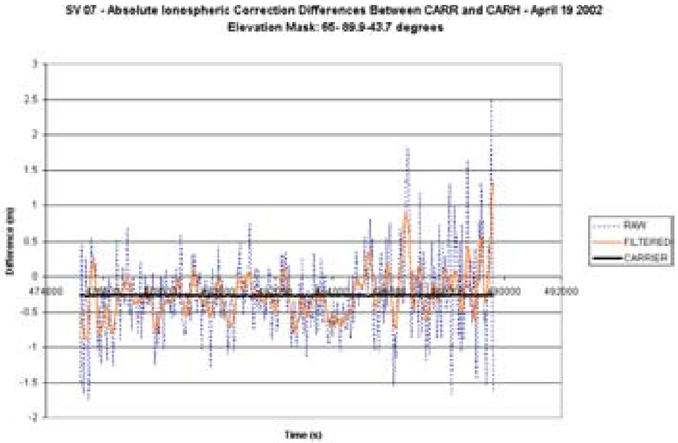

Figure 1: Ionospheric correction differences for SV07 computed at CARR and CARH

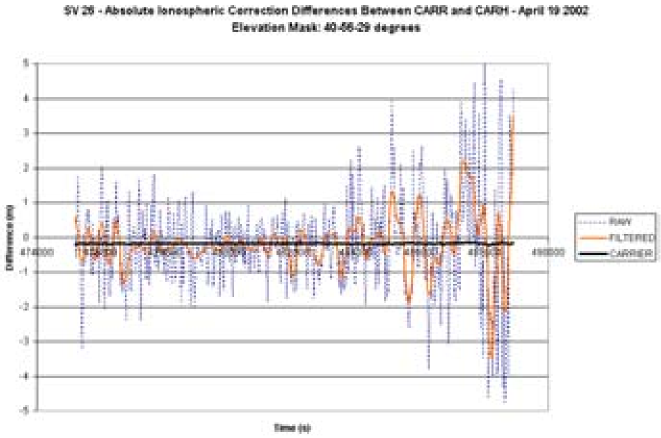

Figure 2: Ionospheric correction differences for SV26 computed at CARR and CARH

Figures 1 and 2 show the 20-30 cm accuracy of the carrier-derived ionospheric correction, and the noise level of the code and filtered ionospheric corrections. The titles also contain the average elevation mask of the satellite at the beginning, middle and end of the data.

Test 2 - Accuracy of the Broadcast Ionospheric Model

As the accuracy of the carrier-phase computed ionospheric correction was shown to be about 20-30 cm, comparisons to the broadcast ionospheric model can be made to this level of confidence. Firstly, two sample plots are presented for each day showing the two ionospheric corrections plotted on the same graph.

Figure 3: Broadcast and Computed Ionospheric Corrections – SV08 – March 27 2002

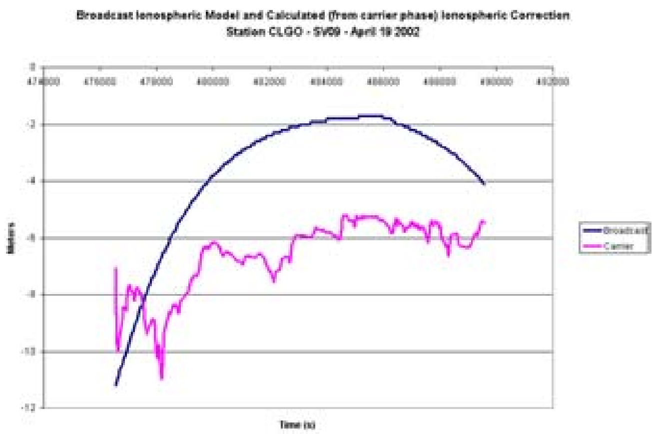

Figure 4: Broadcast and Computed Ionospheric Corrections – SV09 – April 19 2002

The ionosphere can induce rapid random fluctuations of the phase and field strength of a GPS signal, which can induce a loss of lock. These fluctuations are commonly referred to as ionospheric scintillations. L2 is particularly susceptible to experiencing losses of lock, as all civilian GPS receivers capable of tracking L2 must employ either codeless or semi-codeless techniques to recover the encrypted signal. These methods of recovering the P-code experience considerable losses in signal strength with respect to full code correlation (although semi-codeless techniques are superior to codeless techniques). Numerous ionospheric scintillation effects are symptomatic of ionospheric storms.

L2 cycle slips are likely the cause of the increased level of noise on the carrier derived ionospheric correction in figure 4 as opposed to figure 3. This noise could be removed given a more sophisticated ambiguity determination algorithm. Figures 5 to 20 show the difference between the broadcast ionospheric model and the computed ionospheric corrections. Four satellites are presented for each station on both days. These four satellites were chosen because they were observed for the longest periods of time.

Broadcast Ionospheric Model Errors - Station CLGO – March 27 2002

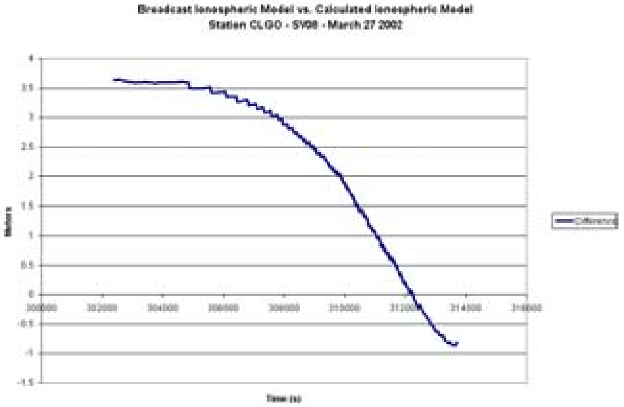

Figure 5: SV08 Broadcast – Computed Ionospheric Correction

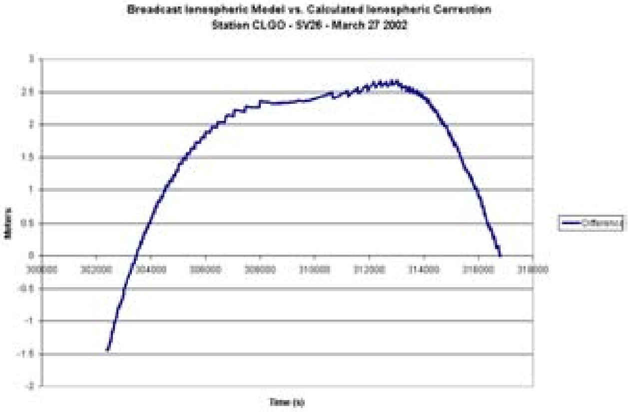

Figure 6: SV26 Broadcast – Computed Ionospheric Correction

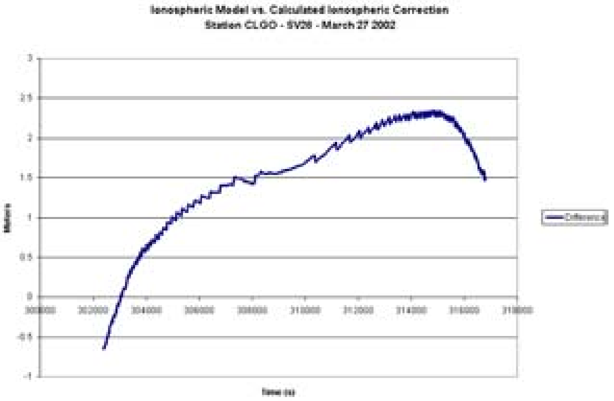

Figure 7: SV28 Broadcast – Computed Ionospheric Correction

Figure 8: SV31 Broadcast – Computed Ionospheric Correction

Broadcast Ionospheric Model Errors - Station KEN1 – March 27 2002

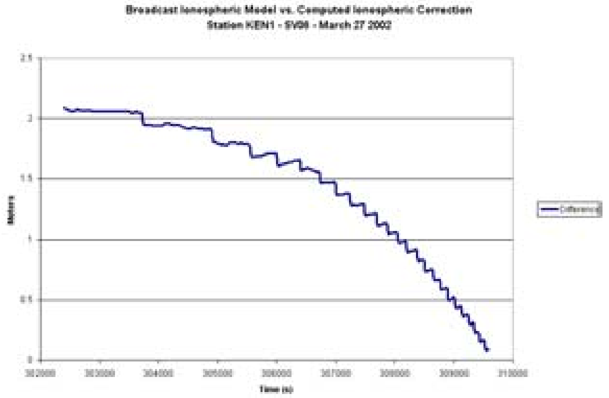

Figure 9: SV08 Broadcast – Computed Ionospheric Correction

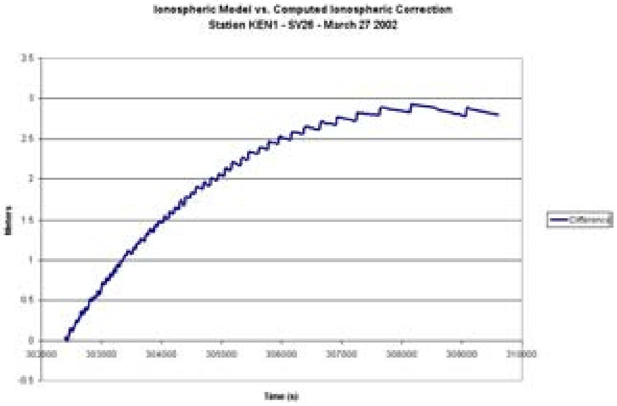

Figure 10: SV26 Broadcast – Computed Ionospheric Correction

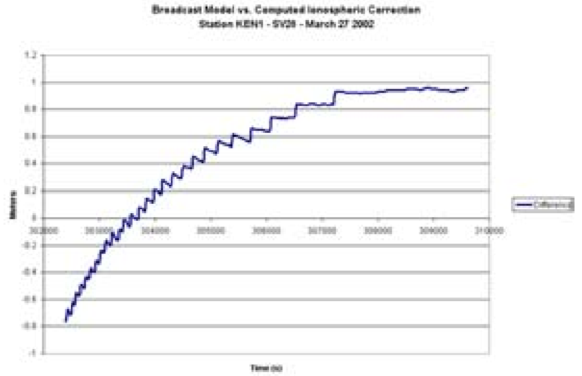

Figure 11: SV28 Broadcast – Computed Ionospheric Correction

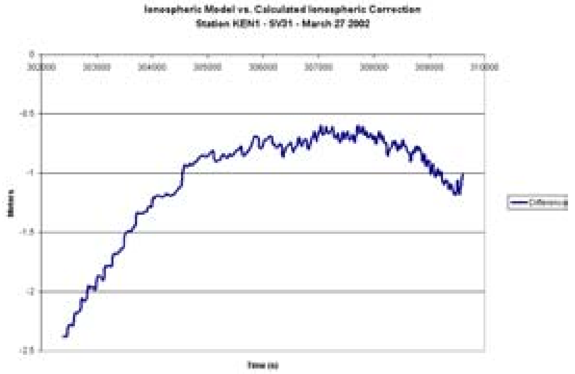

Figure 12: SV31 Broadcast – Computed Ionospheric Correction

Broadcast Ionospheric Model Errors - Station CLGO – April 19 2002

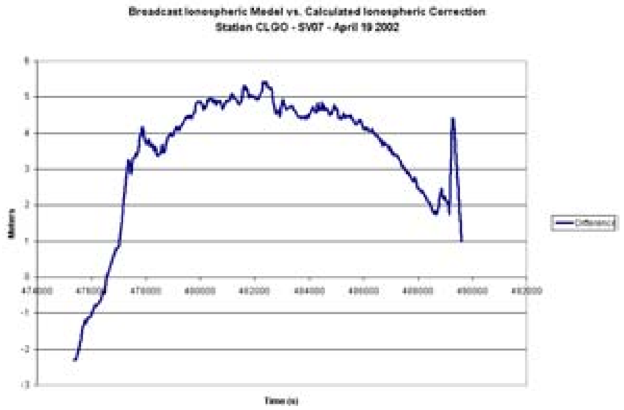

Figure 13: SV07 Broadcast – Computed Ionospheric Correction

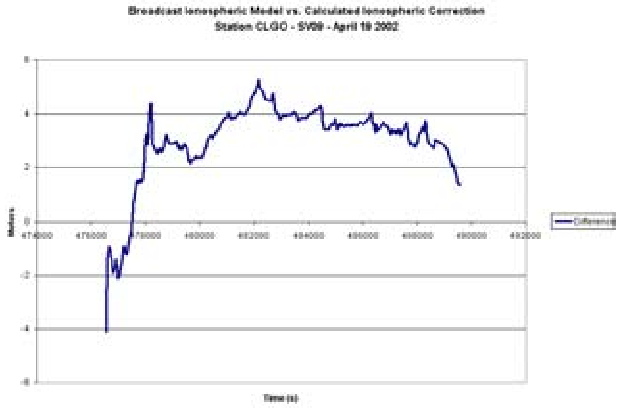

Figure 14: SV09 Broadcast – Computed Ionospheric Correction

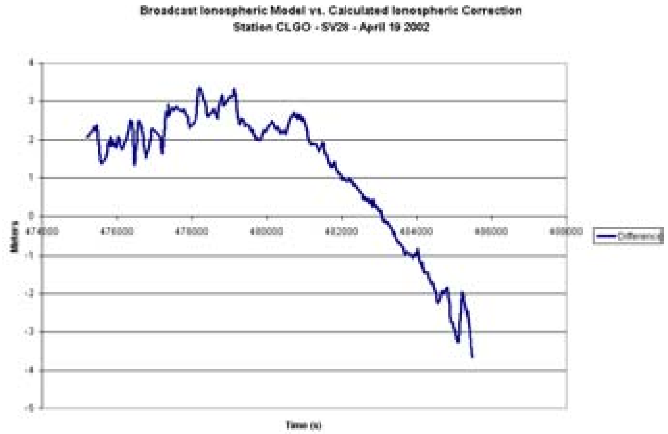

Figure 15: SV28 Broadcast – Computed Ionospheric Correction

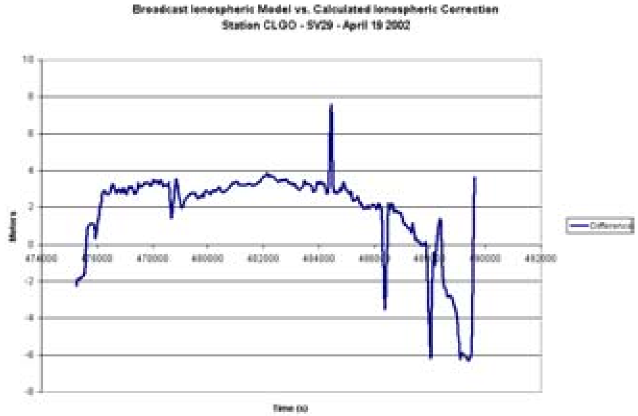

Figure 16: SV29 Broadcast – Computed Ionospheric Correction

Broadcast Ionospheric Model Errors - Station KEN1 – April 19 2002

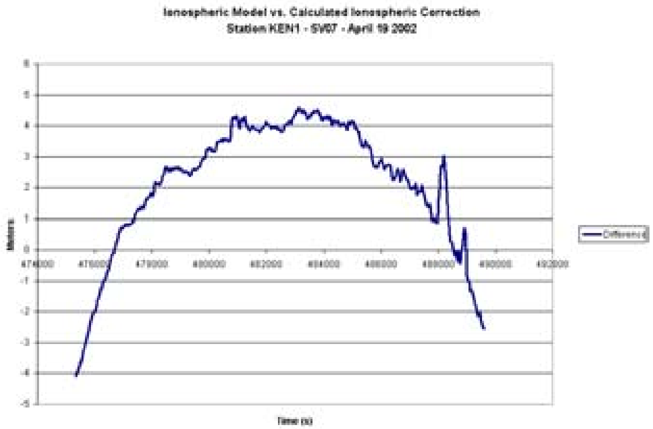

Figure 17: SV07 Broadcast – Computed Ionospheric Correction

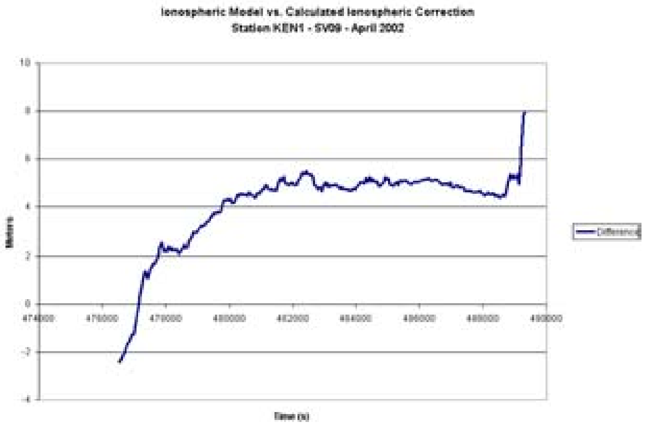

Figure 18: SV09 Broadcast – Computed Ionospheric Correction

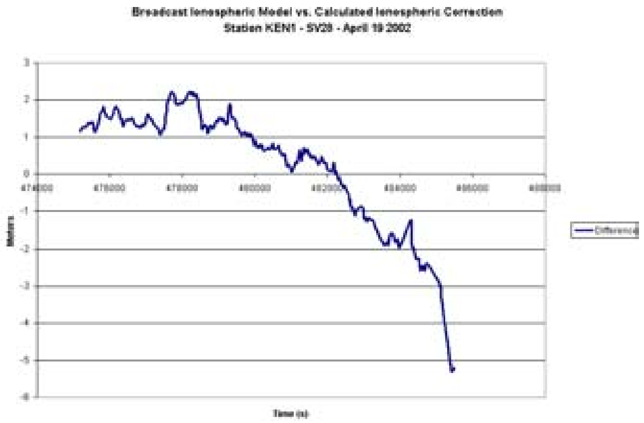

Figure 19: SV28 Broadcast – Computed Ionospheric Correction

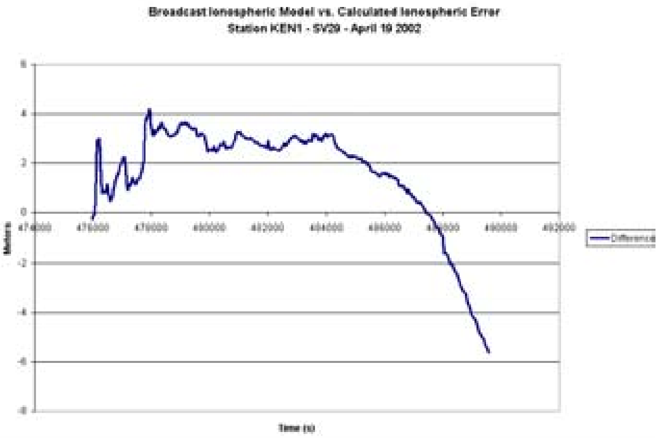

Figure 20: SV29 Broadcast – Computed Ionospheric Correction

Results

The broadcast ionospheric model is simply a smooth correction that is transmitted on the navigation message. One set of parameters is given for the entire earth. The shape of this function resembles the actual observed ionospheric correction on days for which the ionosphere is calm (see figure 3). However during an ionospheric storm, L2 tracking problems cause many filter resets in the ambiguity determination algorithms. As a result of the numerous filter resets, the computed ionospheric correction is likely only good to about 1-2 m.

In order to quantify the accuracy of the ionospheric model, a summary of the RMS errors in the broadcast ionospheric model (assuming the carrier-phase derived ionospheric correction to be the truth value) is presented below:

RMS Errors (m) - March 27 2002		
SV	Station CLGO	Station KEN1
31	2.83	1.15
28	1.67	0.7
26	1.98	2.29
8	2.68	1.59

RMS Errors (m) - April 19 2002		
SV	Station CLGO	Station KEN1
9	3.4	4.46
29	2.97	2.65
28	2.06	1.47
7	3.93	3.01

The average RMS error on March 27 and on April 19 was 1.86 m and 2.99 m respectively. It should be noted that the increased error on April 19 2002 could be simply due to the decreased accuracy of the computed correction caused by many filter resets. Many days of testing, over a much larger selection of satellites should be done to verify these results.

Section 2 – Effects of Neglecting the Ionosphere on C/A Code Measurements on a 500 km Baseline

Procedure

The electron density in the ionosphere varies with space (causing the ionospheric delay to decorelate with distance) and time (due largely to solar activity). Therefore as GPS signals from each satellite travel through different parts of the ionosphere, the ionospheric delay will be different for each satellite, and will vary with time (largely due to the speed of the satellite).

To examine the effect of the ionosphere on C/A code measurements, two tests were performed. The first test examines a day for which there was no unusual ionospheric activity (March 27, 2002) and the second test examines a day for which a severe ionospheric storm was reported (April 19, 2002).

Both tests use data from the IGS stations CLGO and KEN1. These stations are both above 60 degrees latitude, which is a near-auroral region. CLGO and KEN1 are approximately 500 km apart. In both tests, the absolute ionospheric correction (as derived from dual frequency measurements) was calculated for a 4-hour period at both CLGO and KEN1. These absolute ionospheric corrections where then differenced and graphed to show the difference in the calculated ionospheric correction. These values represent the error introduced on the C/A code measurements by the ionosphere if single frequency processing is used.

For each test the differences in three ionospheric corrections are plotted:

- Raw ionospheric correction (derived from code measurements and shown by a broken blue line)
- Filtered corrections (resulting from applying a low pass filter to the raw corrections and shown in orange)
- Carrier-Derived Correction (calculated from phase measurements and shown in black)

The raw ionospheric measurement is subject to a large amount of noise (approximately ±1 m, but varies depending on the elevation mask) as the code measurements themselves are subject to this level of noise. The low-pass filtered corrections reduce the amount of noise by roughly half. The low pass filter uses a very short window size, which is not ideal for this experiment. The short window size is ideal for kinematic applications. The low-pass filtered results could therefore be improved if a larger window size was used.

As in the first section of this report, the carrier-derived ionospheric correction is accurate to about 20-30 cm. Therefore in the following analysis, the carrier phase solution is of predominant interest.

Test 1 - Ionosphere-Induced C/A code Errors - 500 km Baseline - March 27 2002

Presented below is the difference in the absolute ionospheric corrections between the stations CLGO and KEN1. As CLGO and KEN1 are approximately 500 km apart, these graphs show the error introduced by the ionosphere on C/A ranges at this distance if no ionospheric correction is applied. Four satellites are presented for this day, which saw no unusual ionospheric activity.

Larger errors are expected for lower elevation satellites due to the longer propagation time of these signals in the atmosphere. The average elevation mask of the satellite between the two stations is given at the beginning, middle and end of the data is shown at the title of each plot.

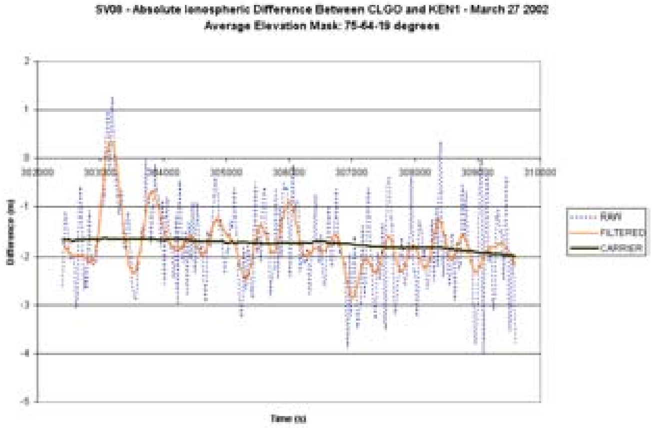

Figure 21: C/A Ionospheric Error Difference on SV 08 Mach 27/2002

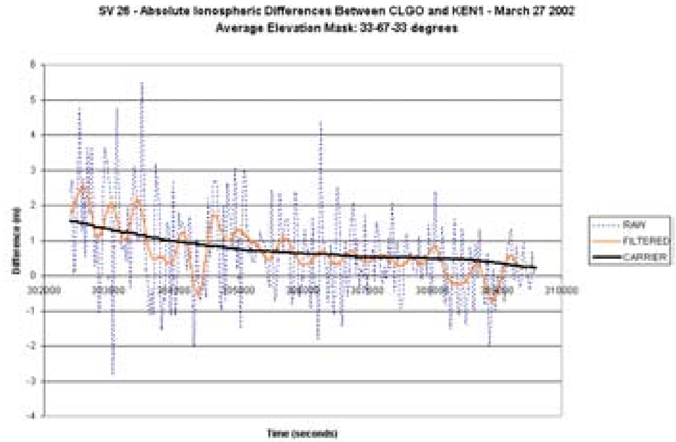

Figure 22: C/A Ionospheric Error Difference on SV 26 Mach 27/2002

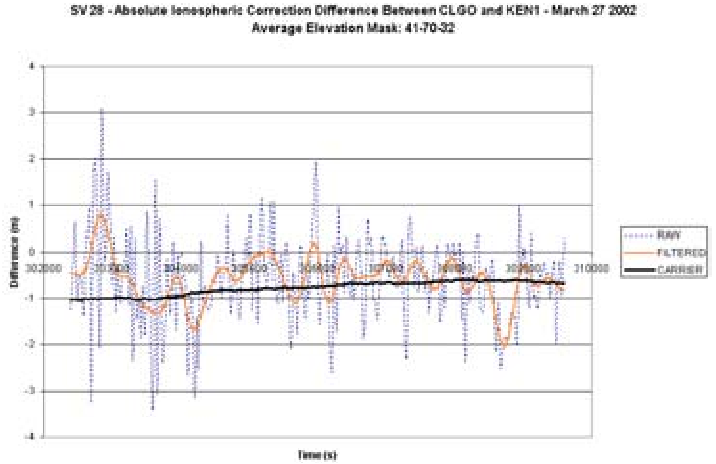

Figure 23: C/A Ionospheric Error Difference on SV 28 Mach 27/2002

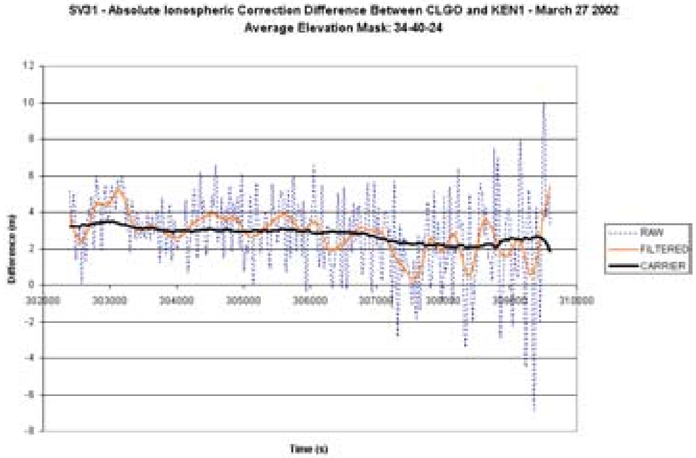

Figure 24: C/A Ionospheric Error Difference on SV 31 Mach 27/2002

Test 2 - Ionosphere-Induced C/A code Errors - 500 km Baseline - April 19 2002

This test is identical to the first, however a significant ionospheric storm was reported on this day. Due to effects such as ionospheric scintillation, which cause L2 cycle slips, the calculated ionospheric correction suffers. This results in an increased noise level in the carrier-derived ionospheric correction.

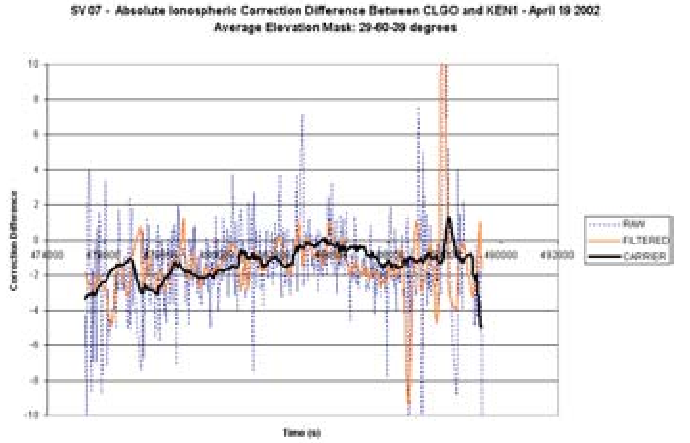

Figure 25: C/A Ionospheric Error Difference on SV 07 April 19/2002

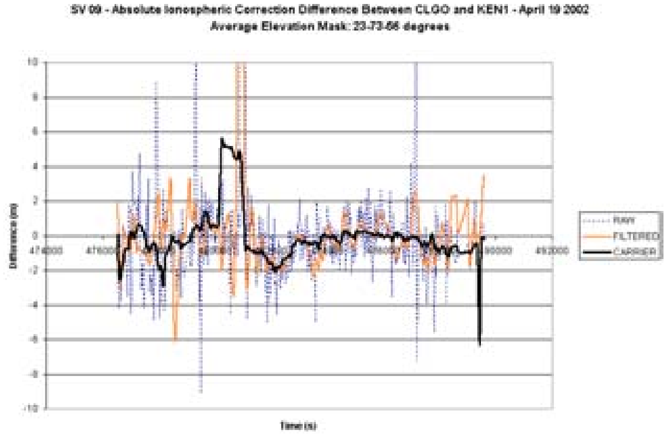

Figure 26: C/A Ionospheric Error Difference on SV 09 April 19/2002

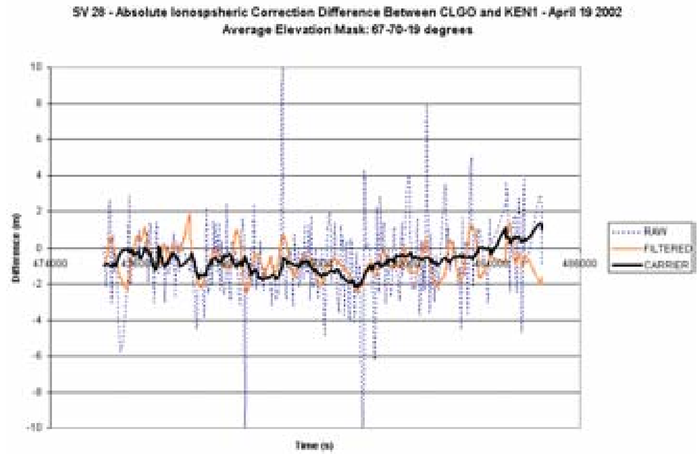

Figure 27: C/A Ionospheric Error Difference on SV 28 April 19/2002

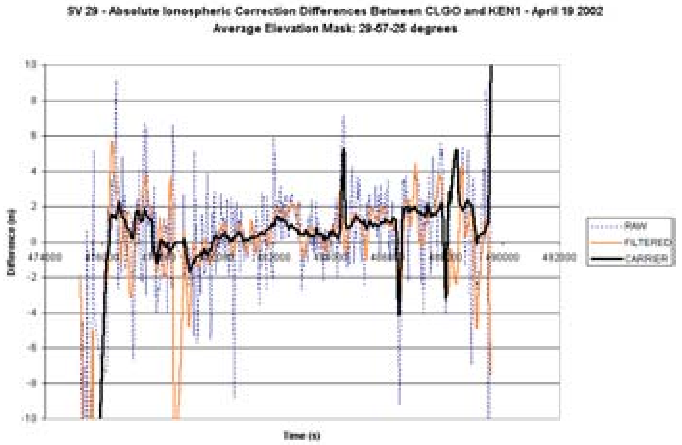

Figure 28: C/A Ionospheric Error Difference on SV 29 April 19/2002

Results

The RMS errors are presented as follows:

RMS Errors - March 27 2002	
SV	RMS (m)
8	1.75
26	0.81
28	0.79
31	2.8

RMS Errors - April 19 2002	
SV	RMS (m)
7	1.63
9	1.5
28	1
29	2.83

The average RMS error for March 27 and April 19 2002 was 1.54 m and 1.74 m respectively. The increased average error on April 19 can likely be attributed to L2 cycle slips, which induce an increased level of noise as compared to March 27. More tests should be conducted to verify the results presented here.