Chapter 1. Introduction

The Federal Aviation Administration (FAA) has been supporting the development of a next generation landing system to be used in the United States, and potentially worldwide. Currently, most precision approaches are conducted under the guidance of the Instrument Landing System (ILS), a 1940s era system still in wide use today [Brady, 1993]. Until 1995, an international agreement existed to phase in the Microwave Landing System (MLS) to replace ILS. The transition plan was changed in favor of the Global Positioning System (GPS), specifically differential GPS (DGPS), because of the expected improvement in benefit to cost ratio. Since 1985 the FAA has been investigating the use of GPS as an aid to navigation not only during landing, but also during other phases of flight such as taxiing and enroute.

Stand-alone GPS provides horizontal accuracy of 100 m (95%) and vertical accuracy of 156 m (95%). To improve accuracy, a ground station can broadcast to local users a set of corrections based on a surveyed antenna position. Such a system, known as differential GPS, provides position accuracy of 10 m or better. Further improvement is possible by incorporating the Doppler shift of the received carrier, which can result in sub-meter position errors. Thus, DGPS can be used for approach guidance under conditions of poor visibility. Table 1.1 [Federal Aviation Administration, 1995] lists the different categories of precision approach as defined for the GPS Local Area Augmentation System (LAAS). The requirements for Category II and Category III are considered the same because it is assumed that when the plane nears the runway, the radar altimeter can take over. The requirements for vertical accuracy are much more stringent

Table 1.1 Accuracy Requirements for Precision Approach

Category	Horizontal Path Following Error (95%)	Vertical Path Following Error (95%)
CAT I	7.9 m	4.3 m
CAT II, III	5.5 m	1.8 m

than for horizontal accuracy for obvious reasons. Although accuracy is improved by differential techniques, the relative performance between horizontal and vertical accuracy is the same — GPS provides lateral guidance that is superior to the vertical guidance.

The purpose of this work is to seek ways to improve the vertical accuracy that can be achieved with differential GPS. Currently, inexpensive temperature compensated crystal oscillators (TCXOs) are used in many receivers to help keep the cost down. Because the receiver must be synchronized with GPS time in order for the system to work, there is a tradeoff in going with a cheap oscillator. The receiver clock has a bias from GPS time which must be solved for. The result is degraded vertical accuracy due to the high correlation between the clock state and vertical position. If the receivers could be synchronized with GPS time by the use of highly stable clocks, then the receiver clock bias could be eliminated [Sturza, 1983]. This not only requires one less measurement in order to solve for position, which increases system availability, but also results in an improved estimate of vertical position.

This dissertation focuses on using the clock as an aid to aircraft navigation, particularly during the approach and landing phase of flight. By improving vertical accuracy, GPS is better able to meet the Category III requirement. The additional measurement also allows for navigation during periods when GPS provides too few satellites to calculate position. However, the clock represents a different type of measurement than a range measurement to a GPS satellite and therefore is subject to different types of errors. This paper seeks to address these error sources in order to determine the impact on clock-aided navigation. The use of an atomic clock would be ill-advised if synchronization between the receiver and GPS time could not be maintained. In the case of differential GPS, we require the ground and airborne receivers to be synchronized with each other (and ideally with GPS time as well) in order to use the clock-aided solution. Thus, we seek methods of managing the clock state such that the errors do not cause a loss of synchronization.

The dissertation begins with a general discussion of position location techniques leading up to satellite-based navigation. From there, an extensive presentation of GPS system characteristics is given. This leads to the concept of clock augmentation as a method of improving GPS vertical accuracy and improving GPS availability. Error sources follow with investigations of antenna rotation effects, temperature effects, and relativistic effects. It will be shown that for GPS users moving on or near the surface of the Earth at moderate speeds, relativistic effects are small. This is a new development in the area of clock augmentation and disproves a claim that has been made to the contrary. Finally, a presentation of several case studies from a flight test is given to illustrate clock-aided navigation in practice. Here, a new method of clock management will be presented which incorporates carrier phase measurements to improve the synchronization between the ground and airborne receivers.