Chapter 5
Conclusions

Optimal estimation methods have been applied in three areas. The first application is in the area of satellite navigation using magnetometer-based methods for autonomous orbit determination. The second application is in the area of vehicle attitude determination and develops a 3-axis measurement system that is based on data from a single GPS antenna mounted on a rotating turntable. The third application is in the area of GPS radio navigation signal tracking and involves the development of optimal semi-codeless dual-frequency GPS techniques for use in ionospheric scintillation monitoring. Estimation methods such as batch filtering, extended Kalman filtering (EKF), and smoothing are employed in these applications.

The satellite navigation application improves a magnetometer-based autonomous orbit determination batch filter and tests it with real flight data from three satellites. Its central idea is to use a filter that estimates corrections to the magnetic field model as well as the satellite's orbital trajectory states.

The test results for one of the satellites show a dramatic improvement in the accuracy of the estimated position when the batch filter includes field-model correction if the \textit{a priori} Earth magnetic field model is not accurate. The peak position estimation error is decreased from 59.50 km without field model corrections to only 2.19 km with 10th order/degree field model corrections. The improvements due to the estimation of field model corrections are less dramatic when a better \textit{a priori} Earth magnetic field model is used. The predicted accuracy from the consider-covariance analysis and orbit overlap tests is consistent with the actual maximum
position errors. The corrected magnetic field has also proven to be unique and realistic.

The application of estimation methods to vehicle attitude determination centers on the experimental evaluation of a new attitude sensor system that uses a single GPS antenna on a rotating turntable. A prototype of this new attitude sensor has been built. The experimental results confirm that the proposed new system can be used to measure 3-axis attitude to an accuracy of 1-2° or better if designed properly.

The effects of estimating common-mode error in addition to attitude also have been tested. Common-mode error estimation amplifies multipath errors. This amplification causes it to have unreasonably large errors compared to a filter that only estimates attitude. Therefore, the new turntable-based GPS attitude sensor should be designed to minimize common-mode errors instead of trying to estimate them. Common-mode error can be minimized by either rotating the turntable at a speed over 1000 rpm or by using a good receiver clock like an ovenized crystal oscillator when the turntable rotation speed is under 1000 rpm. The prototype that has been tested in this study has a poor receiver clock but can rotate at speeds over 1000 rpm. Therefore, it is able to minimize the common-mode error due to clock drift.

The estimation application related to GPS receiver development has been to design EKF/Smoother-based algorithms for optimal semi-codeless tracking of encrypted P(Y) code on weak dual-frequency GPS signals. This optimal algorithm effectively implements seamless transitions between various estimation techniques for the unknown W encryption bit, such as squaring, cross-correlation, soft W-bit estimation, etc.

Two different L2 P(Y) tracking algorithms have been developed; the direct L2 estimation method and the indirect L2 estimation method. The direct L2 estimation method estimates L2 carrier phase, P(Y) code phase, carrier Doppler shift, carrier
Doppler shift rate, and $P(Y)$ amplitude on L1 and L2. The indirect L2 estimation method incorporates physical models of the ionospheric effects on code and carrier phase of the L1 and L2 signals. This method estimates TEC and phase scintillations, and it calculates the code and carrier phases of L2 using the estimated TEC and phase scintillation states and the estimated code and carrier phases of the L1 signal.

The algorithms have been successfully tested with real signals of normal strength from a dual-frequency RF front end connected to a roof-top antenna, with real dual-frequency data to which noise has been added in an intentional degradation, and with simulated signals that experience strong amplitudes fade and rapid phase changes that are typical of ionospheric scintillations.

The smoother shows better estimation accuracy than the EKF because it forms its estimates using additional data, data that extends past a given time at which an estimate is to be calculated. The indirect L2 estimation method maintains lock down to lower $C/N_0$ values than the direct L2 estimation method but is more sensitive to the values of its tuning parameters. Both methods can track the simulated data with strong phase scintillations if the amplitude fades are not too severe. If scintillations cause a large enough amplitude fade, then the L2 tracking algorithms lose lock. The computed estimation error covariances from the EKF/Smaller algorithms are consistent with their actual error performance. When the L2 $P(Y)$ tracking algorithm loses lock, the estimation error covariance corresponding to the carrier phase state increases to over $50^\circ$. Thus, the estimation error covariance can be used to predict the potential for loss of lock.

A steady-state covariance analysis has been applied to find the $C/N_0$ threshold for loss of lock based on the computed steady-state standard deviation of the carrier phase tracking error. This threshold is a function of the signals' $C/N_0$ levels on the L1 and L2 frequencies. The threshold curve for the indirect L2 estimation falls at lower
C/N₀ values for both frequencies than the direct L2 estimation method because the former method is able to use lower bandwidths for its EKF and thus is able to maintain lock down to lower C/N₀ values. The C/N₀ thresholds over which the EKF and smoother algorithms maintain lock agree roughly with the tracking results for the simulation data.