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THE CSMOOTH COMMAND - PRELIMINARY

INTRODUCTION

The purpose of this paper is to provide insight regarding the effects of the CSMOOTH command on the operation of a NovAtel GPS receiver. The CSMOOTH command is designed to allow the user to control the degree to which carrier phase smoothing is applied to the pseudorange measurements of the receiver.

Carrier phase smoothing is a process within a GPS receiver that combines the *absolute* but *noisy* pseudorange measurements with the *accurate* but *ambiguous* carrier phase measurements to obtain a good solution without the noise inherent in pseudorange tracking. Basically, a phase smoothing filter will start with raw pseudorange measurements to establish absolute position. Progressively, more weight will be placed on the carrier phase information and less on the raw pseudorange data to provide a smoothed pseudorange output. The term 'smoothing' describes how the high frequency noise is eliminated from the pseudorange measurements (thereby smoothing out a plot of the range residuals).

It would appear to make sense, then, to apply as much carrier smoothing as possible in order to eliminate the inherent code noise (including multi-path). Unfortunately, increased carrier smoothing can have negative effects on the GPS receiver performance. Combining measurement data from two sources (pseudorange and carrier phase) affects the dynamic response of the receiver and can lead to significant errors in the presence of increased of ionospheric activity.

The CSMOOTH value is given in units of seconds/cycle (inverse of bandwidth) and has factory default setting of 20. The range of the value is 20 to 1000 inclusive. The remainder of this paper will illustrate the significant effects that changing the CSMOOTH value can have on several aspects of the GPS receiver performance. It is important to remember that the CSMOOTH command is intended for specific applications only and its use may not improve the general performance of the receiver.

GPS RECEIVER TRACKING

In order to understand the concepts that are described within the text of this paper, it may help to highlight basic GPS receiver principles. Tracking of the GPS code signal is accomplished using a feedback control system called a Delay Lock Loop (hereinafter called a DLL). Carrier phase smoothing of the code measurements (pseudoranges) is accomplished by introducing data from the carrier tracking loops into the code tracking system. The degree to which either the DLL or

the carrier phase information controls the code tracking system, and thus the amount of carrier smoothing applied to the pseudoranges, can be modified using the CSMOOTH command.
The CSMOOTH value is inversely proportional to the bandwidth of the DLL in the GPS receiver. Changing this value will affect several characteristics of how the code is tracked. There are advantages and disadvantages to high and low CSMOOTH values. Several considerations will be discussed here:

- The attenuation of low frequency noise (multi-path) in pseudorange measurements,
- The effect of time constants on the correlation of phase and code observations,
- The rate of "pulling-in" of the code tracking loop (step response),
- The effect of ionospheric divergence on carrier smoothed pseudorange (ramp response).

Once again, the purpose of carrier smoothing is to reduce high frequency noise inherent in the pseudorange measurements. Increasing the CSMOOTH value will effectively decrease the size of the DLL bandwidth and attenuate lower frequency noise such as multi-path. Although this is generally an advantage, it is necessary to understand the adverse effects of decreasing the DLL bandwidth on the code filter performance. The following sections provide some detailed information regarding each of the considerations listed above.

LOOP FILTER RESPONSE

The default CSMOOTH value for all NovAtel GPS receivers is 20. Figure 1 illustrates the response of the code loop filter to different frequencies. The critical points on the response graph consist of the 3dB and 10dB points of attenuation.

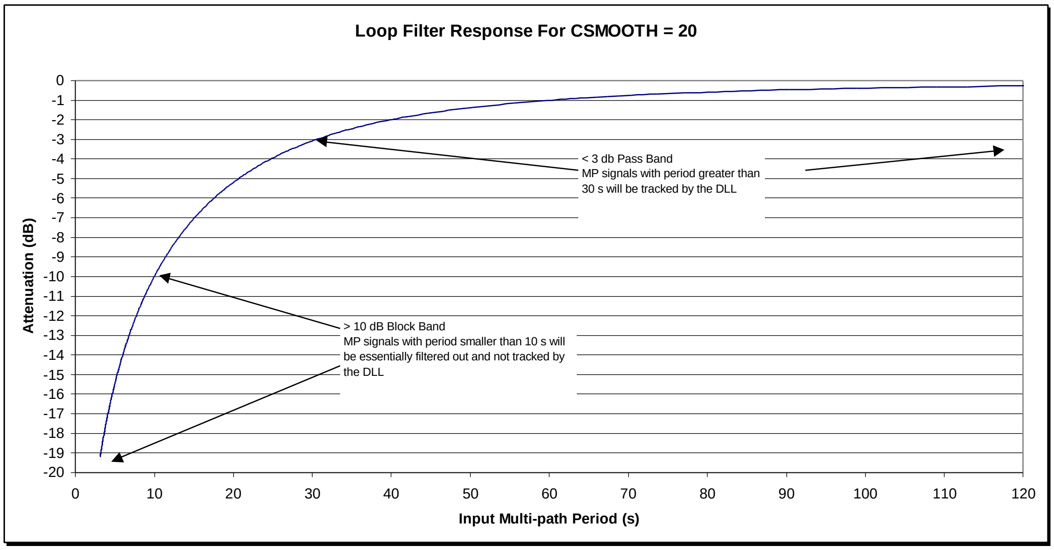

Figure 1

All signals with a period above the 3dB point will be tracked by the loop. Any signals with a period below the 10dB point are essentially eliminated from the loop. With a CSMOOTH setting of 20, only high frequency noise is filtered out. Assuming a typical period of 1000 seconds, multi-path signals will be tracked by the DLL and degrade the output pseudoranges.

As the CSMOOTH value is increased, more weight is placed on the phase loop information in the code tracking control system (which is immune to code multi-path). Figure 2 shows the loop filter response for four different CSMOOTH values. The narrow DLL bandwidth associated with the higher CSMOOTH values will effectively attenuate lower frequency noise.

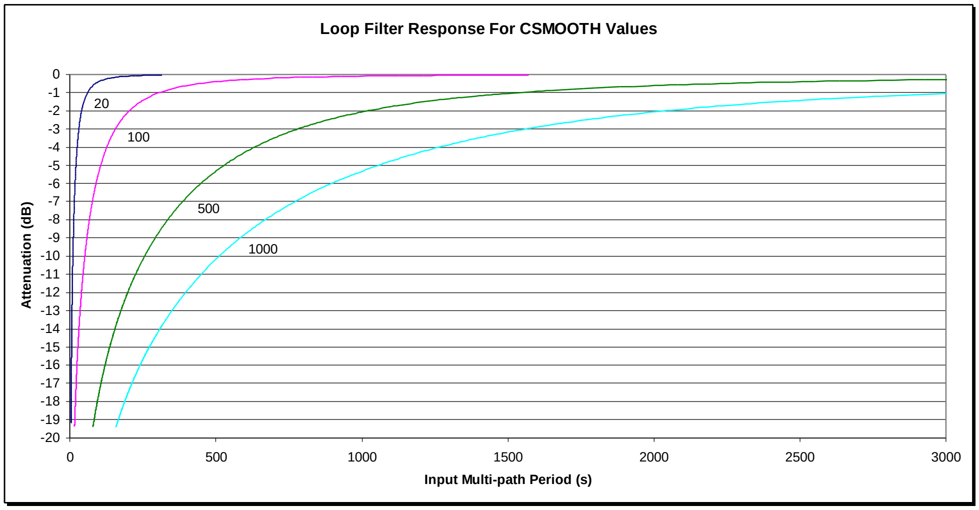

Figure 2

Figure 3 provides a simple illustration of the critical points in the DLL for different CSMOOTH values. It is clear that very high CSMOOTH values are necessary to effectively attenuate low frequency noise such as code multi-path. This is an advantage of increased carrier smoothing.

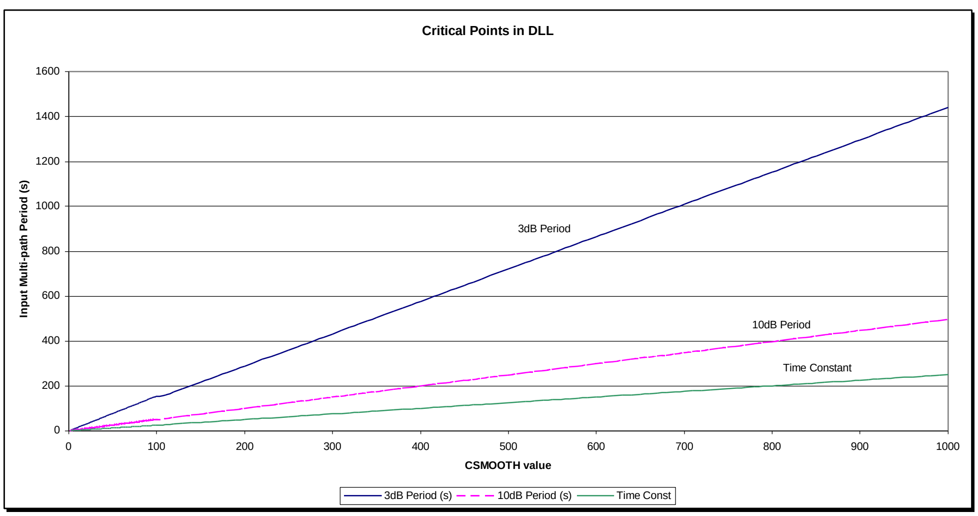

Figure 3

Figure 3 also indicates the time constant of the loop for different values of CSMOOTH. Although the pseudo-range measurements are independent of each other, there can be a lot of correlation between the phase measurements and the pseudo-ranges when the data from the two sources is combined in the carrier smoothing process. This dependence is an important consideration when the carrier data and pseudo-range information are to be used together in some application (in post-processing software, for example). The time constant of the loop and the sampling interval of the data dictate the degree of this correlation. In order to maintain independent phase and code measurements between epochs, the data interval should be no greater than about 3 time constants. Obviously, high CSMOOTH values, and therefore longer time constants, will decrease the maximum sampling rate that may be used to acquire independent data.

LOOP STEP RESPONSE

Since the CSMOOTH command essentially changes the bandwidth of the DLL, it will significantly impact the dynamic nature of the loop. One measure of these characteristics is the ability of the loop to respond to a step function in the signal. This type of response is important in the "pulling-in" of (fixing on) the GPS code signal. Figure 4 illustrates the step response of the DLL with the default CSMOOTH setting of 20. The shape of the curve describes the response of a first order filter. It is important to note how well the filter will track the step. The ERROR line represents the difference between the current measured pseudorange and the actual value.

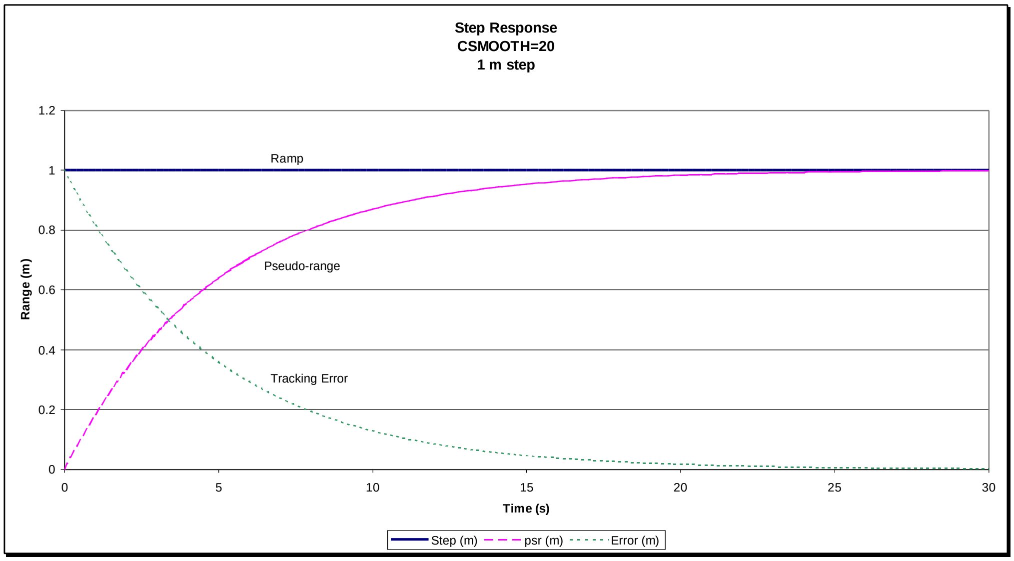

Figure 4

It is desirable for the DLL to be responsive to these step functions. Figure 5 plots the filter response of different CSMOOTH values for a 1-meter step. It is obvious that an increase in CSMOOTH value yields a dramatic decrease in response to the step function. This illustration is characteristic of a feedback loop when the bandwidth is reduced.

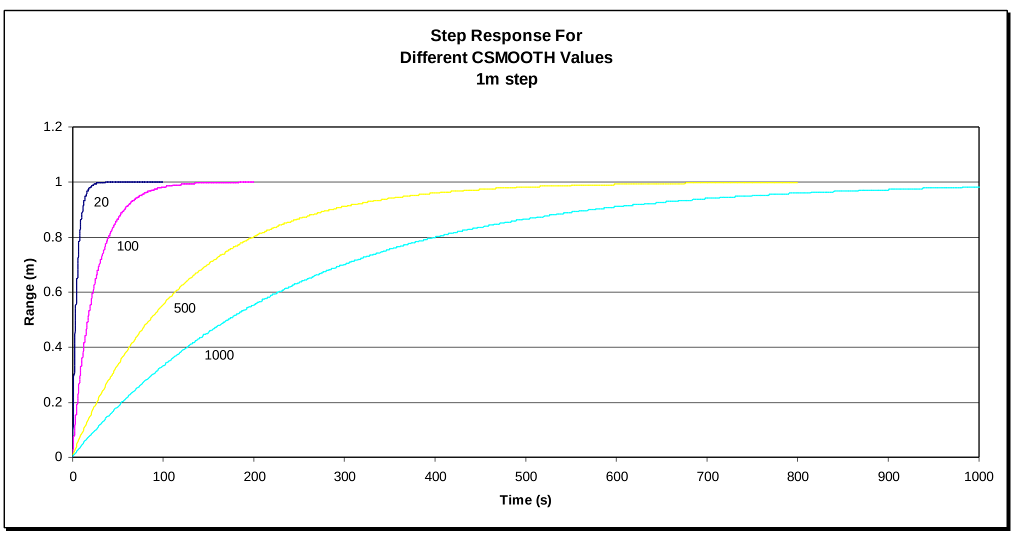

Figure 5

Large CSMOOTH values, although useful for filtering out low frequency noise, will yield a sluggish code filter and may degrade lock-on, tracking, and re-acquisition. The above figures illustrate the ability of the loop to respond to a constant step function. It is also necessary to analyze how changes in the CSMOOTH value will affect the ramp response of the loop. This is relevant in the context of the ionospheric interference encountered by GPS signals.

LOOP RAMP RESPONSE

When the GPS signal travels through the ionosphere, it is affected in two ways. The modulated part of the signal (the code) is delayed momentarily while the phase of the carrier wave is advanced. The code delay will distort the pseudorange measurements. As a result, the pseudorange measurements and carrier phase derived measurements will tend to diverge over time. Since carrier smoothed data is constructed based on both code and phase derived ranges, this divergence between the two will cause problems. By analyzing the ability of the feedback control system to track a ramp rather than a step, it is possible to characterize the response of the loop to this divergence. Once again, the response is highly affected by the bandwidth of the DLL and therefore the CSMOOTH value.

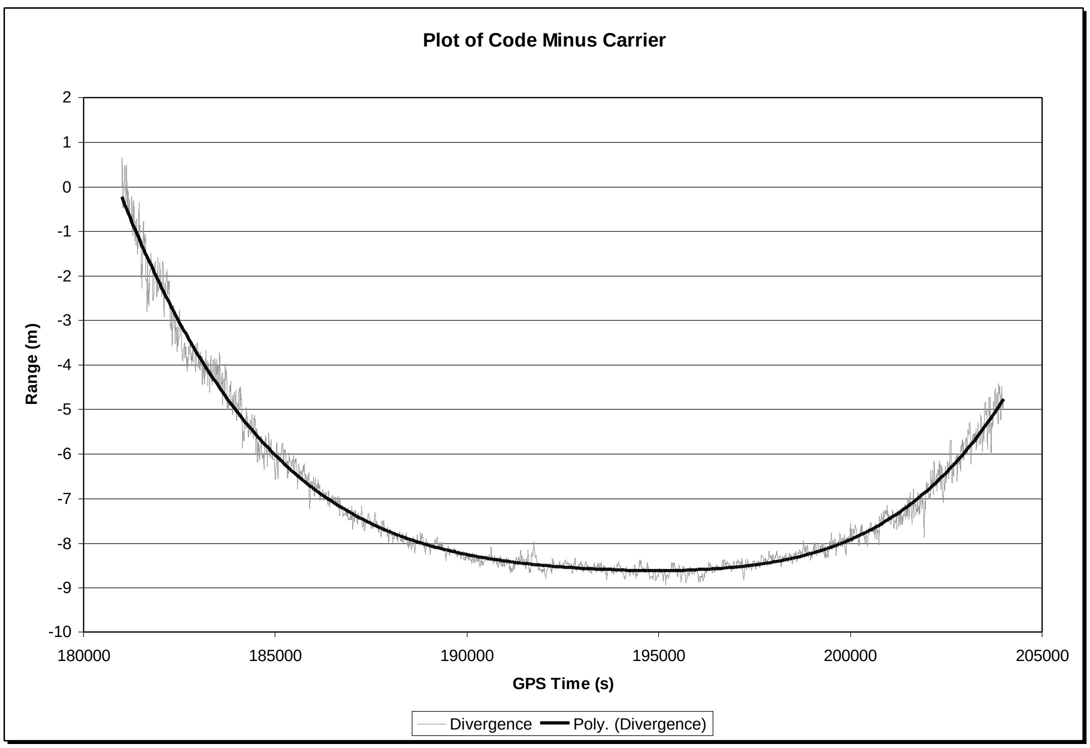

Figure 6

Figure 6 illustrates the nature of range divergence between code and carrier measurements as a satellite moves across the sky. The high frequency noise represents the code noise that is mitigated by the carrier smoothing technique. Superimposed on the actual graph is a best-fit polynomial that approximates the divergence. Tracking the divergence is most difficult when the slope of this graph is greatest (i.e. at the beginning and end of the plot). To investigate the worst case ramp response of the loop it is necessary to estimate the slope of the graph in these critical areas. Figures 7 and 8 demonstrate this procedure.

The beginning and end of the code-minus-carrier plot are estimated with a linear equation. The beginning of the plot represents the greatest rate of divergence (thus the worst case scenario) and will be examined in more detail.

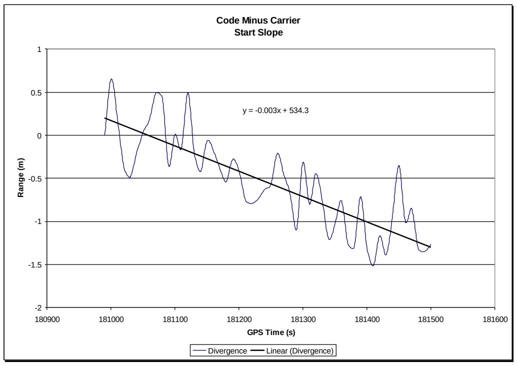

Figure 7

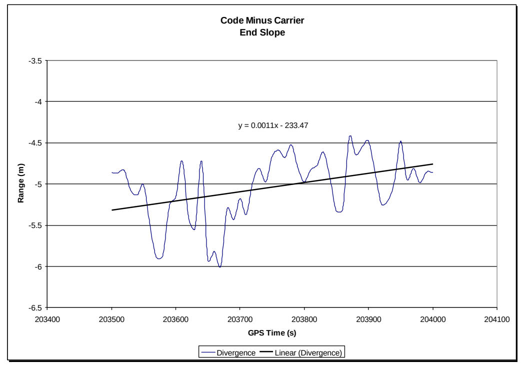

Figure 8

Figure 9 demonstrates the response of the code-tracking loop to the ramp shown above in figure 7 for the default CSMOOTH value of 20. It is important to note the offset between the measured range value and the ramp. The ERROR line on the graph displays this value and tends toward an error of 1.5 centimeters which, in this case, is well below typical receiver noise (which is shown by the high frequency oscillation in figure 6). As the slope of the ramp decreases, so does the tracking offset error.

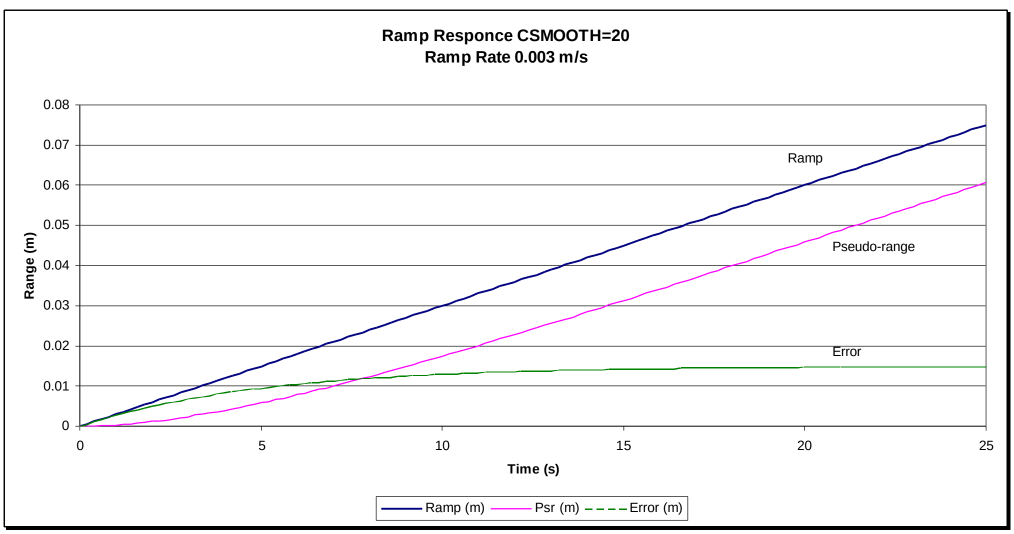

Figure 9

Increasing the value of the CSMOOTH will increase the tracking offset error. Figure 10 shows the ramp response for different values of CSMOOTH. The offset error quickly becomes significant as the CSMOOTH value is increased beyond 100. Once again, these plots are based on a relatively high rate of divergence to illustrate a worst case scenario. This magnitude of error can be encountered when tracking satellites that are low on the horizon or during periods of high ionospheric activity.

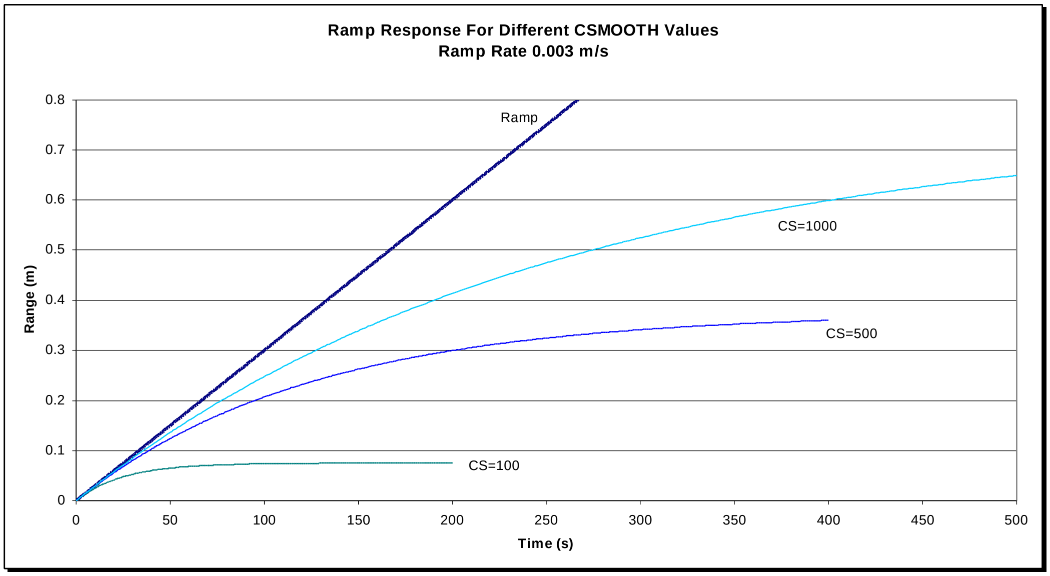

Figure 10

CONCLUSIONS

To summarize, the primary reason for applying carrier smoothing to the measured pseudoranges is to mitigate the high frequency noise inherent in all code measurements. It was illustrated above that adding more carrier smoothing by increasing the CSMOOTH value would filter out lower frequency noise, including some multi-path frequencies.

The adverse effects of higher CSMOOTH values on some performance aspects of the receiver were also demonstrated. Specifically, the time constant of the tracking loop is directly proportional to the CSMOOTH value and will affect the degree of dependence between the carrier phase and pseudo-range information. Phase and code Data collected at a sampling rate greater than about 3 time constants of the loop will be correlated (the greater the sampling rate, the greater the correlation). This correlation is not relevant if only positions are logged from the receiver, but is an important consideration if the data is combined in some other process such as post-mission carrier smoothing. It was shown that a narrow bandwidth in a feedback loop will impede the ability of the loop to track step functions. Steps in the pseudorange will be encountered during initial lock-on of the satellite and when working in an environment conducive to multi-path. A low CSMOOTH value will allow the receiver to effectively adapt to these situations.

Also, increased carrier smoothing may cause problems when satellite signals are strongly affected by the ionosphere. As seen in figure 6, the rate of divergence between the pseudoranges and phase-derived ranges is greatest when the satellite is low in the sky since the GPS signal must travel through a much "thicker" ionosphere. The tracking error of the receiver will be greatest at these times when a lot of carrier smoothing is implemented. In addition, changing periods of ionospheric activity (diurnal changes and the 11-year cycle) will influence the impact of large CSMOOTH values. It is important to realize that the advantages of carrier smoothing do not come without some trade-off in receiver performance. The factory default CSMOOTH value of 20 was selected as an optimal compromise of the considerations outlined in this paper. For the majority of applications, this default value should be appropriate. However, the flexibility exists to adjust the parameter for specific applications by users who are familiar with the consequences.