5.0 Navigation Performance

5.1 Error Analysis

If things worked all of the time and errors did not occur a lot of engineers would be out of work. The primary factors that determine positioning and velocity errors are errors in measuring the range from the satellite and the geometry of the satellites with respect to the receiver.

5.1.1 Ranging Errors

As shown in table 5-I the ranging errors of the GPS system are generally divided into 3 areas.

The first area is Space and Control. These are errors in the satellite atomic clock combined with the errors in the orbital parameters supplied by the control segment. Due to the fact that clock errors appear as orbital radius errors these effects are very hard to separate. The other entry in the table is the navigation message. The navigation message is a curve fit to the orbit. Because of the curve fit time span, the number of correction terms used and the data resolution its representation adds more error to the ephemeris message

The second area is environmental effects. These are errors produced by the space an atmospheric environment. The upper atmosphere is ionized and causes the radio signal to be delayed. Since this delay is frequency dependent the use of two frequencies can measure this delay. The other major effect is the delay caused by the lower part of the atmosphere or troposphere. To a large degree this effect is known and can be removed by the receiver software. The last effect is multi-path. The signal can be reflected off of objects in the vicinity of the antenna. These paths are of course longer than the direct path so the correlation function is distorted and the signal tracking is disturbed.

The third area is receiver effects. These are primarily caused by random noise in the rf signal chain and the receiver clock.

Table 5-I
Ranging Errors

Error Type	Error Source	Value
Space and Control	Clock & Ephemeris	1.5 m
	Navigation Message	0.2 m
Environment	Ionosphere	
	Troposphere	0.4 m
Receiver	Multipath	
	Thermal Noise	2.0 m

5.1.2 Range Rate Errors

As shown in table 5-II the range rate errors of the GPS system are also generally divided into 3 areas.

The first area is Space and Control. These are errors in the satellite atomic clock combined with the errors in the orbital parameters supplied by the control segment. Due to the fact that clock errors appear as orbital radius errors these effects are very hard to separate. The other entry in the table is the navigation message. The navigation message is a curve fit to the orbit. Because of the curve fit time span, the number of correction terms used and the data resolution its representation adds more error to the ephemeris message

The second area is environmental effects. These are errors produced by the environment. The upper atmosphere is ionized and causes the radio signal to be delayed. Since this delay is frequency dependent the use of two frequencies can measure this delay. For single frequency receivers there is information provided in the navigation message to reduce this error. The other major effect is the delay caused by the lower part of the atmosphere or troposphere. To a large degree this effect is known and can be removed by the receiver software. The last effect is multi-path. The signal can be reflected off of objects in the vicinity of the antenna. These paths are of course longer than the direct path so as shown in Figure 5-xx the correlation function is distorted and the signal tracking is disturbed.

The third area is receiver effects. These are primarily caused by random noise in the rf signal chain and the receiver clock.

Table 5-II
Range Rate Errors

Error Type	Error Source	Value
Space and Control	Clock & Ephemeris	
	Navigation Message	
Environment	Ionosphere	
	Troposphere	
Receiver	Multipath	
	Thermal Noise	

5.1.3 Effect of Geometry, Dilution of Precision

While Dilution of Precision is a useful indication of the effects of satellite-receiver geometry it is clear from data measurements that it is not a reliable indication of accuracy. DOP analysis assumes that the ranging measurement errors are not correlated when in fact they are highly correlated. The Ionosphere and Troposphere errors are correlated and a strong function of elevation. Analyzing data such as presented in section 5.3 computing the average pseudorange for horizontal accuracy and vertical accuracy the vertical pseudorange error is about 50% larger. This is strong evidence that dilution of precision is not a very good method of estimating error.

$$Cov(dx) = \left(H^T H\right)^{-1}$$

5.1.4 Covariance Analysis

When analyzed by using a weighting matrix with cross correlation taken into account.

$$Cov(dx) = \left(H^T W^{-1} H\right)^{-1}$$

$$\begin{bmatrix} \rho_{1,1} & \rho_{1,2} & \rho_{13} & \cdot & \rho_{1,x-1} & \rho_{1,x} \\ \rho_{1,1} & \rho_{2,2} & \rho_{1,1} & \cdot & \rho_{1,x-1} & \rho_{1,x} \\ \rho_{1,1} & \rho_{1,1} & \rho_{3,3} & \cdot & \rho_{1,x-1} & \rho_{1,x} \\ \cdot & \cdot & \cdot & \cdot & \rho_{1,x-1} & \rho_{1,x} \\ \rho_{1,1} & \rho_{1,1} & \rho_{1,1} & \rho_{1,1} & \rho_{x-1,x-1} & \rho_{1,x} \\ \rho_{1,1} & \rho_{1,1} & \rho_{1,1} & \rho_{1,1} & \rho_{1,1} & \rho_{x,x} \end{bmatrix}$$

5.2 Measured Performance

Figures 5-1 through 5-8 are data taken at 1 minute intervals over 52 hours. The results are consistant with a UERE of about 2 meters and a UERRE of about 0.01 m/sec.

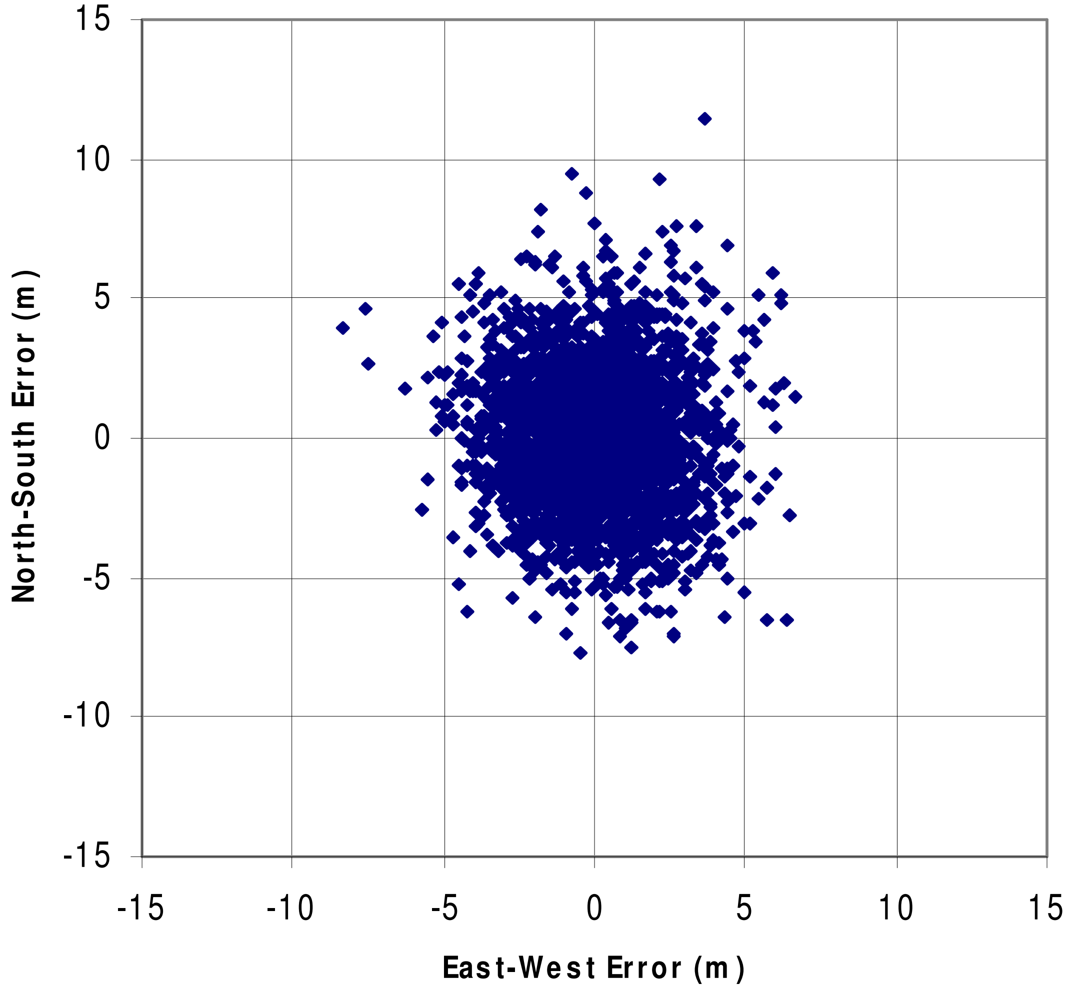

Figure 5-1
Horizontal Position Accuracy

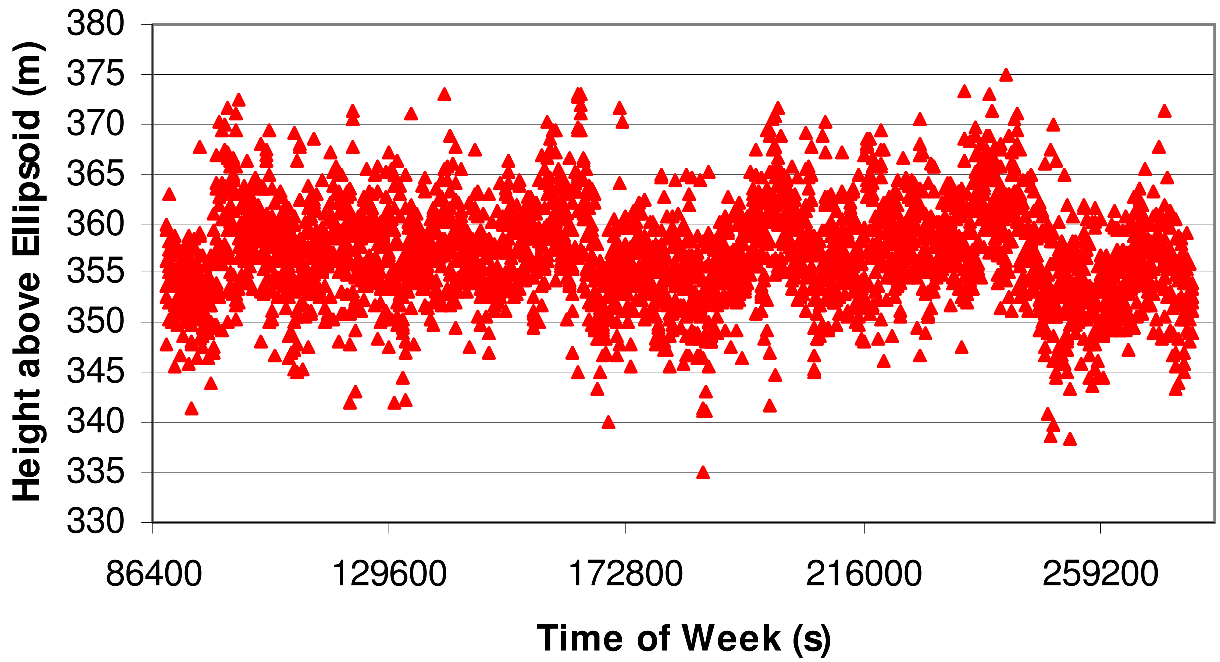

Figure 5-2
Vertical Accuracy vs Time

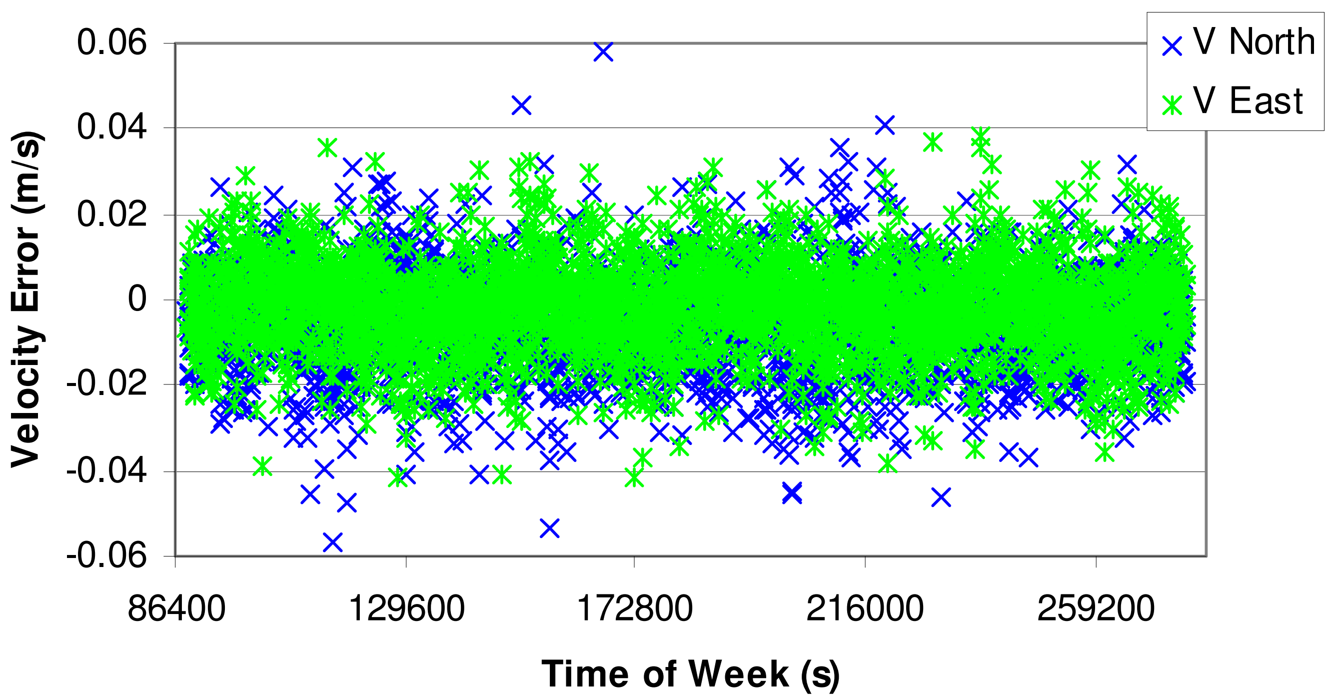

Figure 5-3
Horizontal Velocity Error

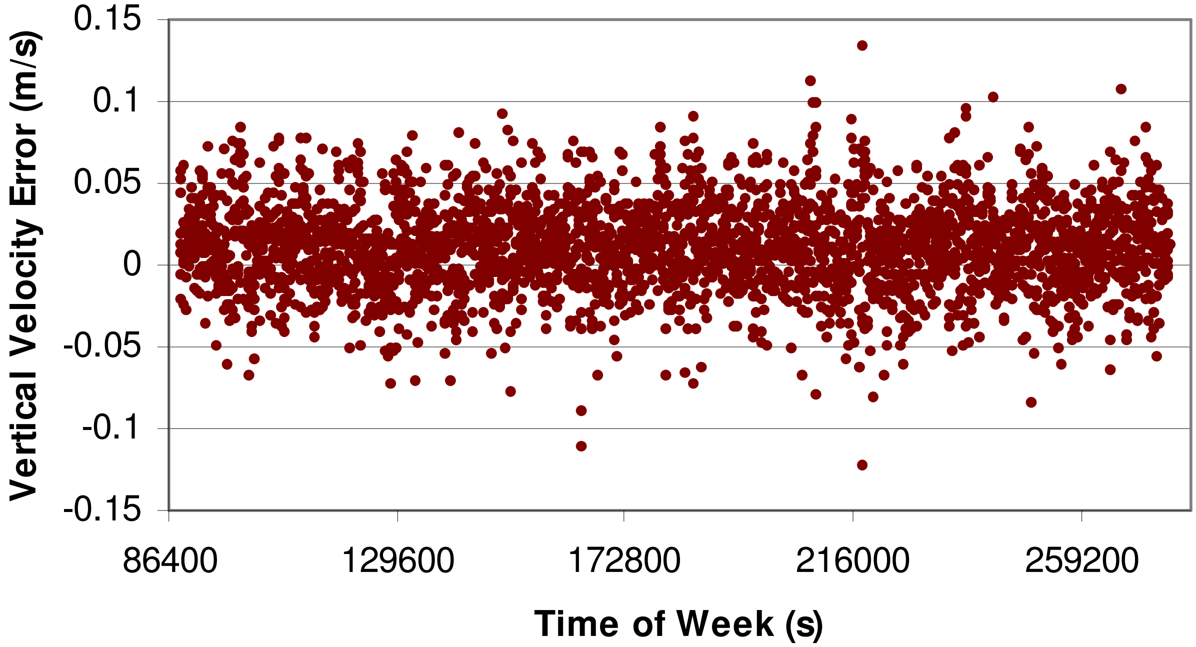

Figure 5-4
Vertical Velocity Error vs Time

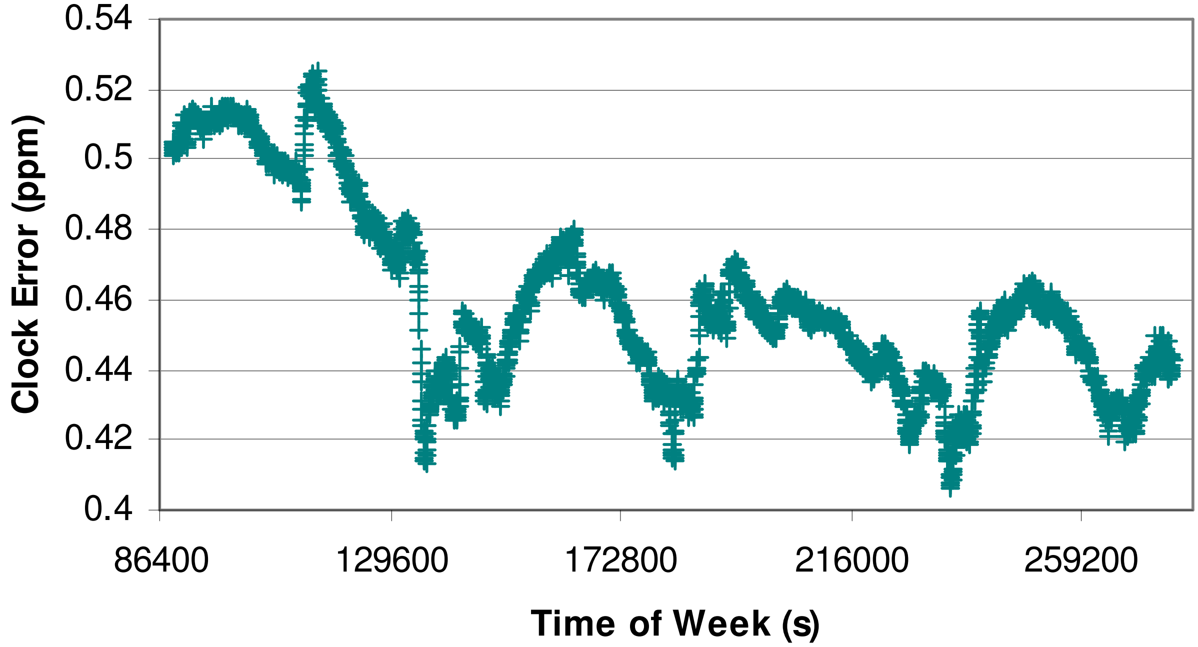

Figure 5-5
Clock Frequency Error vs Time

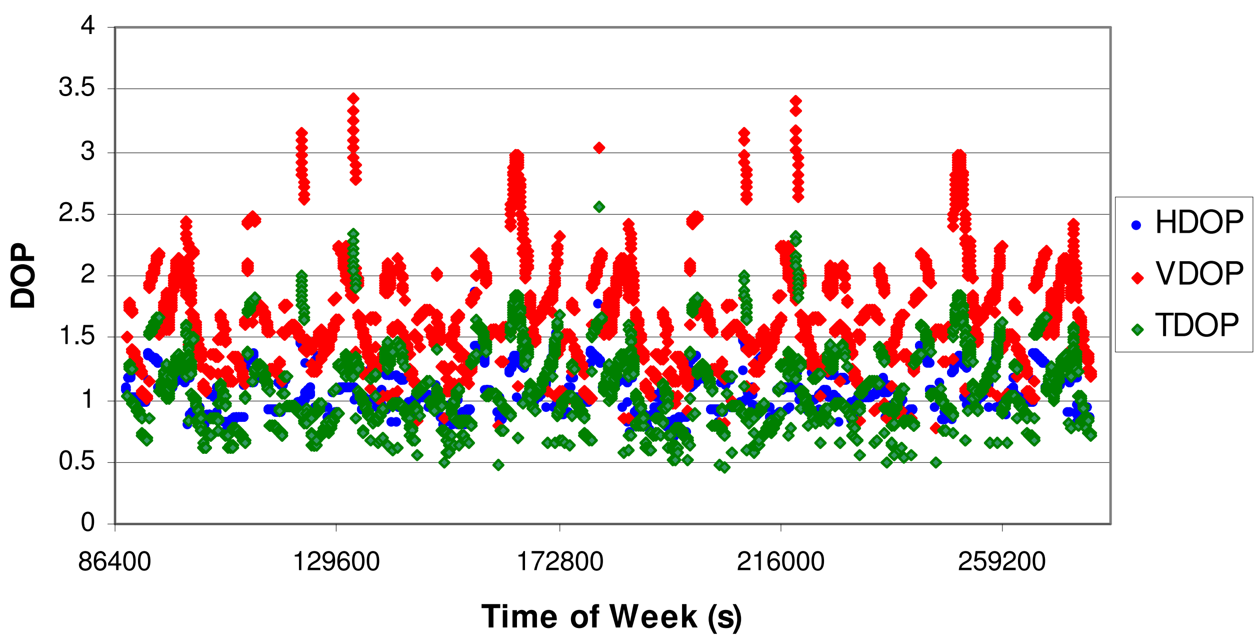

Figure 5-6

Dilution of Precision vs Time

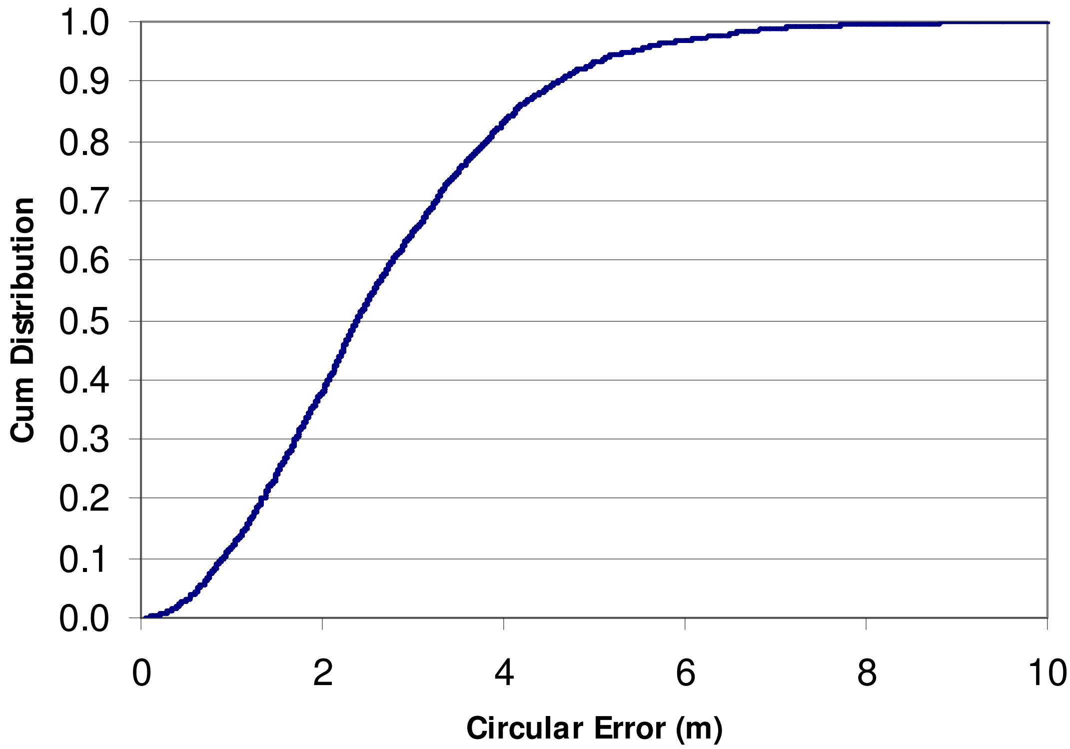

Figure 5-7
Circular error distribution

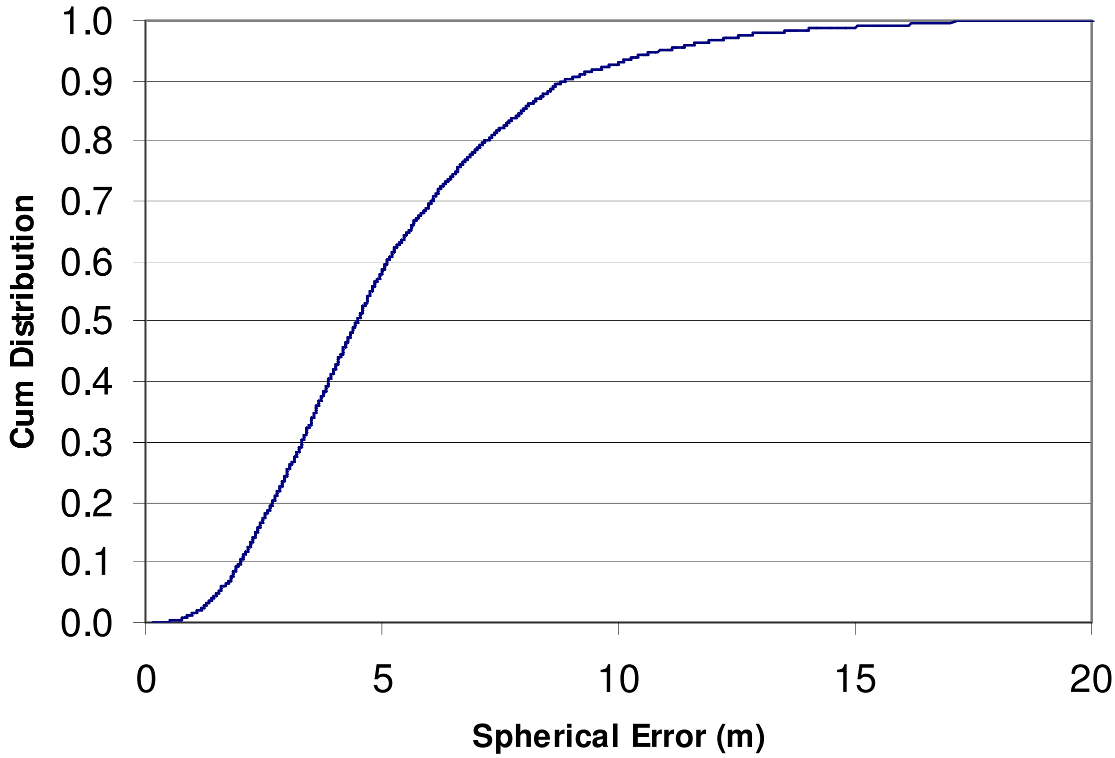

Figure 5-8
Spherical Error Distribution