Chapter 9. Conclusions

It has been shown that using stable clocks can improve vertical accuracy in differential GPS systems. This stems from the fact that the vertical dilution of precision (VDOP) is reduced when the ground and airborne receivers are synchronized. The full extent of the VDOP improvement is not realized unless there is perfect synchronization because clock errors result in position errors if not corrected. It has been shown that maintaining synchronization is not a simple matter of purchasing highly stable atomic standards and connecting them to the ground and airborne receivers.

Hardware variations due to temperature effects cause the clocks to drift relative to one another. Better performance could be achieved if the receiver were designed specifically for a stable clock. The Z-12 receivers used for most of the experiments presented are not specifically designed to operate using a highly stable clock. The external reference input allows for oscillators from 1 to 21 MHz to be connected. The hardware required for this capability is subject to temperature variations on the order of 10 meters or more. Even when the temperature variations are reduced by hardwiring an oven controlled crystal oscillator (OCXO) as in the MITRE experiment with Novatel receivers, excursions of up to 10 meters are seen which would be very difficult to model. Thus, optimal clock aiding requires a receiver specifically designed to run off a highly stable reference, such as rubidium or cesium. The effectiveness of clock aiding is diminished if the hardware stability is not as good as the clock stability.

Two of the missing relativity terms for GPS receivers that were derived by Deines were not verified experimentally. It has been shown that relativity errors for a GPS receiver are not satellite dependent. A flight test experiment specifically designed to confirm or refute the claim that such errors exist proved that these errors in fact do not exist. There is a discrepancy between the satellite relativistic corrections and the receiver relativistic corrections that does not seem appropriate — a relativistic expert should review the derivation of Deines to determine where the misinterpretation is.

It should be noted that the relativity experiment did not test time dilation, which is accepted as correct. There is a similar term used to correct GPS satellite clocks, and intuitively such a term should be used to correct receiver clocks on moving platforms. A simulation showed that the time dilation term would reach 4.1 cm (using velocity in the ECI frame) for a receiver moving at 55 m/s relative to the ground station for 12 minutes at 39° N latitude. Compared to the hardware variations due to temperature changes, this is a small term. However, if a system were designed for clock coasting with calibrated clocks and minimized hardware variations, time dilation could be a significant error.

It is also intuitive that the receiver clock should be corrected for a difference in gravitational potential if the receiver is on a platform at some altitude above the surface of the Earth. Again it is noted that a correction for gravitational frequency shift is applied to the satellite clocks. It makes sense that a similar correction should be applied for airborne receivers. It was shown that for a receiver at 39° N latitude with an altitude of 10,000 ft above the geoid, this error would reach a magnitude of 0.1 m after 1000 seconds (~17 minutes). Thus, the gravitational term is small for users near the Earth, but potentially significant.

Antenna rotation has been shown to cause clock errors as well. Experiments showed that rotating the antenna causes a clock offset equal to one L_1 wavelength for each revolution. This error would be easy to model. The effect on dual frequency receivers is more difficult to assess because of the aiding of the L_2 carrier with the stronger L_1 carrier.

It has been shown that clock stability and hardware stability are the primary concerns for clock aiding of GPS receivers. The relativistic effects are small and represent rate errors that could be modeled. Thus, a clock model can be used if there is sufficient clock and hardware stability. A new method of modeling was introduced whereby carrier phase measurements are used to assist the formulation of a second order clock polynomial. This has three benefits: 1) the model is more accurate than a model based only on code phase measurements, 2) the model requires less prior data to determine accurate polynomial coefficients, and 3) the model is able to follow quick changes in the clock offset without filtering delays. It was shown that a good model can be used with stable clocks to improve vertical accuracy. Clock-aided navigation over a three minute period was demonstrated using only three satellites and the last calculated clock polynomial. For these reasons, clock-aided navigation should be part of the FAA plan to rely on differential GPS for precision approach and landing of aircraft.