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## Software and system development of a smartphone-based flight-tracking device to enhance flight instruction

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SOFTWARE AND SYSTEM DEVELOPMENT OF A SMARTPHONE-BASED FLIGHT-  
TRACKING DEVICE TO ENHANCE FLIGHT INSTRUCTION

A Thesis by

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Bachelor of Science, Wichita State University, 2011

Submitted to the Department of Aerospace Engineering  
and the faculty of the Graduate School of  
Wichita State University  
in partial fulfillment of  
the requirements for the degree of  
Master of Science

May 2013

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SOFTWARE AND SYSTEM DEVELOPMENT OF A SMARTPHONE-BASED FLIGHT-  
TRACKING DEVICE TO ENHANCE FLIGHT INSTRUCTION

The following faculty members have examined the final copy of this thesis for form and content, and recommend that it be accepted in partial fulfillment of the requirement for the degree of Master of Science with a Major in Aerospace Engineering.

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James E. Steck, Committee Chair

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Animesh Chakravarthy, Committee Member

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John Harrison, Committee Member

## DEDICATION

To my late mother who taught me to go after my dreams,  
to seek but not avoid challenges, and to always give my best

## ACKNOWLEDGEMENTS

Writing a thesis is a long, time-consuming, but very rewarding undertaking—a task that could not have been done without the help and support of many others that deserve credit and recognition. First and foremost, I want to express my appreciation to my advisor and committee chair, Dr. James Steck, for his support, guidance, and encouragement throughout this research. I also would like to thank the other members of my thesis committee: Dr. Animesh Chakravarthy and John Harrison. Special thanks go to Christian Kindel, whose assistance was invaluable in the development of the first prototype. Finally, I want to thank Ryan Benyshek, Bill Kusmez, and Landon Unruh for their time and effort during the flight test phase.

## ABSTRACT

The research conducted and described herein revolves around the development and flight testing of a smartphone application, which can serve as an affordable flight monitoring and recording device for individual flight instructors and flight schools. A detailed analysis of device components, a feasibility study, and preliminary testing found the Apple iPhone capable of collecting and transmitting pertinent flight data in real time. In its initial form, the application gathers and records flight data for review and debriefing. Further development has enabled flight instructors to conduct remote supervision, from the ground, of solo students while they are flying an aircraft. The flight instructor is able to observe the real-time performance of the student via a telemetric data feed and provide accurate feedback both during the flight and during the post-flight debriefing. The system consists of a transmitting smartphone onboard an aircraft and a computer on the ground. Using the received data, a flight simulator provides visual feedback to the flight instructor, such as an animated inside view of the cockpit. A comprehensive series of evaluation tests was conducted with several test pilots on the ground and during various operations and flight regimes, including taxiing, low level traffic pattern operations, performance turns, cross-country flights, and instrument approaches. Results were used to investigate the performance limits of the iPhone in combination with CFiTrack, an iPad/iPhone universal application that integrates multiple data sources in order to report flight and navigation data wirelessly and in real time, and found the application sufficiently accurate to aid in beginner-level flight training.

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## LIST OF ABBREVIATIONS

AGL	Above Ground Level (Altitude)
AOPA	Aircraft Owners and Pilot Association
ASCI	Application-Specific Integrated Circuit
CFR	Code of Federal Regulations
CSV	Comma-Separated Values
DOF	Degree of Freedom
FAA	Federal Aviation Administration
FAF	Final Approach Fix
FAR	Federal Aviation Regulations
FTD	Flight Training Device
GPS	Global Positioning System
IDE	Integrated Development Environment
IFR	Instrument Flight Rules
ILS	Instrument Landing System
iOS	iPhone Operating System
IP	Internet Protocol
KIAS	Knots Indicated Airspeed
KTAS	Knots True Airspeed
LTE	Long-Term Evolution (Wireless Communication Standard)
Mbps	Megabits per Second
MEMS	Microelectromechanical System
MHz	Megahertz

## LIST OF ABBREVIATIONS (continued)

ms	Millisecond
MSL	Mean Sea Level (Altitude)
NTSB	National Transportation Safety Board
RF	Radio Frequency
RPM	Rotation per Minute
SDK	Software Development Kit
TSA	Transportation Safety Administration
UDP	User Datagram Protocol
UI	User Interface
VFR	View Flight Rules
VHF	Very-High Frequency

# CHAPTER 1

## INTRODUCTION

In the last decade, the global usage of mobile phone devices has undoubtedly increased significantly. Along with the development of high-speed bandwidth technologies has come the introduction of smartphone and tablet applications, which can utilize this communication medium for various purposes. Many innovative mobile device applications have become a vital aid to today's general aviation community. For example in 2012, the Federal Aviation Administration (FAA) approved the Apple iPad as an electronic flight bag, an electronic information management device that helps flight crews perform flight management tasks more easily and efficiently, for American Airlines. The research conducted and described herein explores the development of a concept that allows the tracking of civilian aircraft via mobile smartphone devices by receiving flight data, including position, heading, airspeed and more. The implementation of such a technology could not only provide significant contributions to aviation safety but also affect economic considerations. Used as a flight training aid, such a system could reduce the amount of flight training needed. Based on the number of student pilots per year, even an average reduction of one hour flight time per student to complete the training would conserve an estimate of 400,000 gallons of fuel.

According to FAA statistics, the number of private pilot certificates (initial rating) issued over the past ten years has noticeably declined, as shown in Figure 1. In 1979, the total number of private pilot certificates had reached 343,276, as compared to 229,767 certificates held in 2009, resulting in a 33% decrease. Similar statistics also reveal a decline in student pilots: The total number of student certificates in the United States fell from 210,180 in 1979 to 72,280 in

2009. These statistics suggest a higher dropout rate among student pilots. Less than 50% of them actually completed their training and received their license in 2009.

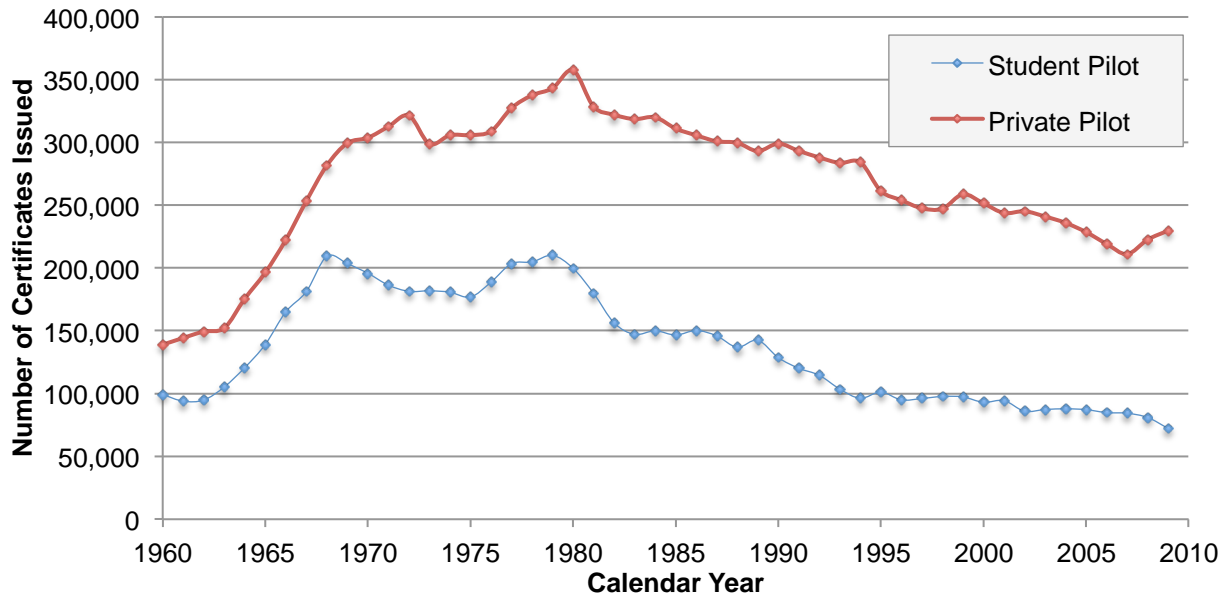


Figure 1. Original airmen certificates issued.

According to the Aircraft Owners and Pilot Association (AOPA), “student pilots drop out of training at a rate that approaches 80%” [1]. The rising cost to complete flight training is contributing to this declining trend. However, according to Mark Benson, chairman of the renowned market research firm APCO Insight, “The lack of educational quality, customer focus, community, and information sharing are the four key reasons student pilots drop out of flight training” [1]. Furthermore, society still perceives aviation as a dangerous endeavor. A sophisticated way to monitor solo or dual training activity and give feedback to the pilot would enhance the quality and effectiveness of flight training immensely. In turn, this could result in reduced insurance costs and lower accident rates for student pilots. Relating this to economic considerations, the potential for less required flight time would also lower the cost to complete flight training.

Also, expanding this concept from general aviation pilot training to benefit government agencies, the FAA, Transportation Safety Administration (TSA), and National Transportation Safety Board (NTSB) could benefit greatly from the information that a system as described above could provide. The transparency of flight activity, especially in times where air traffic is growing, seems a fertile environment for such an application. It is interesting to note that the FAA has recently begun an investigation into the possibility of lifting the ban on smartphone data usage (not to include voice transmission) during airline flights [2]. This could have a substantial impact on the development of the herein described system. The system would no longer act as simply a flight training aid, but rather as a global personal or business flight-tracking tool.

## **1.1 Research Objective**

The primary goal and focus of this research was the improvement of flight training, which would contribute to increased aviation safety. The objective was to develop and test a system that can optimize the amount of time a student needs to fulfill the required experience requirements in order to obtain his/her license. Aeronautical experience requirements as defined by FAA regulation 14 CFR 61.109 [3] state that a person who applies for a private pilot certificate with an airplane category and single-engine class rating must log at least ten hours of solo flight time (flight time without an instructor on board). Once a student has gained enough experience and is signed off by the flight instructor to go on a solo flight, a great responsibility rests on the shoulders of the instructor, ultimately responsibility for the student's life. The sudden transition from receiving dual training with an instructor onboard to handling the aircraft entirely on his or her own is a transition that often intimidates the student subconsciously and interferes with learning. While not limited to the initial solo transition, the system developed in this thesis

should allow a flight instructor to monitor an advanced student who is undertaking a cross-country flight. Regulation 14 CFR 61.109 [3] also states that the minimum of ten hours solo flight training must include at least five hours of solo cross-country time. This includes one solo cross-country flight of no less than 150 nautical miles total distance, with full-stop landings at three points and one segment of the flight consisting of a straight-line distance of more than 50 nautical miles between takeoff and landing locations. To alleviate these initial fears from soloing and to enhance the effect of learning, this research is directed at developing a flight-data tracking system that uses mobile phone technology and can provide valuable evaluation and supervision tools to the flight instructor.

## **1.2 Motivational Consideration**

The primary motivation for conducting this research was the desire to implement innovative and widely accessible technology to enhance the quality and efficiency of flight instruction. Being a certified flight instructor, I know firsthand about the responsibility and risk that a flight instructor carries at all times. Learning the reason for the high dropout rate among private pilot students has sparked an interest in the development of a training aid that would increase the success of more students. The decision to focus on smartphones was driven by the fact that smartphone technology is a relatively new addition to the world of consumer electronics. From a marketing standpoint, this suggests a wealth of possibilities that has not yet been explored. According to the FAA, in 2011, the total number of flight instructors in the United States was estimated to be 97,409, a number that, without a doubt, advocates a well-sized customer base. Professional flight schools would certainly benefit from such a system as well.

### **1.3 Literature Review**

Some innovative research on improvements to flight training has been directed towards high-end flight simulators or flight training devices (FTDs). Kirton et al. [4] reflected on the new generation level 6 FTDs that feature enhanced visual performance and realism for view flight rules (VFR) pilots to reduce the amount of required training. The cost to purchase and operate modern FTDs in a private pilot training environment, however, raises the question of cost effectiveness and fiscal risk involved with using such technology for beginner-level training. Hence, this thesis explores an alternate avenue for enhancing the quality and safety of flight training using real-time telemetry for flight data recording. Initial investigations on the use of telemetry in aviation indicated a preexisting interest of aerospace enterprises to offer aircraft location tracking. Miller et al. [6] described the design and construction of a real-time, ground-based telemetry tracking device that relays satellite data to a ground control station. Yet the system described seems far outside an appropriate budget for a general aviation flight school or an individual flight instructor.

Alternate, lower-cost, intensive systems were investigated, which still allow the integration of flight data recorders or flight tracking devices into flight instruction. Kumar et al. [7] described a concept in the early 1990's when technology had not advanced to allow low-cost, real-time flight tracking and streaming using mobile phone devices. He investigated the reconstruction of recorded data by developing a Kalman filter as a state estimator to drive a post-flight simulation. He identified the benefits of such a system as the ability to reexamine a training flight in detail, use data for debriefing and tactic analysis, evaluate a pilot's performance, and investigate accidents.

Much of the past research and development of flight data recorders was directed towards post-flight reconstructive methods: Slane et al. [8] researched a low-cost approach to recording flight data in general aviation. He described an analytical reconstruction of pertinent flight conditions using a system that is solely based on global positioning system (GPS) data. Kim et al [4] described the analysis of various flight parameters to determine structural fatigue after cumulative aircraft usage. Their work is based on the research, development, and successful testing of a small, lightweight flight data recorder by Cicero et al. [9]. However, their recorder also required a post-flight analysis and did not allow real-time and remote flight tracking. The concept of obtaining motion data remotely and in real time for flight recording was explored by Ashish and Chougule [10], who describes a method by which data is transferred via an XBEE-RF module. Their proposed method allowed for real-time, web-based flight tracking of GPS-based position data.

The concept of obtaining position and motion data from a smartphone's inertial sensors is not new and has been explored and improved over time ever since smartphones were first introduced. Niu et al. [11] proved that inertial microelectromechanical system (MEMS) sensors could be used for car navigation. They investigated the integration of inertial sensor data during GPS signal outages and obtained enhanced positioning performance along with acceptable altitude estimations. Migrating delicate MEMS sensor technology into aviation, however, poses the question of measurement fidelity and errors based on higher forces and angular momentums acting on an aircraft as opposed to a car. Sachs [12] described the errors associated with each sensor and how combining an array of sensors can eliminate some of these errors. He discussed this process of utilizing multiple sensors to correct each other, known as sensor fusion.

Throughout the development of various releases of the iPhone's operating system (iOS), sensor fusion was tied into the iOS system and provided to the software developer.

The previous work conducted and described by others contains valuable information on methods used and presents a good foundation for further research. Much of the progress at the time was limited by the available technology or it was too cost intensive and bore a high fiscal risk. This research will combine some of the features of developed systems and optimize them for flight instruction on the basis of a low-cost system that is available to the general public. The following chapters describe the design, development, testing, and integration of a prototype of CFiTrack, an iPhone-based universal flight-tracking system that integrates with multiple data sources in order to report flight and navigation data wirelessly and in real time.

## CHAPTER 2

### CFITRACK—APPLICATION AND SYSTEM DESIGN

The development of a cell phone-based flight-tracking system required a detailed analysis of the hardware and performance of modern smartphones. Starting with the conceptual design, this chapter will describe the development stages of such a system with focus on the Apple iPhone 5. In the second part of this chapter, feasibility considerations are researched and addressed, in particular the minimum hardware required to allow a successful realization of such a system.

#### 2.1 Conceptual System Design

The design parameters that contributed to the conceptual design and consequent development of the CFiTrack prototype were driven by critical stages during flight instruction. These include the transition from dual flights to first solo flights, solo cross-country flights, and maneuver practices. The basic design of a smartphone-based system for remote flight tracking is relatively simple. It consists of a transmitting smartphone device located onboard the aircraft, as well as a receiving computer on the ground. At the beginning of a flight, the student takes the smartphone device onboard the airplane and initiates the CFiTrack smartphone application. The user interface of the prototype application was kept simple and user friendly. It allows the user to specify an IP address of the ground station and provide a toggle button to turn the streaming feature on or off. Basic flight parameters displayed on the smartphone screen are for reference purposes only and not to be used for piloting the aircraft. Upon transmission, the ground station receives via the Internet a continuous downstream from the smartphone, which contains flight data used to reconstruct a model of the aircraft, as shown in Figure 2. The modeling and

animation of the aircraft is done using X-Plane, a fairly modifiable simulation platform by Laminar Research. The flight instructor on the ground uses it to visualize and monitor the flight.

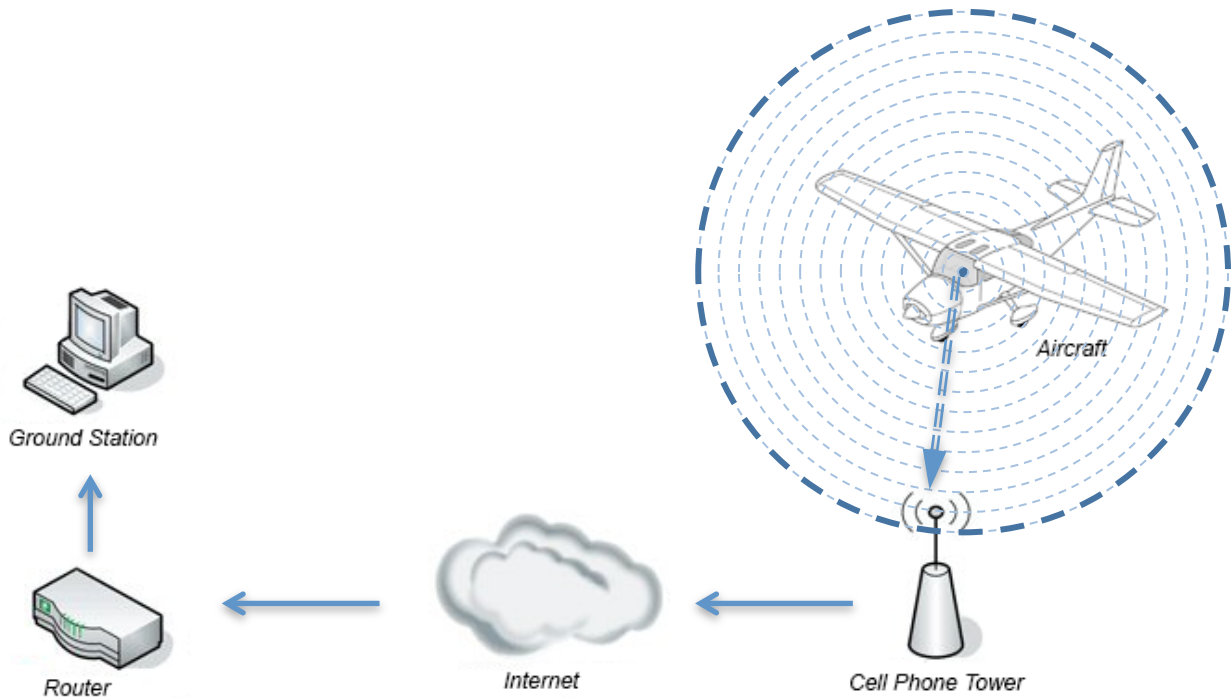


Figure 2. Conceptual design layout.

## 2.2 Development Overview

The development of a system that is specifically tailored to enhance flight instruction as described above is rather elaborate and multilateral, involving a multitude of resources to accomplish various objectives. To clearly structure the development of this system and of the smartphone application as a central component, this project was divided early into several developmental stages:

**Stage 1—Conceptual Design (Year 1, October 2012):** The first stage was the conceptual design and development of a smartphone application that would act as a flight data recorder, referred to in the airline industry as a “black box.” An initial study of the smartphone itself provided information on how the internal sensors may be used to provide sufficient real-

time readings. Based on the sensor outputs, this application records the position, attitude, and motion of the aircraft, which can be plotted when back on the ground, allowing the instructor to debrief the flight with the student. This low-cost, mobile-device-based flight data recorder provides the instructor and the student with visual post-flight feedback for both instructed dual flights and also solo flights. It allows the instructor to review, debrief, and critique more effectively. However, this method only provides a primitive representation of the flight history, requires manual data processing using a graphing software, and does not offer real-time information to the instructor.

**Stage 2—(Year 1, November 2012):** This second stage introduced the idea of a ground station, also referred to as the client computer. While a student solos (no instructor on board) the aircraft, a client computer receives a live downlink from the iPhone with the telemetric data of the aircraft. This allows the instructor on the ground to monitor the student's actions and performance. Communication between the smartphone and computer is conducted via the cell phone data network (3G/LTE Standard). The key conceptual component of this development stage is the extraction and relay of pertinent sensor information to the client computer or ground station. Once the client computer receives the telemetric data, it feeds it into a flight simulator, which can provide a visual, real-time, in-cockpit simulation for the instructor, corresponding to the data provided by the host smartphone inside the flying aircraft. Utilizing two-way communication as well as the information provided by the smartphone, the flight instructor can now verbally intervene as a virtual flight instructor when necessary, creating a new transitional form of flight instruction.

**Stage 3 and Beyond (post thesis):** At this point, an additional smartphone device acting as client would replace the host computer. During this stage a client application will be

developed to construct the real-time visualization of the aircraft's state based on the telemetric data provided by the host mobile device. Initially, the flight instructor may contact the student when necessary via common VHF radio communication (118.000–136.000 MHz). Further development could incorporate an LCD display located inside the aircraft, which could show messages from the flight instructor on the ground. Alternatively, two-way voice communication, via smartphone application, could tie into the aircraft intercom system.

### **2.3 Feasibility Considerations**

The fundamental idea of this smartphone application is the introduction of remote flight instruction, whereby a flight instructor can observe and supervise one or multiple flights without actually being onboard the aircraft. In order to accomplish this, several concerns need be addressed and taken into account. The single most important concern is whether a smartphone device contains the required hardware to obtain sufficient sensor data to support such a system. A detailed analysis of the iPhone's hardware components and sensor performance is discussed in Chapter 4. In order to provide a representation of an aircraft in motion, the iPhone must provide very specific information:

**Location.** To obtain the current location of an aircraft, the iPhone should be able to determine its own position based on external inputs. This seemingly trivial task could be performed by either a satellite-based GPS navigation system, cell phone tower triangulation, or ideally both. The sampling rate at which the position updates are populated is of importance as well, because it may delay the representation of an aircraft substantially. For example, a Cessna 172 in cruise configuration travels at approximately 110 KTAS [13]. At a nominal sampling rate of 1 Hz, the aircraft would have traveled 185 feet in any direction between consecutive position updates. It is beyond a doubt that such inaccuracies would not be acceptable for this application.

***Orientation.*** The depiction of an object in motion represents itself as a rather difficult undertaking. To obtain directional orientation (heading), it would require nothing more than a compass. However, when engaged in non-level flight, a conventional two-dimensional compass would likely fail to provide accurate directional information. Hence, the iPhone must be capable of resolving three-dimensional geomagnetic data into a present heading. Gyroscopes and accelerometers could provide a fast and reliable way to gather lateral and longitudinal rotation and orientation data. The gyroscope provides turn rate, which, once integrated, offers a heading to the user. The accelerometer then supplies a tilt compensation, which will be discussed in a later chapter.

***Translational and Rotational Motion.*** Accelerometer data could be integrated to give translational velocities; however, this method is rather inaccurate. The alternative to measuring groundspeed based on differentiating position with respect to time can also result in significant error. Each position update can be offset by up to five feet, hence resulting in a substantial measurement error. Instead, most smartphones calculate groundspeed at any given moment by measuring the Doppler shift in the GPS signals from the satellites. Turn rate is the inherent output of the gyroscope and thus can be used directly from the sensor. Note that in order to obtain an estimate for indicated airspeed, a correction for current wind direction and speed must be implemented. However, this would exceed the scope of this thesis and will be explored in future research.

***Communication.*** While airborne, the smartphone must be capable of relaying pertinent information to the ground station using the cellular data communication. The latest broadband communication standard—LTE (long-term evolution)—used in consumer electronics provides peak download rates of 10+ Mbps. In order to obtain the required bandwidth, sufficient network

coverage must be ascertained. Among the four major wireless carriers (AT&T, Verizon, T-Mobile, and Sprint), Verizon was ranked highest in overall network coverage and reliability. Hence, Verizon Wireless was selected as the wireless service provider for this research. With 87% nationwide LTE coverage, only very few remote areas of the United States are subject to signal loss, as shown in Figure 3. A simple performance test was conducted using an iPhone 5 and Verizon's recommended application for bandwidth tests, Mobile Speed Test by Ookla. Five test runs were conducted during different times on a weekday. The captured down rates averaged **13.1 Mbps**, and upload rates averaged **3.67 Mbps**. The latency ranged from 72 ms to 688 ms in the areas and altitudes of ideal-to-poor reception. Results of the bandwidth tests were very satisfactory and proved the necessary connectivity for a continuous data stream to the ground station in terms of bandwidth and latency.

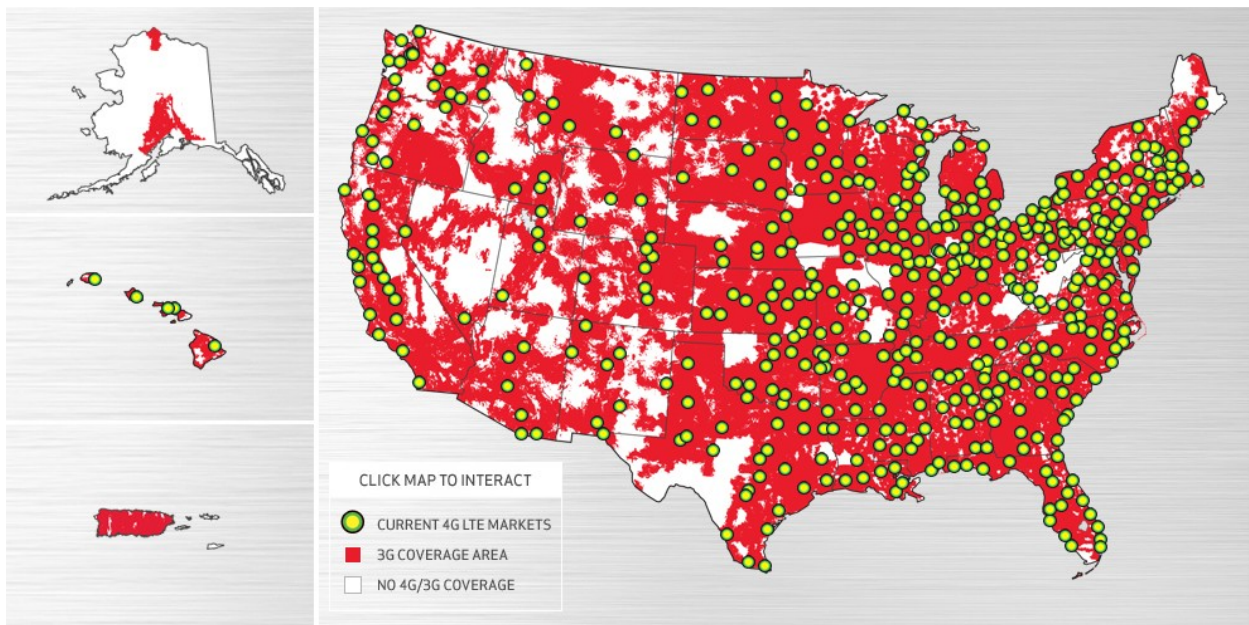


Figure 3. Coverage map for Verizon Wireless (courtesy of Verizon Communications Inc.).

In addition to the lateral coverage and performance evaluations at ground level, efforts were also directed at determining the much less-documented vertical range that assures proper

signal integrity during cruise flight at altitude. Since the reliability of cell phone reception at altitude is practically undocumented, a simple altitude range check was conducted. The test aircraft, a 1970 Mooney M20-E, shown in Figure 4, was flown on three legs of a cross-country flight: from Newton, Kansas (KEWK), to Emporia, Kansas (KEMP); then to Salina, Kansas (KSLN); and back to Newton, as depicted in Figure 5.



Figure 4. Mooney M-20E.

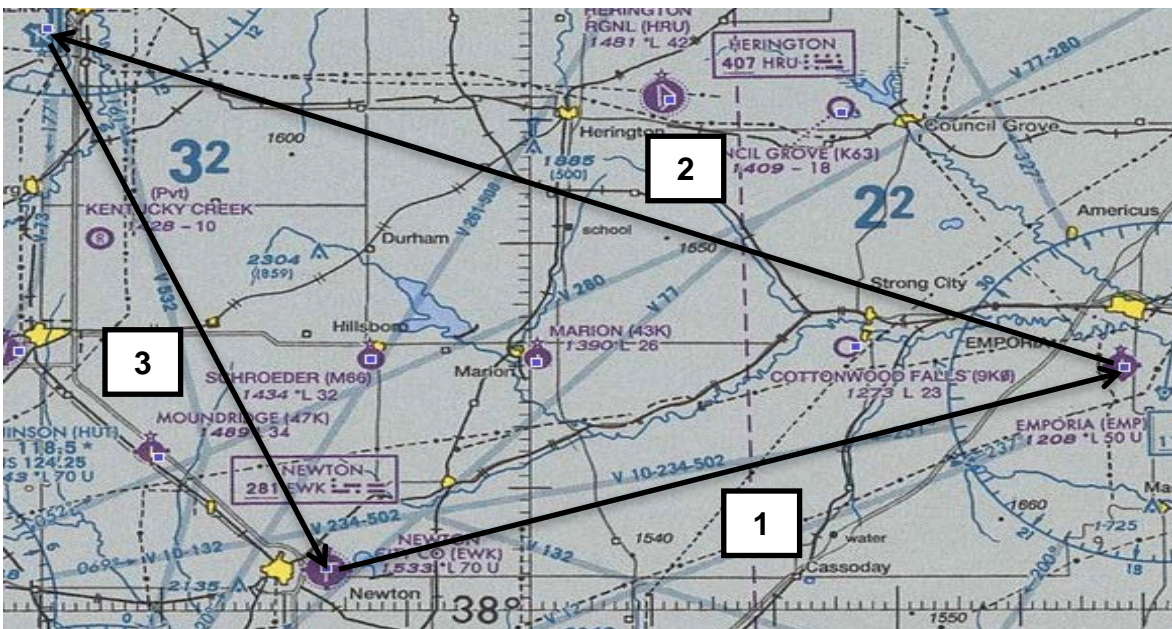


Figure 5. Route for reception evaluation (courtesy of SkyVector).

During this flight, the smartphone (iPhone 5) was positioned on a slip-resistant rubber mat on a side panel of the passenger side. The triangular course was flown at varying altitudes from 1,000 to 8,000 feet above ground level (AGL). The signal strength was rated on a scale of 0 to 5 based on the number of indicated bars on the phone. Additionally, data connectivity was distinguished between LTE (fastest), 3G, and EDGE (slowest). Table 1 shows reception readings at altitude as they were obtained during the flight. A visual representation of the data is depicted in Figure 6.

TABLE 1

VERIZON 3G/LTE NETWORK RECEPTION EVALUATION AT ALTITUDE

Flight Leg	Altitude (ft. AGL)	Signal Strength	Data Connectivity	Down/Up (Mbps)
1	1000	3/5	LTE	9.1/3.4
	2000	3/5	LTE (Roaming)	5.3/3.4
	3000	4/5	LTE	1.0/0.2
	4000	2/5	LTE	8.1/10.1
	5000	2/5	3G	9.6/11.9
	6000	1/5	n/a	0/0
	7000	1/5	n/a	0/0
	8000	0/5	n/a	0/0
2	1000	2/5	LTE	11.4/6.2
	2000	4/5	3G	3.4/1.1
	3000	2/5	LTE	8.3/2.2
	4000	2/5	LTE	1.1/0.1
	5000	1/5	n/a	0/0
	6000	1/5	EDGE	0.1/0.1
	7000	0/5	n/a	0/0
	8000	0.5	EDGE	0/0
3	1000	5/5	LTE	6.5/2.3
	2000	4/5	LTE	8.3/2.4
	3000	4/5	LTE	4.3/1.9
	4000	2/5	3G	1.1/0.5
	5000	3/5	3G	0/0
	6000	1/5	EDGE	0/0
	7000	1/5	n/a	0/0
	8000	0/5	n/a	0/0

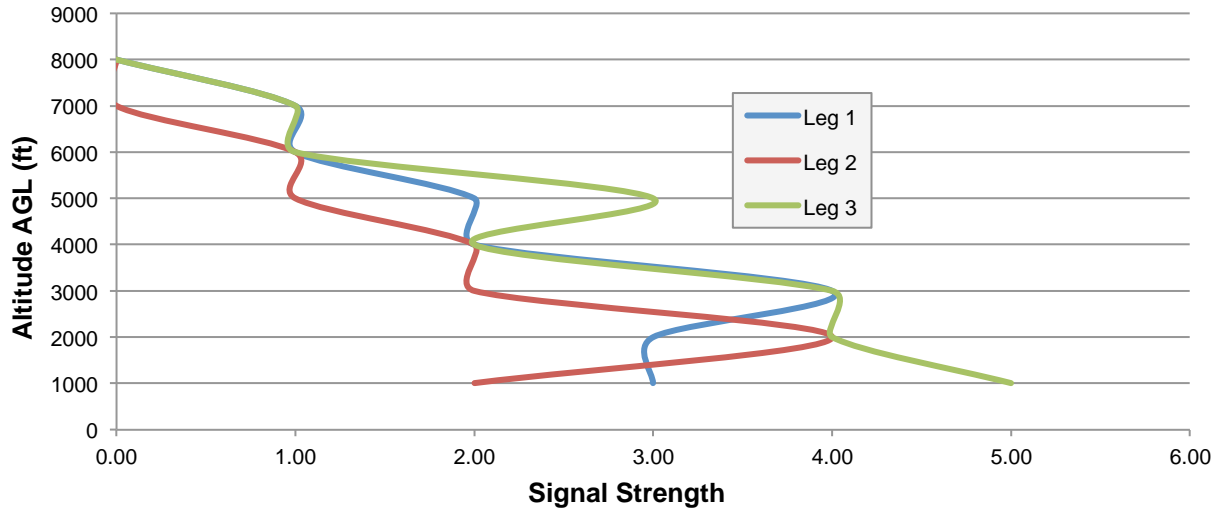


Figure 6. Signal strength at altitude.

Generally speaking, cell phone reception and data connectivity were adequate within 2,000 feet AGL and within the shaded areas on the coverage map shown in Figure 5. The test revealed an interesting characteristic regarding the reception at higher altitudes. The recorded data suggested an expected decline in signal strength and quality; however, between 4,000 and 6,000 AGL, the performance exhibited a sudden peak in download and upload rates, and then suddenly dropped. At times, reception was detected at peak altitudes of up to 8,000 feet AGL. However, the quality of the signal was marginal and sporadic. Fortunately, for beginner-level flight training, altitudes generally remain within 3,000 feet AGL, even during cross-country flights over more sparsely populated parts of the country. Reception during operations near the ground, such as takeoffs and landings, was consistently adequate and comparable to reception while driving a car. In summary, preliminary research and design efforts indicate that a smartphone, if equipped with sufficient sensors, could provide real-time information on the flight dynamics of an aircraft. A detailed analysis of the Apple iPhone will involve examining its hardware components in order to provide a more profound view on the feasibility of this concept.

## CHAPTER 3

### INERTIAL SENSORS

The term “smartphone” was first introduced in 1993 when IBM launched the “Simon” [14]. Much has changed since then. The idea of a mobile communication device that could do more became reality, and turned into an evolution of the conventional cell phone, with the release of the first iPhone in September of 2007. Since its release, the iPhone has undergone five revisions and, with more than 250 million units sold worldwide [15], has become one of the most sought-after multimedia communication gadgets ever released. As a part of modern consumer electronics, smartphones are a generation of mobile phones capable of processing multi-faceted applications and services including email and Internet. Modern smartphones are equipped with a wide array of sensors and processors “turning the once single-minded cell phone into a mobile personal computer” [16].

While the concept and methods described herein could apply to most modern smartphones in one way or another, technical specifications as well as research conducted and described in the following chapters are based solely on the iPhone 5. This chapter provides technical insight into the internal components used in this latest release of the Apple iPhone. It investigates whether the information that is obtained from the internal sensors of the device can provide sufficient data to act as a foundation for flight data recording and streaming. Based on the sensor dynamics, this chapter will also introduce techniques to reduce sensor bias and improve the quality and precision of the resulting data. After all, sensor accuracy and speed are of indisputable importance in the development of a mobile flight tracking and monitoring device, particularly when used for remote flight instruction.

### 3.1 Chipset Architecture

The main circuit board of the iPhone 5, shown in Figures 7 and 8, is equipped with a broad assembly of sensors and communication components. For the purpose of this research, the primary focus is directed at components that assist in determining the aircraft's location (longitude, latitude, and altitude) and orientation (Euler angles).

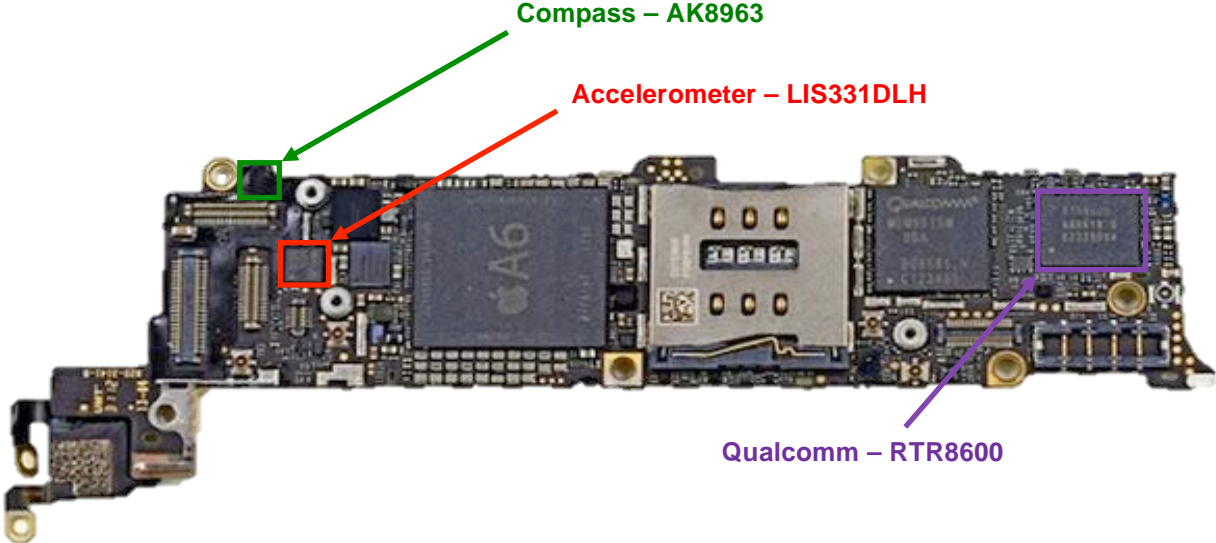


Figure 7. iPhone 5 main circuit board (front view, courtesy of Chipworks Inc.).

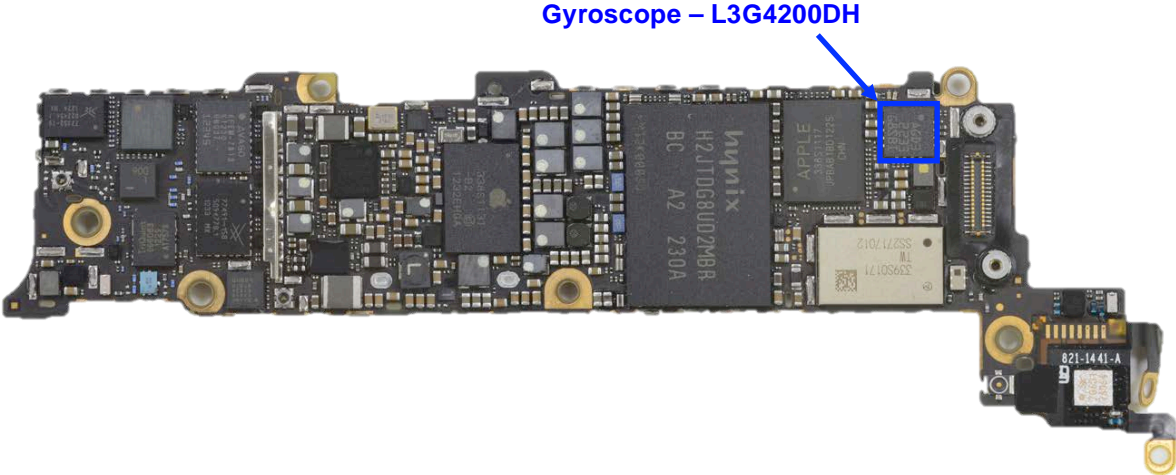


Figure 8. iPhone 5 main circuit board (back view, courtesy of Chipworks Inc.).

Advancements in microchip technology allow for mechanical sensors to be scaled down to a few millimeters, while maintaining reasonable accuracy, full functionality, and reliable sensor outputs. These components are also referred to as microelectromechanical system (MEMS) sensors and are all located on the main circuit board of the iPhone 5. The relevant MEMS sensors include an accelerometer, gyroscope, electric compass, and GPS, which provide raw data of translational acceleration, angular velocity, geomagnetic compass heading, and location coordinates, respectively. The axes of the iPhone are shown in Figure 9.

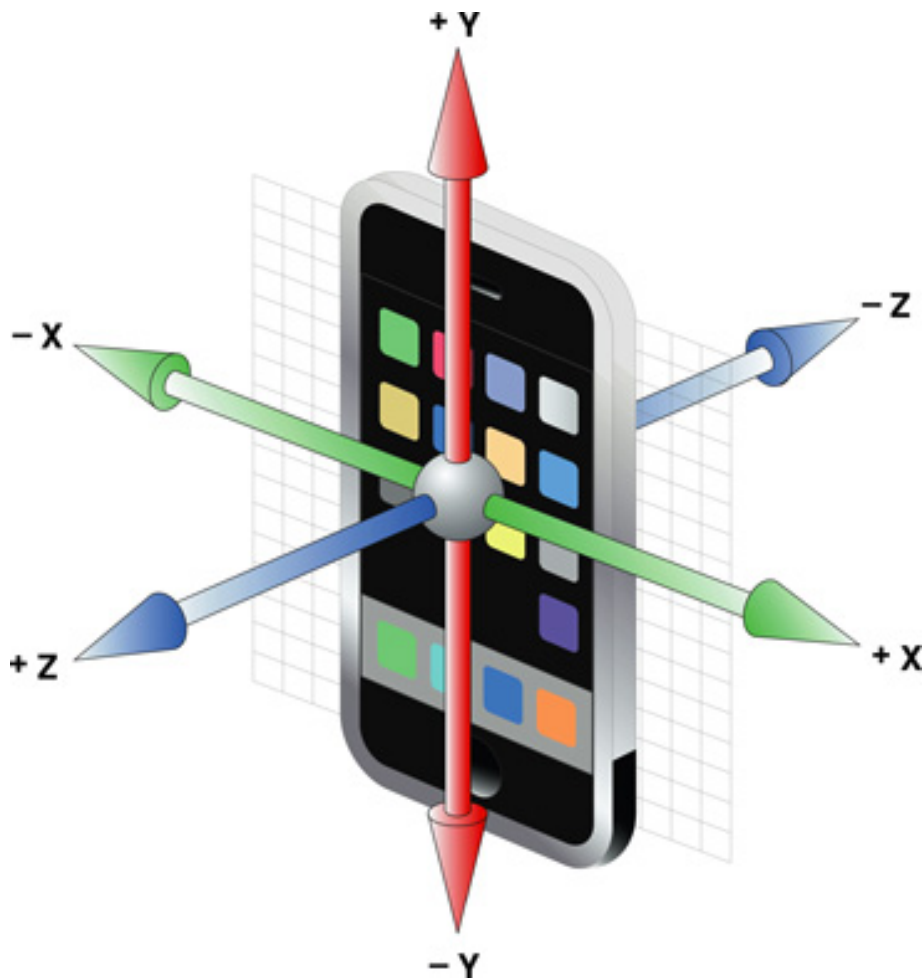


Figure 9. iPhone motion axes.

Inertial sensors present the key ingredient for the herein described concept of a mobile flight tracking and monitoring system, which assists in what could be called remote flight instruction. It should be noted that a significant amount of data preprocessing such as integration of angular velocity and amplification takes place on the hardware level of the iPhone. A series of filters are used to eliminate sensor-specific noise and to reduce the amount of sensor bias. Signal conditioning is performed by a dedicated integrated circuit. Many sensors are combined with application-specific integrated circuits (ASCIs). Figure 10 shows an ASCI attached to the top of the accelerometer used for the iPhone 5. Exact details of sensors, oftentimes undisclosed by the manufacturer, would also exceed the scope of this work and detract from its primary purpose. Details of relevant sensors are discussed in the following pages of this section.

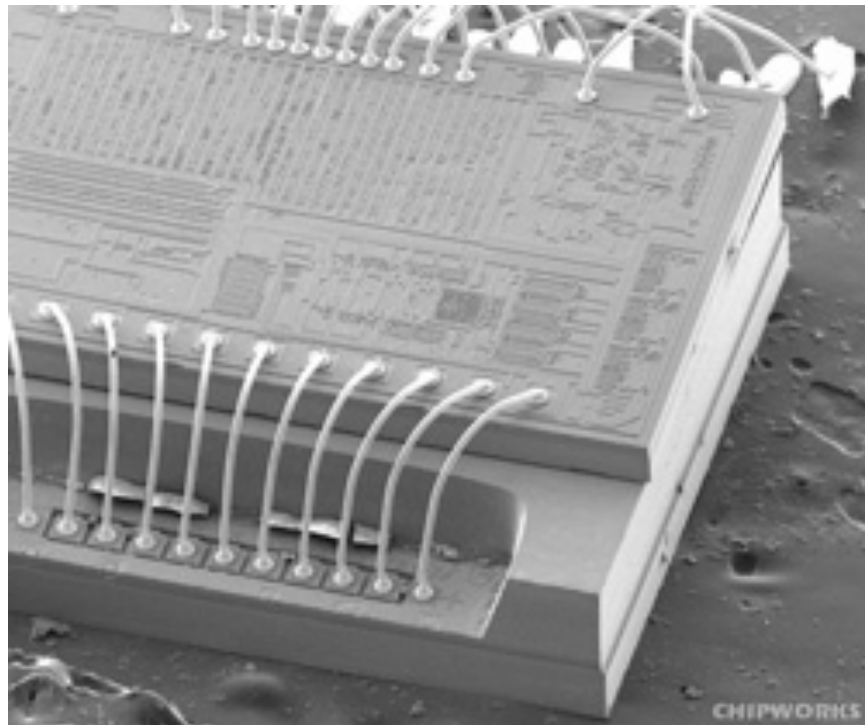


Figure 10. iPhone accelerometer with ASCI chip (courtesy of Chipworks Inc.).

## Accelerometer

The iPhone 5 features the LIS331DLH (STMicroelectronics), a three-axis MEMS digital accelerometer shown in Figure 11. Unlike conventional spring-loaded accelerometers, the LIS331DLH relates acceleration to the displacement of a proof mass.

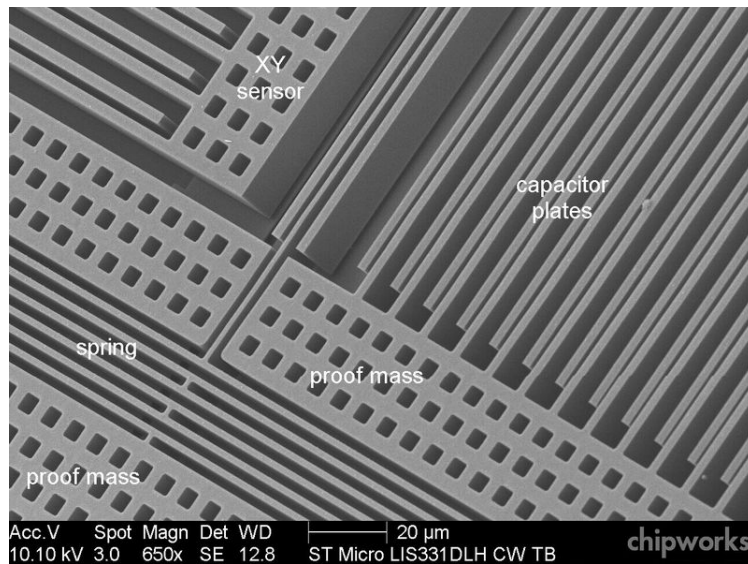


Figure 11. LIS331DLH teardown (courtesy of Chipworks Inc.)

Once the iPhone is accelerated, this displacement results in a deflection of capacitive half bridges and hence a change in capacitance. This capacitive differential is detected, amplified, and converted to a digital output signal, which can then be utilized by various device applications.

Sensor specific performance characteristics are listed in Table 2.

TABLE 2

LIS331DLH SPECIFICATIONS

Parameter	Minimum	Typical	Maximum
Measurement Range (g)		±2.0	
Sensitivity (mg/digit)	3.5	3.9	4.3
Sensitivity Change vs. Temperature (%/°C)		±0.01	
Typical Zero-G Level Offset Accuracy (Mg)		±20	
Zero-G Level Change vs. Temperature (Mg/°C)		±0.1	

## Compass

With the release of the iPhone 5, Apple introduced the latest generation three-axis MEMS digital compass manufactured by Asahi Kasei Microdevices, which is shown in Figures 12 and 13. The AK8963 is a high-resolution sensor that transduces geomagnetic fields into output voltage, providing the iPhone with fast and accurate heading information. AK8963 specifications are shown in Table 3.



Figure 12. AK8963 digital compass (courtesy of Asahi Kasei Microdevices Corp.).

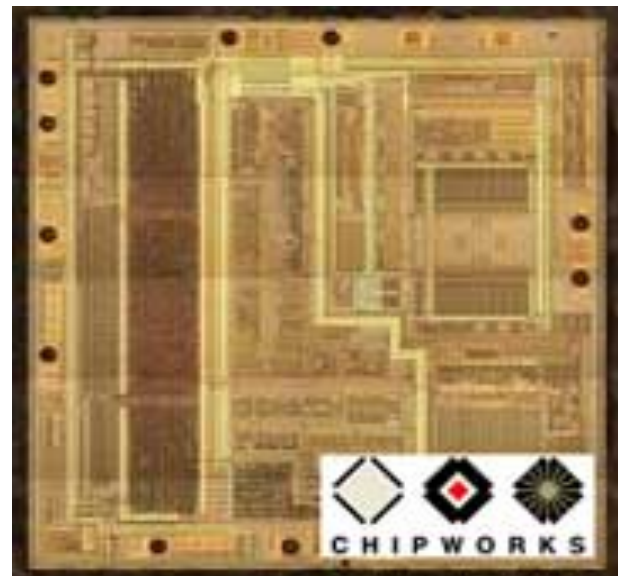


Figure 13. AK8963 die (courtesy of Chipworks Inc.).

TABLE 3

AK8963 SPECIFICATIONS

Parameter	Minimum	Typical	Maximum
Measurement Range ( $\mu\text{T}$ )		$\pm 4900$	
Resolution ( $\mu\text{T}$ )		0.6	
Operating Temperature Range ( $^{\circ}\text{C}$ )	-30		85
Product Dimensions (mm)	1.6 x 1.6 x 0.5		

## GPS

The Qualcomm RTR8600 is a multiband/mode RF receiver used on the iPhone 5, which serves as a multifunction communication device. It provides location data to the user using assisted GPS (A-GPS) technology wherein cell towers and mobile hotspots are also incorporated to provide a complimentary source of location data when the satellite reception is poor or not available. Additionally the RTR8600 combined with the MDM9615M, shown in Figure 14, provides a high-speed data link based on the 4G LTE communications standard. Even though data packets that are relayed to a target device are relatively small, a high-speed up/downlink allows for an increased sampling rate to improve the representation of orientation and location.

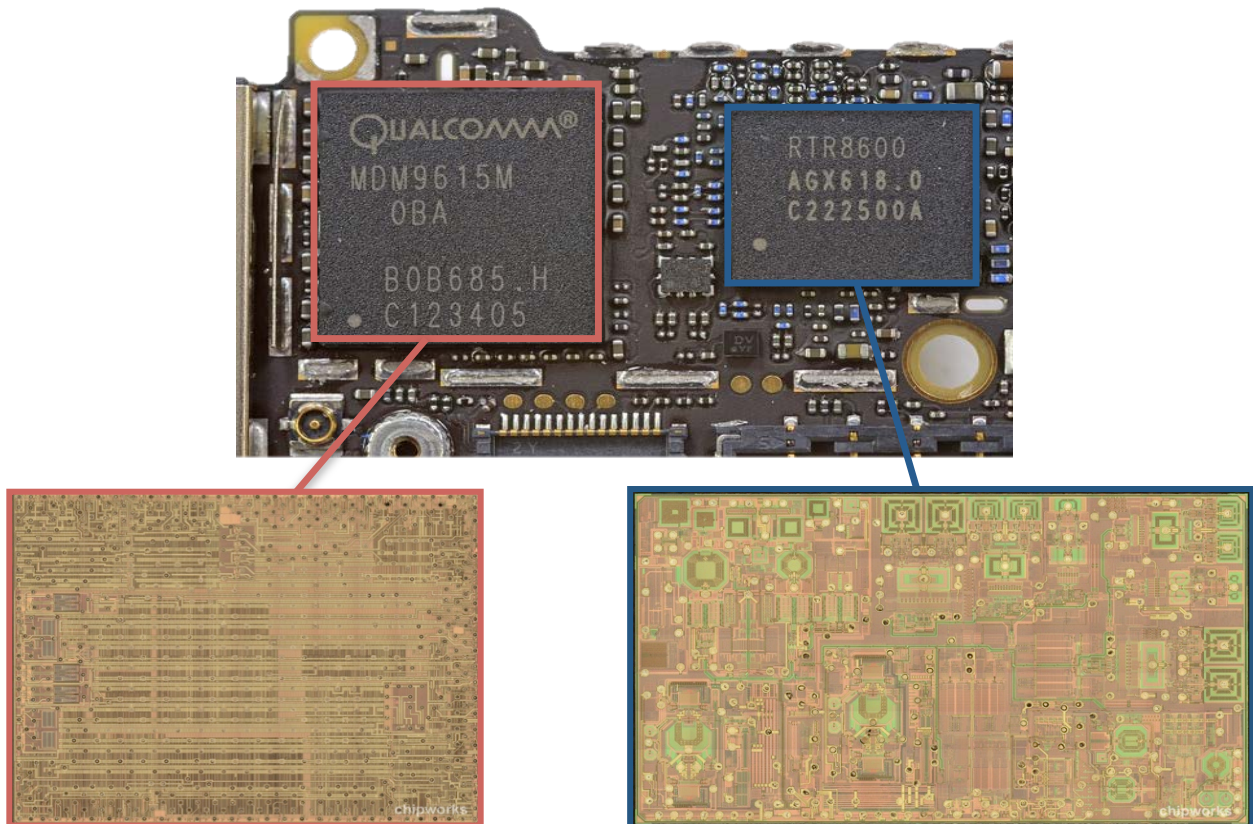


Figure 14. iPhone 5 main circuit board (partial view, courtesy of Chipworks Inc.)  
MDM9615M die (left), RTR8600 die (right).

## Gyroscope

The L3G4200DH (STMicroelectronics) motion sensor shown in Figure 15 is a three-axis MEMS digital gyroscope. Due to very recent developments in MEMS technology, gyroscopes are relative new to consumer electronics. Unlike the previously discussed compass and accelerometer, a gyroscope does not measure external inputs such as magnetic fields or gravity. Gyroscopes detect angular velocity based on the device rotation. It should be noted that MEMS gyroscopes used in consumer electronics do not exhibit an actual rotation. Instead they contain rapidly oscillating MEMS structures that are stimulated by the Coriolis effect.

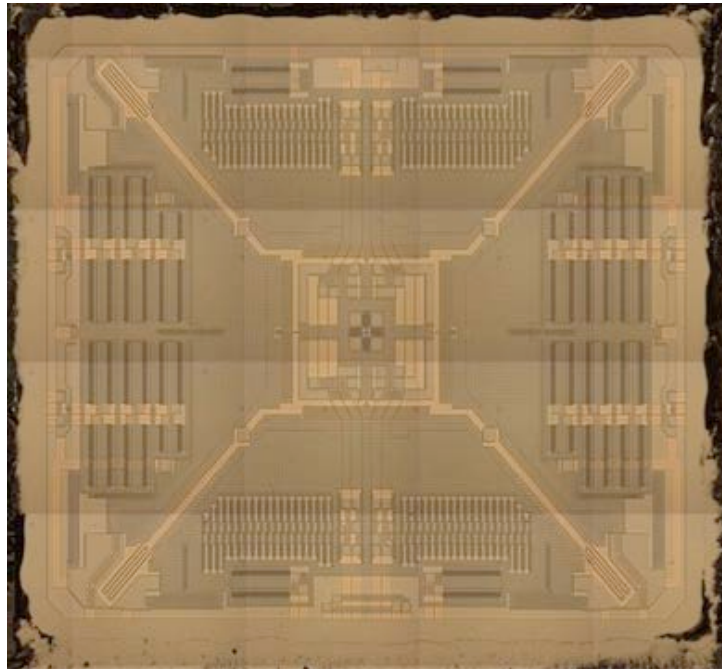


Figure 15. L3G4200DH die (courtesy of Chipworks Inc.).

The induced force component flexes the internal structure and promotes a change in capacitance. The capacitive differential is then related to the shift in the external reference frame, which provides an angular velocity output. Figures 16 and 17 show the axis definitions and microscopic close-up of the gyroscope, respectively.



Figure 16. L3G4200DH axis orientation.

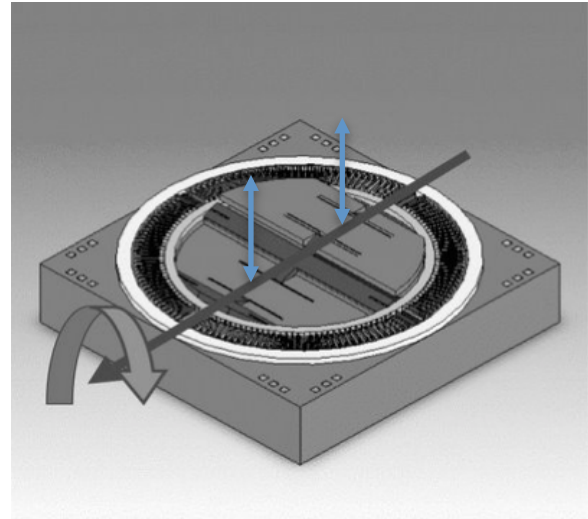


Figure 17. MEMS digital gyroscope.

TABLE 4

L3G4200DH SPECIFICATIONS

Parameter	Minimum	Typical	Maximum
Measurement Range (dps)		±250, ±500, ±2000	
Sensitivity (Mdps/digit)		8.75, 17.5, 70	
Sensitivity Change vs. Temperature (%)		±2	
Operating Temperature Range (°C)	-40		85
Digital Output Data Rate (Hz)		100/200/400/800	
Product Dimensions (mm)	4 x 4 x 1.1		

### 3.2 Sensor Data

In theory, the iPhone is equipped with sufficient inertial sensors to provide the flight instructor on the ground with accurate, up-to-date information on the flight condition of his/her solo student. The iPhone's iOS and its application programming interface provide a gateway to access raw accelerometer, gyroscope, and magnetometer data by using CMMotionManager, an iOS framework that delivers device motion data. During the initial phase of research, a third party iPhone application was purchased and utilized. "Sensor Data," released by Wavefront Labs

[17], is a user friendly and versatile data collection tool. This application provided all the basic features needed for proof of concept and initial testing but also exhibited several weaknesses, in particular those related to resolution and accuracy of sensor data. In order for the flight instructor to properly evaluate a student's performance during flight or in a post-flight debriefing, it is important to minimize delays during data collection and transmission. Initial testing revealed such delays and sampling-rate constraints, and strongly suggested a focus on performance improvements during the development phase of the system. These improvements include the correction for drift and tilt errors, which are described in the following section.

### **3.3 Drift, Sensor Fusion**

Determining and representing orientation based on raw sensor data is a challenging task in itself. A mathematical model of a dynamic system is almost always bound to yield uncertainties and errors. Additionally, sensor bias and input noise only amplify output error. For example, turn rate, the native output of a primitive gyroscope, is in itself inadequate to determine the orientation of the aircraft. In order to obtain Euler angles, the rotation rate must be integrated with respect to time. The integration process, however, evokes a negative mathematical side effect that is characteristic of all systems that obtain direction by integration of angular velocity. Aircraft vibration and other noise become part of the integrand and contribute a drift error to the output heading. Figures 18, 20, and 22 show ambient noise within the angular velocity measured by the iPhone's internal gyros about the X, Y, and Z axes of the body fixed-axis system (note that the raw data was collected by a prototype of CFiTrack). Integrating turn rate with respect to time creates a relatively clean and fast response of the desired angular output. However, by itself, it is an inaccurate representation of orientation. The integration of noise essentially results in substantial drift, as can be seen in Figures 19, 21, and 23.

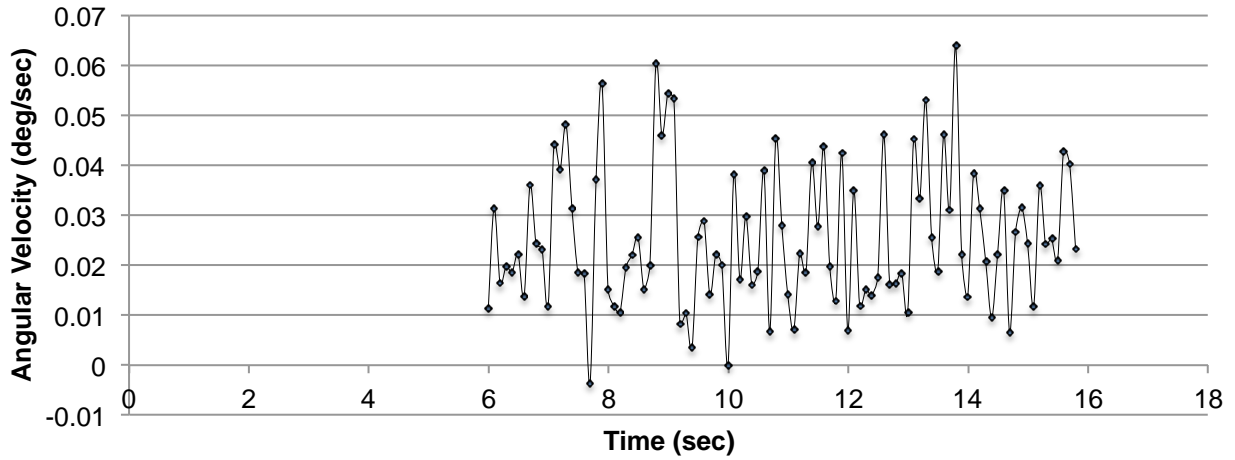


Figure 18. Angular velocity about X-axis.

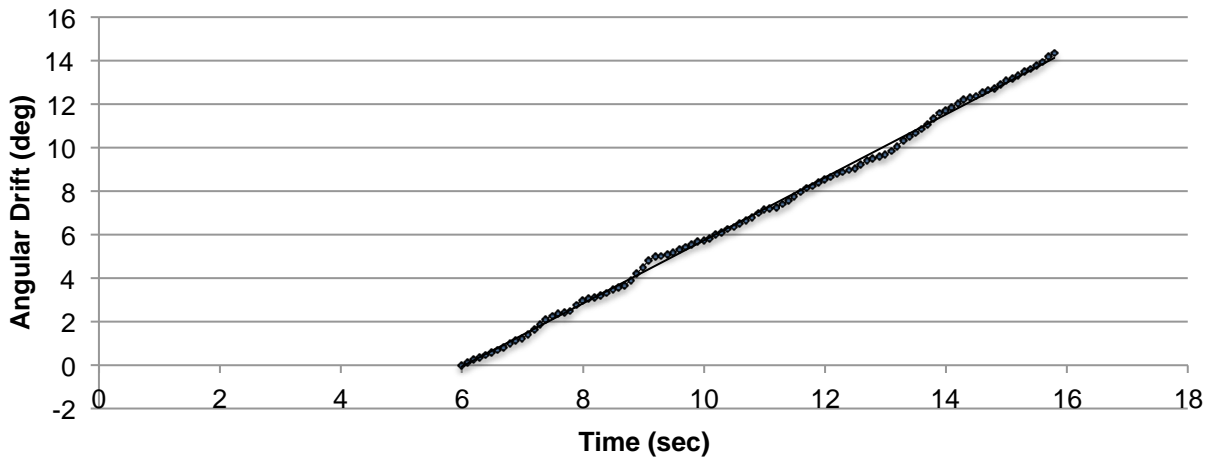


Figure 19. Angular drift about X-axis.

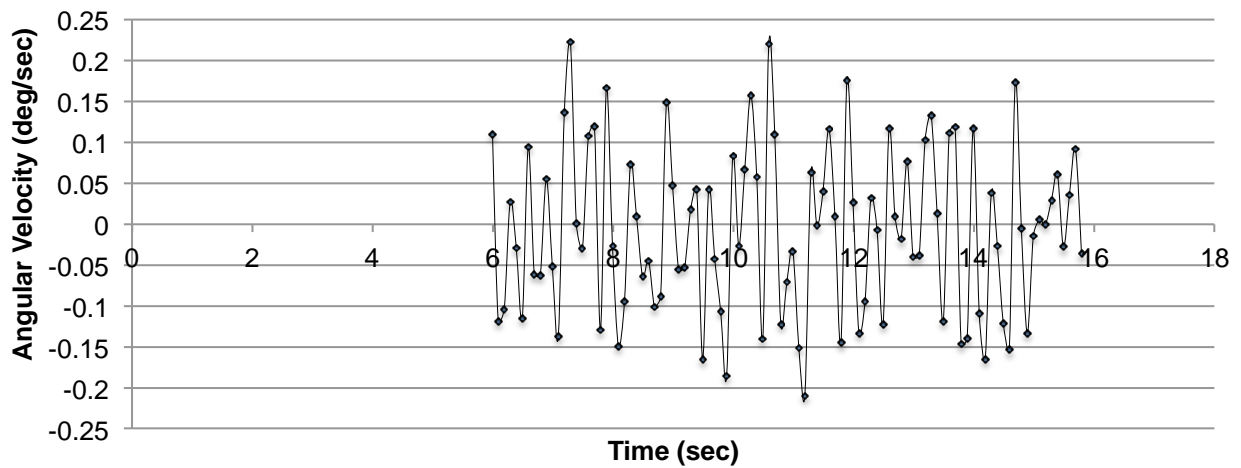


Figure 20. Angular velocity about Y-axis.

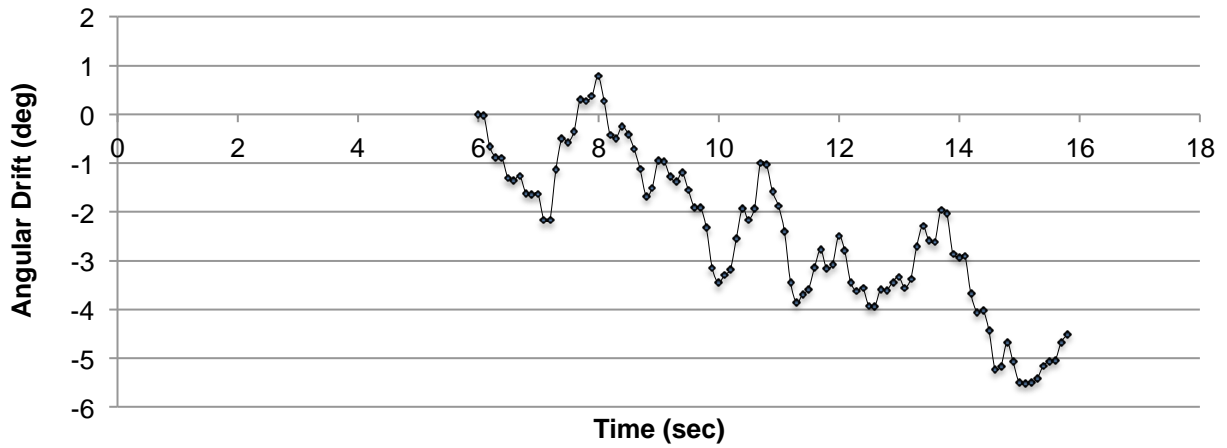


Figure 21. Angular drift about Y-axis.

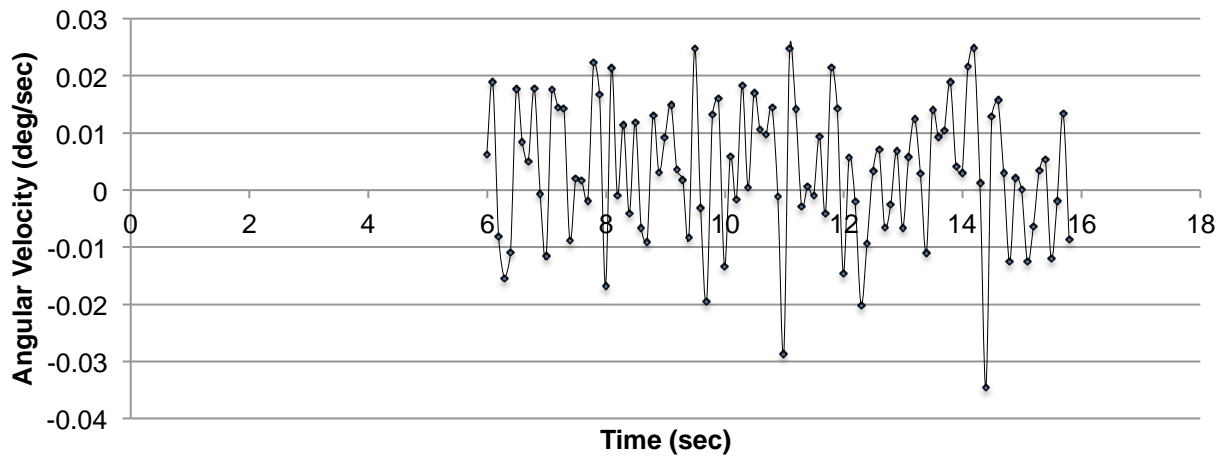


Figure 22. Angular velocity about Z-axis.

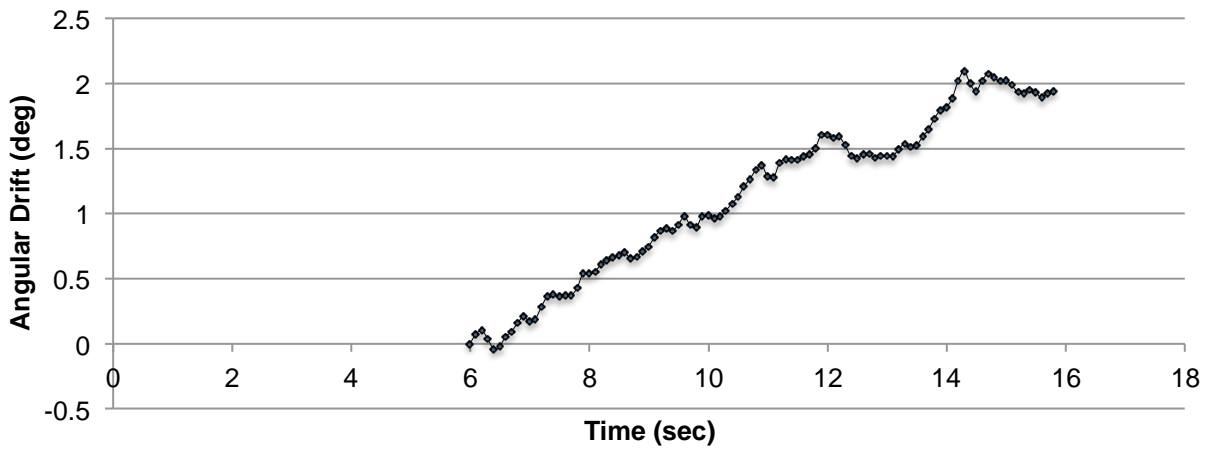


Figure 23. Angular drift about Z-axis.

Apart from drift, the gyroscope by itself is not capable of converting from the body fixed-axis system to the earth fixed-axis system and, therefore, cannot relate the angular output to orientation relative to the earth fixed-coordinate system. The resulting angle would present a heading change, rather than a desired absolute heading with respect to magnetic north. Other sensor components such as the magnetic compass and the accelerometer exhibit similar error characteristics. Unlike the rotation derived from the gyroscope, the output signal of the magnetic compass is fairly noisy. This noise is mostly attributed to environmental magnetic pollution and the absence of output integration as was done for the gyroscope.

To accommodate both error correction for sensor bias and a reference frame connecting earth and body fixed-axis systems, research was directed towards sensor fusion. Sensor fusion refers to the strategic consolidation of select sensor data for optimized performance and accuracy. To obtain a fast response, yet an accurate representation of the iPhone's orientation, Apple introduced internal the *Core Motion Framework*, which is located on the hardware level for faster processing. Within this framework, the iPhone calls on various device components to provide the most accurate representation of its orientation and motion. Within the core motion algorithm, the iPhone will routinely correct sensor bias by referring to the remaining sensors. To obtain a heading, the iPhone will initially apply the integrated gyroscopic turn rate to its most current orientation. It will then correct the resulting heading with data obtained by the magnetic compass. This allows for a fast short-term response achieved by the gyroscope, while reducing drift and maintaining a reliable and accurate representation of the device orientation. Ordinary mechanical compasses are limited to four degrees of freedom (DOF), which include translational motion along the longitudinal, lateral, and vertical axes, as well as rotation about its vertical axis. However, rotation about the longitudinal or lateral axis is very limited, because it results in dip

errors or total loss of indication. In order to provide the user with an unrestricted three-dimensional six DOF compass, which does not rely on proper positioning of the device, tilt compensation must be accomplished. The concept of a three-dimensional compass is also achieved by sensor fusion. In this case, the accelerometer and gyroscope provide the necessary tilt compensation, thereby allowing compass data for heading information during accelerated or non-level flight conditions such as climbs, descents, and turns.

### **3.4 Data Processing**

A central part and goal of the first development phase was to interface an iPhone with X-Plane and visualize the motion of an iPhone using a flight simulator. In lieu of joystick inputs, the iPhone would provide orientation and location data to the computer on the ground. Prior to developing the actual software, a third-party application, Sensor Data [17], which was described in section 3.2, was utilized to extract device motion data from the iPhone. Using third-party software was a fast and cost effective way to determine whether the concept of tracking the motion of an aircraft would be achievable with a smartphone device. This application has a built-in feature that allows for data to be streamed conveniently to a target computer using user datagram protocol (UDP) packets at a desired sampling rate between 1 and 100 Hz. All applications provided by the Apple App Store are proprietary, closed-source software. Hence, raw data that was streamed by Sensor Data could not be broken down or formatted prior to transmission to the ground station. In order to assure proper transmission and an ideal sampling rate and to obtain an understanding of the format in which the incoming data packets were supplied, a simple python script was used to sort the incoming data and write it to a comma-separated values (CSV) file. The data was generated by mounting the iPhone to a disk, which

was rotating at calibrated rate of 16 RPM. Figures 24 and 25 show an antique record player in combination with a custom-built iPhone 5 mount, which served this purpose well.



Figure 24. Rotation test about Z-axis.



Figure 25. Rotation test about X-axis.

The data was collected at a sampling rate of 10 Hz and plotted over time to depict one entire rotation. The resulting curve was then compared to a target curve, which was obtained from the record player's nominal rate of rotation of 16 rotations per minute (RPM). Figure 26 shows the rotation about the Z-axis. Rotations about the X and Y axes show identical results but are not depicted here.

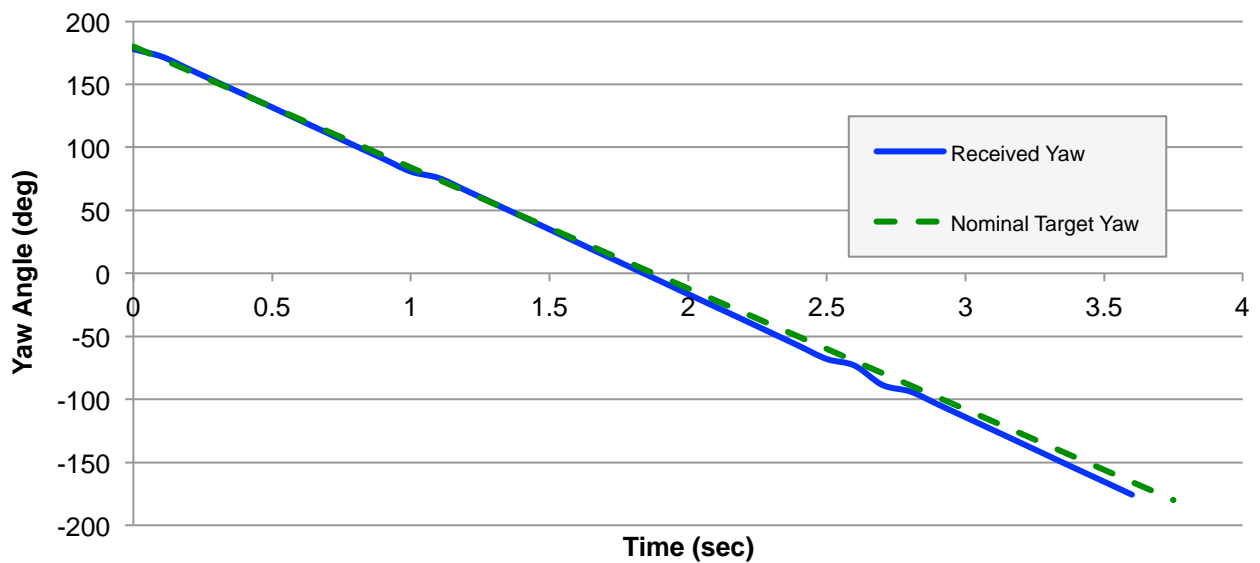


Figure 26. Yaw angle received by ground station compared to target value.

This preliminary test demonstrated that the motion data, which was collected by the iPhone at a 5 Hz sampling rate matches very well with the actual nominal 16 RPM rotation of the record player. Based on the sensor analysis and the preliminary testing, the decision was made to move forward with the design and building of a prototype iPhone application. Design considerations and details of the algorithms and techniques used for the program structure and testing are discussed in the Chapter 4.

## **CHAPTER 4**

### **CONCEPT REALIZATION AND TESTING**

The design and development of CFiTrack involved a significant amount of programming work and the implementation of Objective C, a superset to the common C programming language. Furthermore, a series of preliminary and intermediate tests were conducted to verify the feasibility of the system. This chapter will describe the successive development of the CFiTrack prototype.

#### **4.1 Programming the Application Prototype (CFiTrack)**

For the iPhone and all other iOS- and OSX-based products, Apple provides a comprehensive software development kit that facilitates the development of multifaceted iOS and OSX applications. Xcode, is a versatile integrated development environment (IDE), which allows the compiling and testing of source code on the fly on either a built-in simulator or an actual device. All iOS applications are written in Objective C, an object-oriented programming language. Over the years, object-oriented programming has proven to be an efficient and well-organized equivalent to procedure-based programming. Rather than sequencing a multitude of functions and conditional statements for a given program, Objective C defines objects needed within the program and associates functions and variables with those objects. Doing so promotes the concept of inheritance by which objects inherit capabilities in the form of functions, variables, etc. defined for their super class. Each object can then override inherited class properties. When compared to process-oriented languages, Objective C's most striking attributes are its flexibility, modularity, and simplicity. The model-view-controller architecture provides separation between the program logic (model), presentation layer (view), and controller logic. Doing so assures a more manageable and organized program structure.

A milestone was reached in February of 2013 when the first prototype of CFiTrack was completed and successfully tested. Unlike the third-party software that was initially utilized, the CFiTrack iPhone application was tailored specifically for the purpose of tracking and streaming flight data using `CMMotionManager`. The source code was developed and optimized for this purpose, resulting in significant performance enhancements, which are described later on in this chapter. The program code follows a very intuitive sequence: First, all resource-related objects are imported into the project, namely the *CoreMotion* and *CoreLocation* algorithm. Both supply pertinent sensor data and are accessed through the motion and location manager. After a simple conversion from radians to degrees, CFiTrack displays motion, location, and orientation data on the screen. The motion data consists of groundspeed as a function of longitudinal and lateral displacement. It also includes position data (longitude and latitude) and orientation data ( $\psi$ ,  $\theta$ ,  $\phi$ ). CFiTrack simultaneously transmits the data via UDP packets to the specified IP address. An additional key component of this application is the *GCDAsyncUdpSocket.h* [18] class, a public domain networking framework. Once imported, it provides the required class to run the UDP socket and the communication flow between the iPhone and the target computer. A text field allows the user to conveniently specify the IP address of the ground station without having to recompile the application.

CFiTrack features many advantages over the generic iPhone application that was used for preliminary testing. First, additional required steps of preprocessing the motion data on a second computer were incorporated into the current prototype of CFiTrack. The consolidation of data collection, processing, and broadcasting mitigates the transmission delay, which in turn allows for higher sampling rates of now 20 Hz. The overall location accuracy was improved as well. The iOS program structure provides the following location accuracy constants: “Best for

Navigation,” “Best,” “Nearest Ten Meters,” “Hundred Meters,” “Kilometer,” and “Three Kilometers.” Setting the constant to the highest possible and most precise value of “Best for Navigation” assures optimal lateral and vertical accuracy. While this setting also results in increased current draw, it provides invaluable precision in tracking the location of the aircraft. To reduce battery usage while running CFiTrack, a provision in the source code allows CFiTrack to run in the background without falling into a suspension mode. Due to its rather simple architecture, CFiTrack has proven to have very stable and reliable performance characteristics. It has not exhibited any software crashes since the completion of the prototype in late February.

#### 4.2 Ground Station Interface/X-Plane Integration

As mentioned previously, the Sensor Data application played an important part in determining the feasibility of the concept. During initial testing it was used to send raw motion data from the iPhone to a second computer for reformatting.

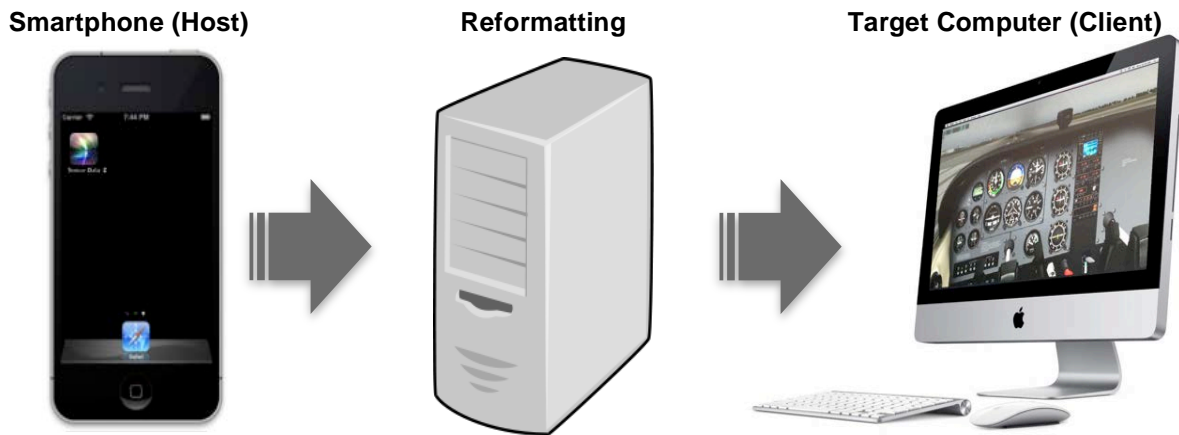


Figure 27. Proof of concept with intermediate processing.

The incoming data was parsed on a separate re-formatting computer (Figure 27) using a script written in Python. The data was sorted into location: longitude, latitude, and altitude as well as

Euler angles for pitch, roll and yaw:  $\psi$ ,  $\theta$ ,  $\phi$ , in order to conform to a format used in the simulation. Once completed, the intermediate processing unit would turn over the parsed data to the target computer for simulation. By incorporating the data handling into the prototype of CFiTrack, this intermediate processing step was avoided, as shown in Figure 28.

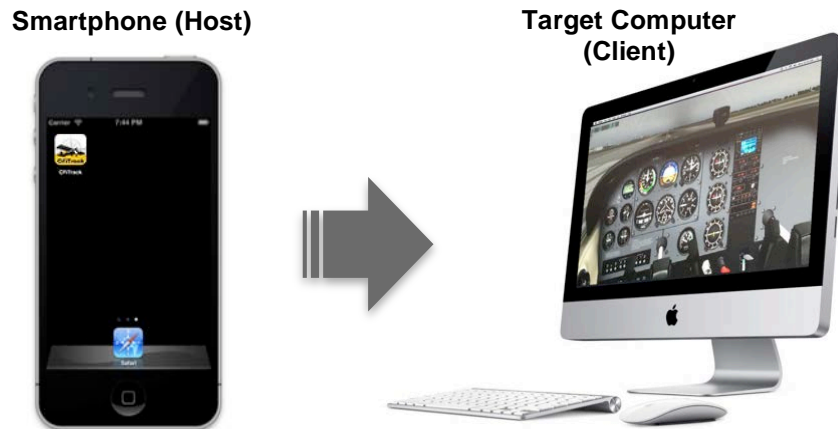


Figure 28. Direct streaming to client.

CFiTrack processes the data internally and sends it to a target computer where, using X-Plane, it visualizes the location, orientation, and movement of the aircraft [19]. With its unique, modular architecture, X-Plane allows for a highly customizable flight simulation platform. Modular plug-ins and a versatile software development kit (SDK) enable the user to modify the user interface, import custom scenery and aircraft, and much more. X-Plane also features a data-input structure that supports external input data. When connected to the Internet, the ground station can be located anywhere in the world and receive aircraft data via UDP packets. Note that in order to allow communication between the iPhone and the ground station, the target computer must have a public IP address. Often the local router/firewall must be configured to permit incoming traffic to pass through and reach the target computer that is running X-Plane. Once

proper traffic permissions are assured, no further setup of either iPhone or target computer is required. The initial interfacing was conducted using X-Plane's built-in data input structure and without the use of a custom plug-in. X-Plane detects and displays incoming UDP traffic automatically.

On a side note, this notion suggests that there are no security provisions in place to protect X-Plane from unwanted UDP traffic. Anyone could control any X-Plane session without authentication, simply by knowing the computer's IP address and the well-documented data-input structure. The aircraft model then acts in slave mode and is controlled solely by incoming UDP traffic. Local control inputs, such as joystick or keyboard commands, are bypassed and superseded by the iPhone's motion data.

This UDP data structure in itself is relatively compact and simple to implement. Reformatting the motion and location data is performed in only six lines of code and integrated into the iPhone application. The aircraft is moved to a new position and orientation at a sampling rate of 20 Hz. Using this method, as opposed to using a custom plug-in, however, has its disadvantages: In order to represent the aircraft accurately, X-Plane requires incoming data packets to be delivered in a specific format. This format is unique to the version of X-Plane and subject to change, provoking compatibility conflicts in any future releases. Also, during initial testing with the built-in data input structure, the airplane was exhibiting performance deficiencies that are discussed in section 4.3 on preliminary testing. To assure compatibility and provide a more accurate representation of the aircraft, a custom plug-in was written to receive incoming UDP packets from CFiTrack. The incoming flight data is written to select data sockets, also referred to as datarefs. These datarefs are the control points for the entire simulation and include aircraft motion and location as well as instrument indications and more. The plug-in was written

in C code and is not universally compatible. It must be compiled and executed on the same system platform as the unit running X-Plane. Using a plug-in as opposed to the previously used UDP data input structure assures higher-version compatibility with future X-Plane releases. Disabling the flight dynamics engine of the model prevents interference with the input data. Selected key components of the plug-in code for the example of the input roll angle  $\Psi$  are shown below:

```
//find datarefs
PhysicsEnableDataRef =
XPLMFindDataRef("sim/operation/override/override_planepath");
YawDataRef = XPLMFindDataRef("sim/flightmodel/position/psi");

//Disable the X-Plane Physics Engine
int IntVals[1];
IntVals[0] = 1;
XPLMSetDatavi(PhysicsEnableDataRef, IntVals, 0, 1);

//check the UDP socket for received packets
addr_len = sizeof their_addr;
errno = 0;
if ((numbytes = recvfrom(sockfd, buf, MAXBUFLen-1, 0,
    (struct sockaddr *)&their_addr, &addr_len)) == -1) {
    if(errno == WSAEWOULDBLOCK) //there is no data
        return -1.0;
}

//Set Datarefs
double x,y,z;
xplane_data* xpd = (xplane_data*) buf[9];

// Translate lat, long, and alt to local coordinates x,y, and z
XPLMWorldToLocal(xpd->lat,xpd->lon,xpd->alt,&x,&y,&z);
XPLMSetDataf(RollDataRef, xpd->roll);
```

### 4.3 Preliminary Testing

Prior to full-scale prototype testing, a series of preliminary tests was conducted to ensure proof of concept, and verify proper communication and adequate sensor outputs. During the initial testing, third-party applications were used for performance evolution.

The iPhone's ability to determine its location while airborne was tested using *GPS Tracks* by DMorneault Navigation. For this test, a well-defined traffic pattern was flown at low altitude and graphically recorded on a map within the application. Figure 29 shows the rectangular course that was flown at the Newton City-County Airport. Figure 30 shows a close-up view of the touchdown zone.

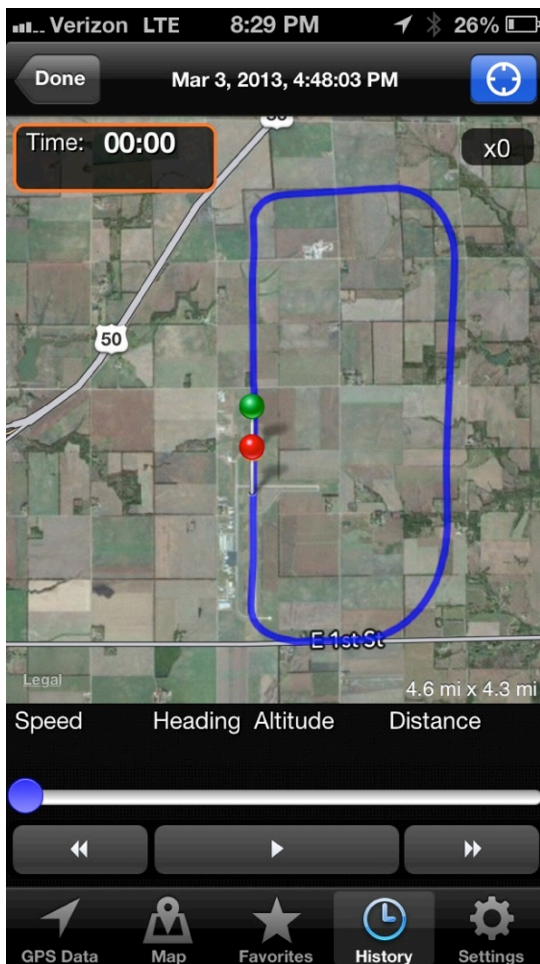


Figure 29. Lateral accuracy test.

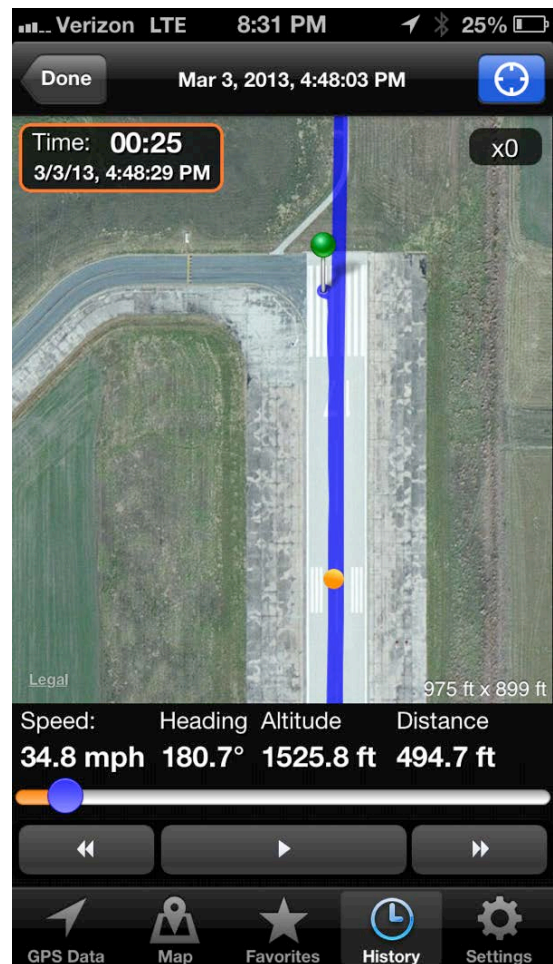


Figure 30. Close-up of takeoff and landing.

The pattern consists of a southbound departure, crosswind, downwind, base, and final leg. The position at the green pin shows the starting point of the recording, while the position at the red pin concludes the recording after rollout with the aircraft at a complete stop. A close-up view, shown in Figure 30 suggests a high level of lateral accuracy during the takeoff roll as well as during the most critical landing phase. The amount of precision with which the iPhone performed was more than satisfactory and fully supported the feasibility of a smartphone-based system for flight tracking.

Wavefront Lab's Sensor Data was used to send position and motion data to X-Plane. This second stage of the preliminary testing validated the iPhone's capabilities of streaming data from all relevant sensors to a target computer via the mobile network. It also provided very conclusive insight on the ability to interface the iPhone and X-Plane. The first series of test runs was performed in a car to test connectivity and show lateral and vertical accuracy. Figure 31 shows the iPhone placed on the dashboard, lining up its Y-axis with the car's longitudinal axis.



Figure 31. Preliminary testing, vehicle setup.

The simulation was started and recorded on the target computer. The starting point of the preselected route was a parking lot on the Wichita State University campus. The endpoint was located approximately 2.5 miles east and 2.5 miles south of the starting point (Figure 32).

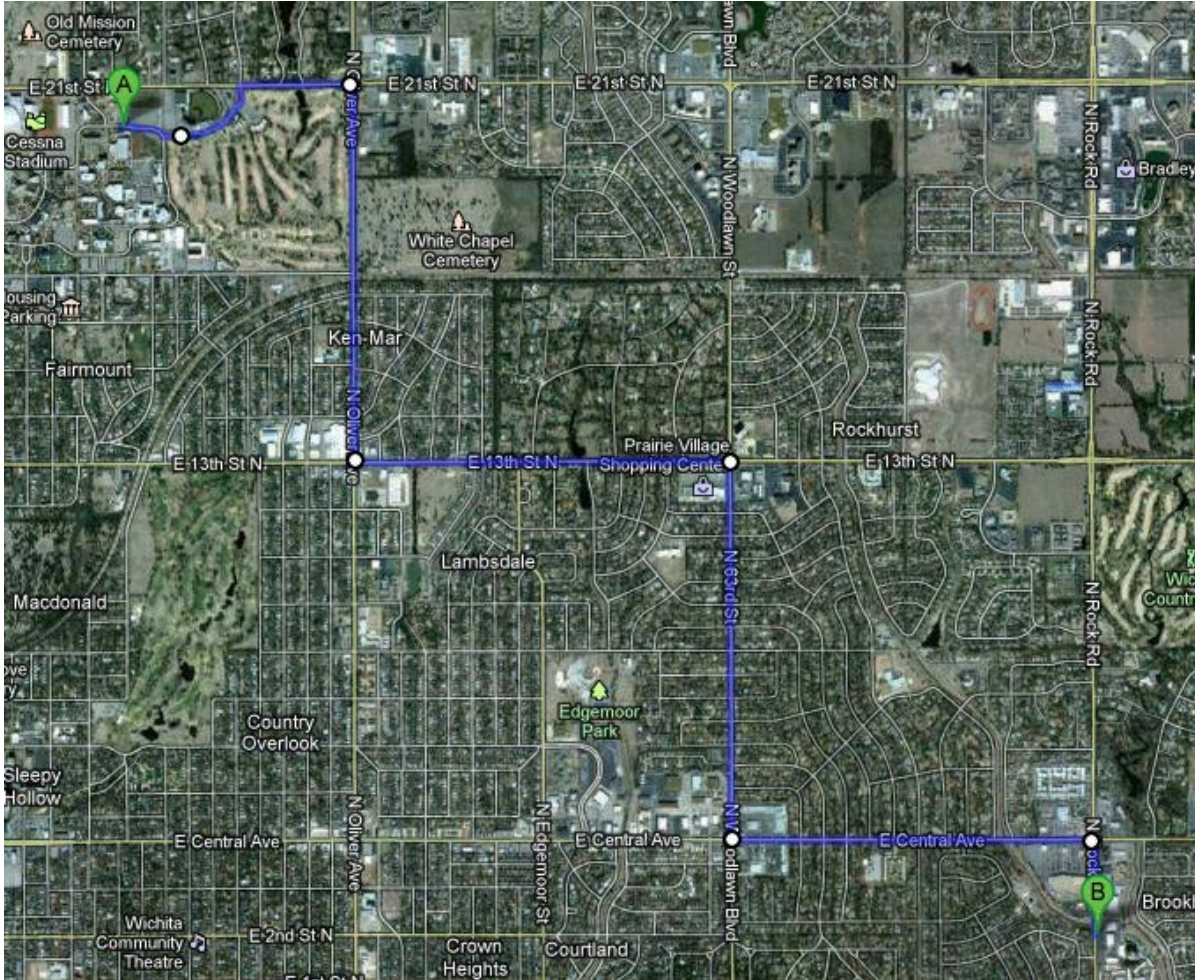


Figure 32. Tracking results of preliminary testing.

For the test, the vehicle commenced on its route while sending data to a computer located on campus. X-Plane successfully visualized the test drive as a semi two-dimensional displacement of a Cessna 172. The position accuracy was acceptable, even though the aircraft was occasionally miss-mapped. Altitude accuracy fluctuated causing X-Plane to project the model below the ground surface. The reason for these phenomena was discovered to be related to the

accuracy setting with which the Sensor Data application was designed and compiled and is not adjustable. With the introduction of CFiTrack, this setting was optimized for best results, mitigating the issue of vertical miss-mapping. The overall responsiveness of the displayed aircraft during turns and frequent stops was more than adequate. Unfortunately with the application configuration at the time, sampling rates were limited to 2 Hz, resulting in slight-to-moderate delays and significant hysteresis in restoring level flight. An intermittent tendency of adverse pitch, roll, and yaw recovery was first assumed to be caused by gyroscopic drift. Further investigation concluded that this effect should most likely be attributed to a sampling rate mismatch and interference of incoming motion and location data with X-Plane's internal physics engine. A custom X-Plane plug-in improved the performance of the simulation but was not introduced until later on in the full-scale prototype testing of CFiTrack.

#### **4.4 Preparation for Full-Scale Prototype Testing**

Developing procedures to test the three-dimensional accuracy of an aircraft simulation model has indubitably posed a noteworthy level of difficulty. Finding a common reference between the actual airplane and the simulation turned out to be most challenging. For example, while in motion, it is nearly impossible for a pilot to determine the exact position and altitude of the airplane by instruments and outside references. This raises the question of how accurate flying visually (VFR) and not solely by instruments or instrument flight rules (IFR) actually is. Even modern instruments have fairly crude resolutions and are subject to various errors. Without the exact and synchronized location and orientation, it is very difficult to compare the motion of the actual aircraft to the X-Plane model. This is due to the lack of a datum or reference that provides a measure for deviation of the aircraft to the model. This effect is even more prevalent at higher altitudes with fewer visual outside references than near the ground. However, the

accuracy during the cruise flight at altitude is not as critical as during takeoff and landing when the aircraft is near the ground. Hence, the main focus during testing for accuracy and reliability of the system should be directed at terminal procedures (arrival/departure) near the airport. During this flight phase, the aircraft performs at higher angles of attack and executes more banking turns than during cruise, creating performance limits at which the iPhone must perform.

The simplest way of comparing the actual aircraft to the simulated model was during taxiing on the ground and ground roll. The advantage over the previously performed preliminary testing in a car is X-Plane's detailed scenery of the airport environment. Unlike roads, taxiways and runways within X-Plane are modeled precisely to match the real world, hence, providing the necessary outside reference.

Testing CFiTrack's performance while airborne during critical landing and takeoff phases was conducted using an instrument landing system (ILS), shown in Figure 33.

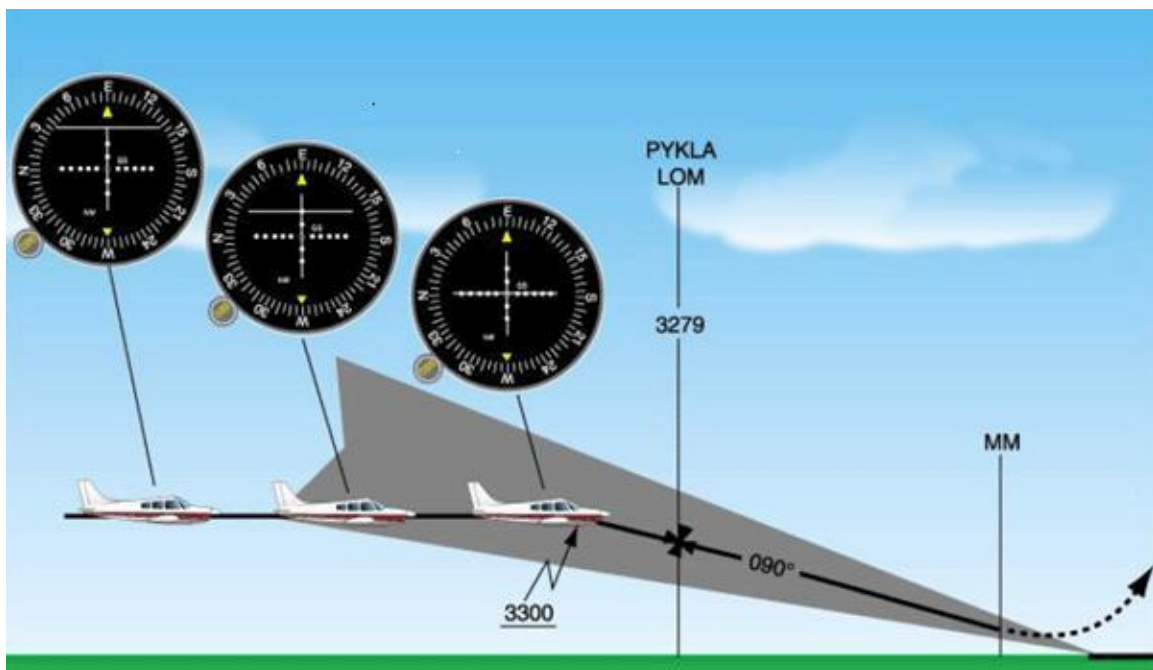


Figure 33. ILS approach system (courtesy of the U.S. Department of Transportation).

Designed for instrument approaches, this ground-based landing system provides lateral and vertical guidance to airplanes equipped with localizer and glideslope displays. To assure a proper flight path, the pilot simply has to align the localizer and glideslope needles with the crosshairs by appropriate control inputs (Figure 33). Doing so assures lateral guidance and a 3° glideslope to the touchdown zone. This method provided a visual reference to the test pilot, allowing him to fly a precise approach and therefore representing a baseline for the ideal landing scenario. To collect data for evaluation, random screenshots of the X-Plane's data output were taken and compared to the baseline approach.

The system performance was also evaluated at cruise altitude. The pilot would trim the aircraft at various altitudes and establish a straight and level attitude. Data points for altitude were collected from the X-Plane output screen. The steps were repeated for standard rate (2° per second) turns to determine proper bank and heading representation.

#### **4.5 Flight and Ground Testing**

Section 4.5 shows a detailed description of the ground and flight tests that were conducted to evaluate the performance of the CFiTrack application in flight and on the ground. All ground and flight tests described herein were conducted upon complete preflight inspection of the airplane. The test pilots were Georg Schirmer (commercial pilot license and certified flight instructor), Bill Kusmez (airline transport pilot and certified flight instructor), Ryan Benyshek (private pilot license), and Landon Unruh (private pilot license). Table 5 shows the type of aircraft used for flight testing, and Table 6 shows a summary matrix of the flight tests, each of which is explained later in more detail.

TABLE 5

AIRCRAFT USED FOR FLIGHT TESTING

Specification	Aircraft 1	Aircraft 2
Model	Cessna 172 P	Mooney M20E
Year	1984	1970
Serial Number	17276113	700046

TABLE 6

SUMMARIZED FLIGHT TEST MATRIX

Type	Test Condition	Objective
<b>Taxi Testing</b>	Surface, $V_{GS} < 20$ KIAS	Lateral and vertical offset, with respect to X-Plane scenery environment
<b>Traffic Pattern</b>	Low altitude (surface to 1,000 ft. AGL) $0 < V < 100$ KIAS	Position and motion offset for received iPhone output data, with respect to onboard instruments
<b>Performance Turns (Steep Turns)</b>	Minimum altitude for performance maneuvers (2,000 ft. AGL), $V_A = 99$ KIAS	Lateral, vertical orientation, and motion offset for received iPhone output data, with respect to onboard instruments
<b>Cross-Country Cruise Performance</b>	Climb out and cruise Altitude: 0 ft. AGL (1,525 ft. at KEWK) to 3,500 MSL, $V_{cruise} \approx 110$ KIAS	<ul style="list-style-type: none"> <li>Position and motion offset for received iPhone output data, with respect to onboard instruments</li> <li>Identification of performance weaknesses of A-GPS system and communication outages at higher altitudes</li> </ul>
<b>Precision Instrument Approach</b>	Published instrument approach procedure: ILS OR LOC RWY 17	Position and motion offset for received iPhone output data, with respect to onboard instruments during published approach procedure

*Ground Testing*

**Taxi Testing**

Test Condition: Surface,  $V_{GS} < 20$  KIAS

Objective: To determine an estimate of the lateral and vertical offset shown in the X-Plane simulation based on the geometry of the aircraft, with respect to the modeled scenery environment.

Procedure/Data Collection:

1. The test pilot initiates CFiTrack and verifies successful data transmission with ground station.
2. The test pilot begins the taxi roll along the taxiway marking to the best of his abilities.
3. The ground observer records the motion of the aircraft as represented by X-Plane simulation.

Data Evaluation:

In a post-flight analysis, the lateral and vertical displacements are estimated based on the visible offset between the representation of the airplane and the modeled surface.

*Flight Testing*

**Traffic Pattern**

Test Condition: Low altitude (surface to 800 ft. AGL),  $0 < V < 100$  KIAS

Objective: To determine the lateral, vertical, orientation, and motion offset shown in the X-Plane simulation based on the received input data, with respect to onboard instruments.

Procedure/Data Collection:

1. The pilot initiates CFiTrack, verifies transmission, and conducts a thorough instrument check to verify accurate readings on the ground. These instruments must include altitude, airspeed, heading, and attitude indicator gauges.
2. The pilot begins the takeoff roll along the runway centerline to the best of his abilities.

3. Once airborne, the pilot maneuvers the airplane along a rectangular pattern to include a departure, crosswind, downwind, base, and final leg.
4. Reference altitudes are 800 ft. AGL (2,325 ft. mean sea level [MSL] for KEWK) during the downwind leg, and 0 ft. AGL (varying MSL) during the ground roll
5. The ground observer records incoming data as well as the motion of the aircraft as the X-Plane simulation is representing it, and requests periodic altitude, airspeed, and heading readings from the pilot/co-pilot.

Data Evaluation:

In a post-flight analysis the lateral, vertical, orientation, and motion offsets are determined based on direct comparison of the input data to the onboard instrument indications.

**Performance Turns (Steep Turns)**

Test Condition: Minimum altitude for performance maneuvers (2,000 ft. AGL),  $V_A = 99$  KIAS

Objective: To determine the lateral, vertical, orientation, and motion offset during performance turns shown in the X-Plane simulation based on the received input data with respect to onboard instruments

Procedure/Data Collection:

1. The pilot initiates CFiTrack, verifies transmission, and conducts a thorough instrument check to verify accurate readings on the ground. These instruments must include altitude, airspeed, heading, and attitude indicator gauges.
2. After departure, the pilot navigates to an altitude of approximately 2,000 ft. AGL.

3. At altitude, the pilot will conduct a series of level 360° performance turns to include bank angles of 45° and 60°. At each bank angle, the completion of a full 360° turn is followed by a change in direction and a second 360° turn forming a figure eight for the given bank angle.
4. The ground observer records incoming data as well as the motion of the aircraft as presented by X-Plane, and requests and records periodic altitude, airspeed, and heading readings from the pilot/co-pilot.

Data Evaluation:

In a post-flight analysis, the lateral, vertical, orientation, and motion offsets are determined based on direct comparison of the input data to the onboard instrument indications.

**Cross-Country Cruise Performance**

Test Condition: Climb out and cruise altitude: 0 ft. AGL (1,525 ft. at KEWK) to 3,500 MSL,  
 $V_{\text{cruise}} \approx 110 \text{ KIAS}$

Objective: To determine the lateral, vertical, orientation, and motion offset during cruise, and to identify performance weaknesses of the A-GPS system and communication outages at higher altitudes.

Procedure/Data Collection:

1. The pilot initiates CFiTrack, verifies transmission, and conducts a thorough instrument check to verify accurate readings on the ground. These instruments must include altitude, airspeed, heading, and attitude indicator gauges.

2. After departure, the pilot navigates to an on-course heading of 172 magnetic north towards KAAO (Colonel Jabara Airport) and proceeds to climb at a desired climb rate of 300 ft./min.
3. The ground observer records incoming data as well as the motion of the aircraft as the X-Plane simulation is representing it, and requests periodic altitude, airspeed, and heading readings from the pilot/co-pilot at intervals of 500 ft. during climb out.
4. Upon reaching 3,500 ft. MSL, the test pilot proceeds on course towards the destination airport (KAAO).
5. The test concludes landing at KAAO.

Data Evaluation:

In a post flight analysis the lateral, vertical, orientation, and motion offsets are determined based on direct comparison of the input data to the onboard instrument indications.

**Precision Instrument Approach**

Test Condition: Published Instrument Approach Procedure: ILS OR LOC RWY 17 (Figure 37)

Objective: To determine the lateral, vertical, orientation and motion offset during an instrument precision approach, shown in the X-Plane simulation based on the received input data, with respect to onboard instruments and a published approach procedure.

Procedure/Data Collection:

1. The pilot conducts a thorough instrument check to verify accurate readings on the ground. These instruments must include altimeter, airspeed, heading, and attitude indicator gauges.
2. The pilot initiates CFiTrack and verifies successful data transmission with the ground station.
3. The pilot is vectored by the instructor ground via Skype to the final approach fix (FAF - Outer Marker. LOM) to begin the approach.
4. Based on flight and navigation instruments, the pilot maneuvers the aircraft as depicted in the approach plate.
5. The varied reference altitudes are depicted on the approach plate shown in Figure 34.
6. The ground observer records incoming data as well as the motion of the aircraft as the X-Plane simulation is representing it, and requests periodic altitude, airspeed, and heading readings from the pilot/co-pilot.

#### Data Evaluation:

In a post-flight analysis the lateral, vertical, orientation, and motion offsets are determined based on direct comparison of the input data received by X-Plane, the actual flight information received from the cockpit, and the desired flight path as depicted on the approach plate (Figure 34).


NEWTON, KANSAS

AL-5582 (FAA)

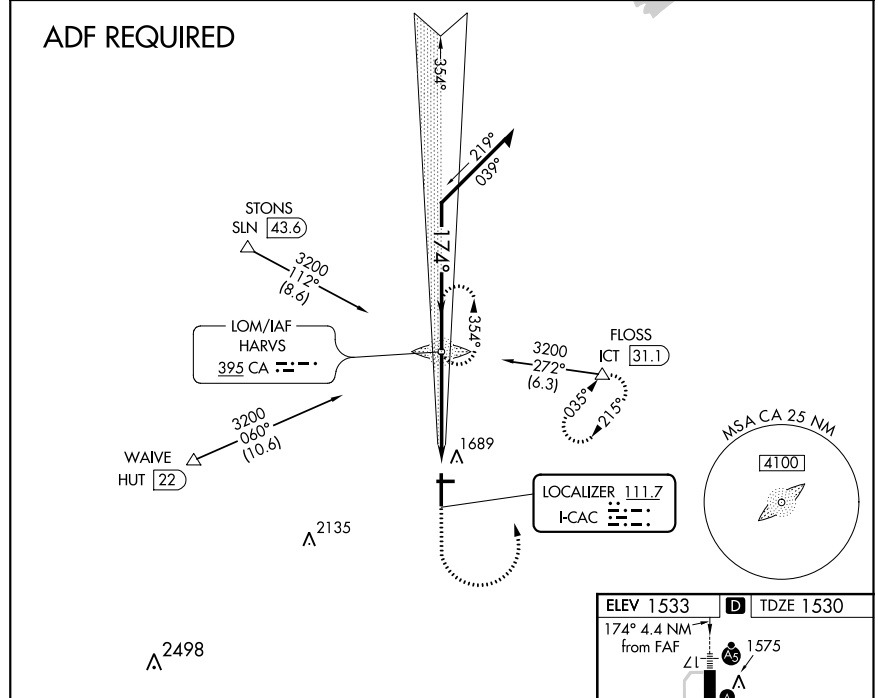
LOC I-CAC <b>111.7</b>	APP CRS <b>174°</b>	Rwy Idg <b>6705</b>
		TDZE <b>1530</b>
		Apt Elev <b>1533</b>

**ILS or LOC RWY 17**  
NEWTON-CITY-COUNTY (E/WK)

▼ If local altimeter setting not received, use Wichita Mid-Continent altimeter setting and increase DA to 1817/MDAs 100 feet. For inoperative MALSR increase S-LOC 17 Cat D visibility to 1/4 mile. ADF Required.

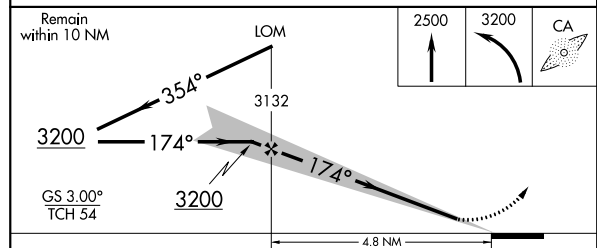
MALSR  MISSED APPROACH: Climb to 2500 then climbing left turn to 3200 direct HARVS LOM and hold.

AWOS-3 <b>123.875</b>	WICHITA APP CON <b>125.5 306.2</b>	CLNC DEL <b>126.55</b>	UNICOM <b>123.0 (CTAF) 1</b>
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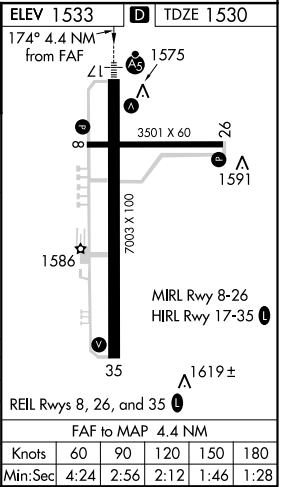


NC-2, 07 MAR 2013 to 04 APR 2013

NC-2, 07 MAR 2013 to 04 APR 2013



CATEGORY	A	B	C	D
S-ILS 17	1730-1/2 200 (200-1/2)			
S-LOC 17	1900-1/2 370 (400-1/2)		1900-3/4 370 (400-3/4)	
CIRCLING	2000-1 467 (500-1)		2100-2 567 (600-2)	



NEWTON, KANSAS  
Amdt 4A 11321

38°03'N-97°17'W

NEWTON-CITY-COUNTY (E/WK)  
**ILS or LOC RWY 17**

Knots	60	90	120	150	180
	Min:Sec	4:24	2:56	2:12	1:46

Figure 34. KEWK ILS 17 published approach procedure (courtesy of U.S. Department of Transportation)

## CHAPTER 5

### RESULTS

Based on the test matrix provided in Chapter 4, flight tests were conducted on the ground and at various flight regimes to include evaluation during taxiing, in the traffic pattern, during performance turns, on a cross-country flight, and during an instrument approach. Results were used to investigate the performance limits of the iPhone in combination with CFiTrack.

All flight tests were conducted without the use of an autopilot or any other artificial flight controller. Hence, any pilot- or turbulence-induced discrepancies from the desired target flight conditions were documented to rule out any bias and contributed to the overall performance assessment. The pilot would self evaluate his flying performance in a modified Cooper-Harper rating scale using the rubric shown in Table 7.

TABLE 7

RUBRIC: MODIFIED COOPER HARPER SCALE

Item\Score	1 (Excellent)	2 (Good)	3 (Fair)	4 (Marginal)	5 (Deficient)
Airspeed	+/- 1 kts	+/-5 kts	+/-10 kts	+/- 20 kts	20+ kts
Altitude	+/- 10 ft	+/- 20 ft	+/- 50 ft	+/- 100 ft	100+ft
Heading	+/- 1 deg	+/- 5 deg	+/- 10 deg	+/- 20 deg	20+ deg
Bank	(+/- 1 kts)	+/- 5 deg	+/- 10 deg	+/- 20 deg	20+ deg

#### 5.1 Taxi Testing

Even though the taxi test was based on a somewhat crude visual approximation of the position offset, it provided a good measure for the lateral and vertical precision of the iPhone and CFiTrack. Figure 35 shows the aircraft as it is taxiing along the centerline of the taxiway. The

pilot remained within less than one foot of the taxiway centerline, ruling out most of the steering error as a source for the offset in aircraft position.



Figure 35. Test aircraft during taxi testing.

Figures 36 and 37 provide a measure for the lateral and vertical accuracy for the X-Plane model during the taxi and ground operations.



Figure 36. X-Plane screenshot for lateral performance evaluation.



Figure 37. X-Plane screenshot for vertical performance evaluation.

Throughout this test, deviations in terms of display accuracy remained within approximately 10 feet. Generally, the lateral representation appeared slightly more accurate than the vertical one. Occasionally the aircraft would disappear in the ground leaving only the shadow silhouette. The orientation (heading), however, seemed to be mostly correct.

## 5.2 Traffic Pattern

Figure 38 shows the desired pattern (red) and the pattern as it was actually tracked by the ground station (blue). Results show a remarkably close match between the desired and recorded tracks, which suggests a more than adequate lateral accuracy in flight. The resolution of the received and recorded data allowed the ground station to distinguish even minor deviations from a desired track. A slight overshoot can be seen after each turn and was also reported by the pilot.

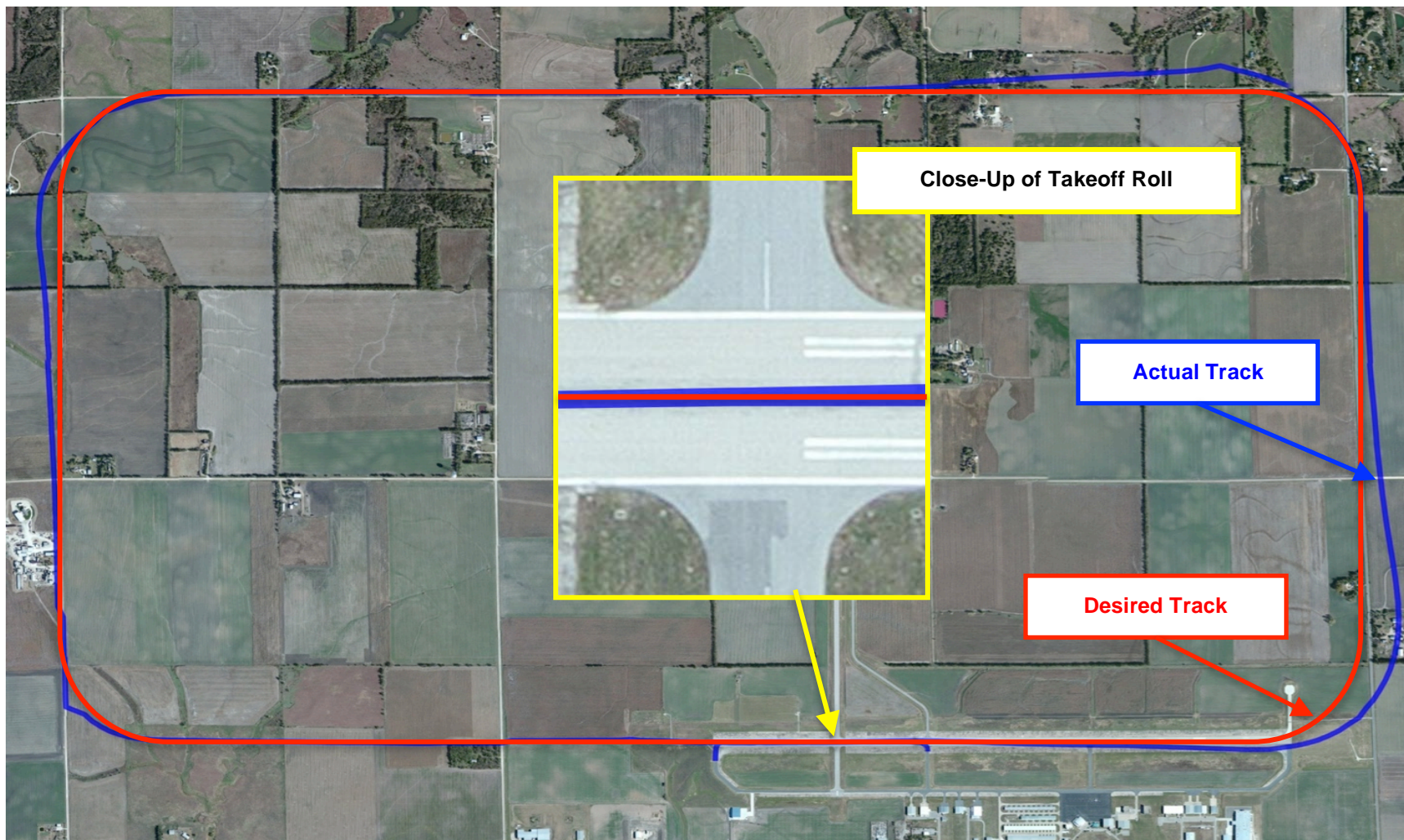


Figure 38. Traffic pattern (top view).

Figure 39 shows the altitude and groundspeed that was recorded during the second traffic-pattern phase of testing. The target altitude for 2,300 ft. MSL (800 ft. AGL) during the downwind leg was tracked very accurately. Most irregularities are within +/-50 ft. and, therefore, meet commercial pilot (CPL) practical test standards for airmen certification. Variations are the result of turbulences and pilot input error. The recorded groundspeed indicates 10 knots higher than target speed on the downwind leg, which was likely due to a 12-knot wind component at the time of testing.

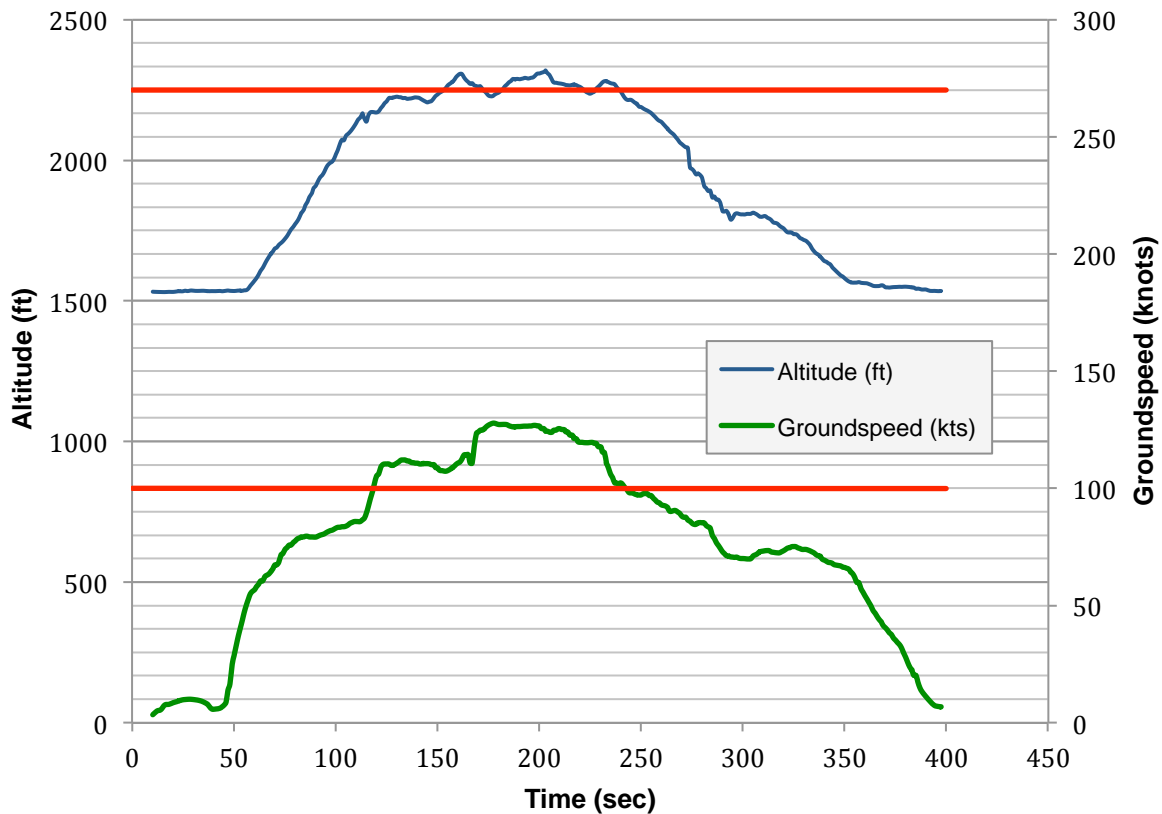


Figure 39. Recorded altitude and groundspeed.

Figure 40 shows the three-dimensional flight path of the aircraft. Note that for illustration purposes, the aspect ratios of x, y, and z are not proportional.

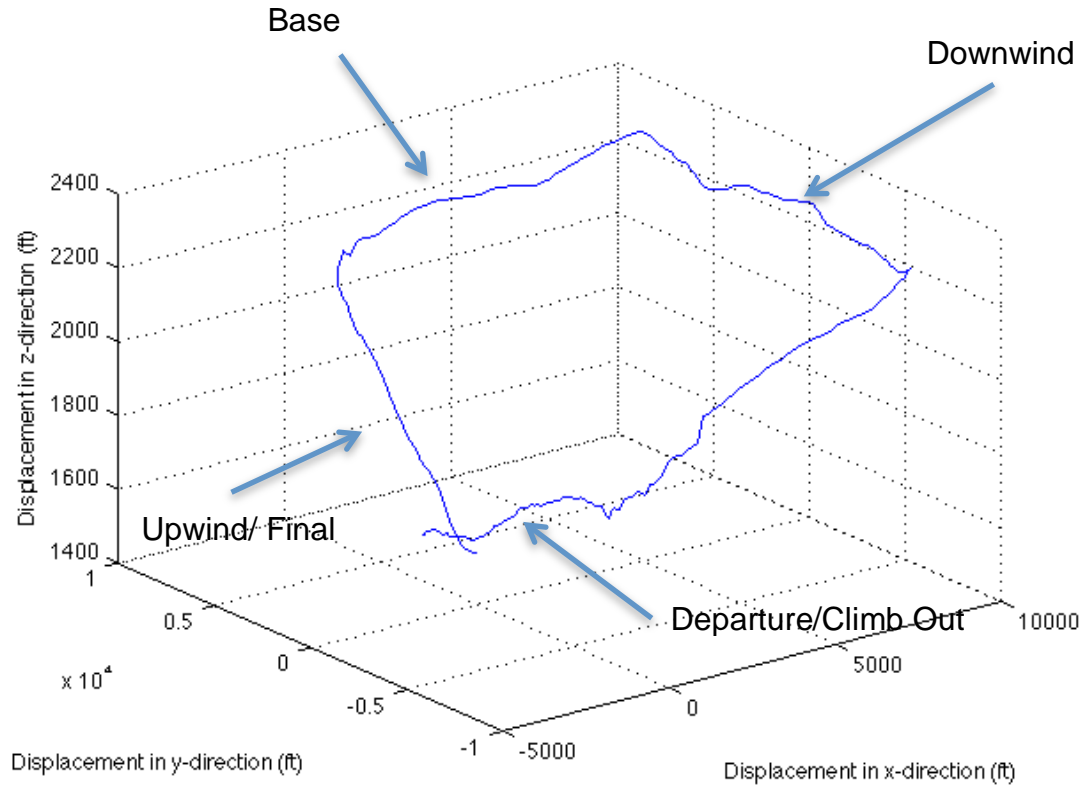


Figure 40. Traffic pattern (3D).

As for all maneuvers, the test pilot completed a modified Cooper-Harper rating scale after the flight. Table 8 shows the performance accuracy during the maneuver as perceived by the pilot, eliminating any bias that could affect the evaluation of the system.

TABLE 8

SELF EVALUATION DURING TRAFFIC PATTERN WORK

Item	Score
Airspeed	2
Altitude	3
Heading	2
Bank Angle	2
Score: 1 (Excellent) 2 (Good) 3 (Fair) 4 (Marginal) 5 (Deficient)	

### 5.3 Performance Turns (Steep Turns)

Testing the behavior of the iPhone and CFiTrack during performance turns provided invaluable information on the lateral-directional tracking and the representation of the aircraft.

Figure 41 shows the performance turn as depicted by X-Plane on the ground.



Figure 41. X-Plane model during 45° performance turn.

Figure 42 shows the view from inside the airplane cabin as well as an outside photograph of the airplane during the 45° performance maneuver. The photos and screenshot were timed and taken synchronously. Based on the data that was received from the aircraft, several plots were computed to obtain a visual representation of the flight, also including a 3-D view, as shown in Figure 43.



Figure 42. In cockpit (top) and aerial photo (bottom) during performance turn.

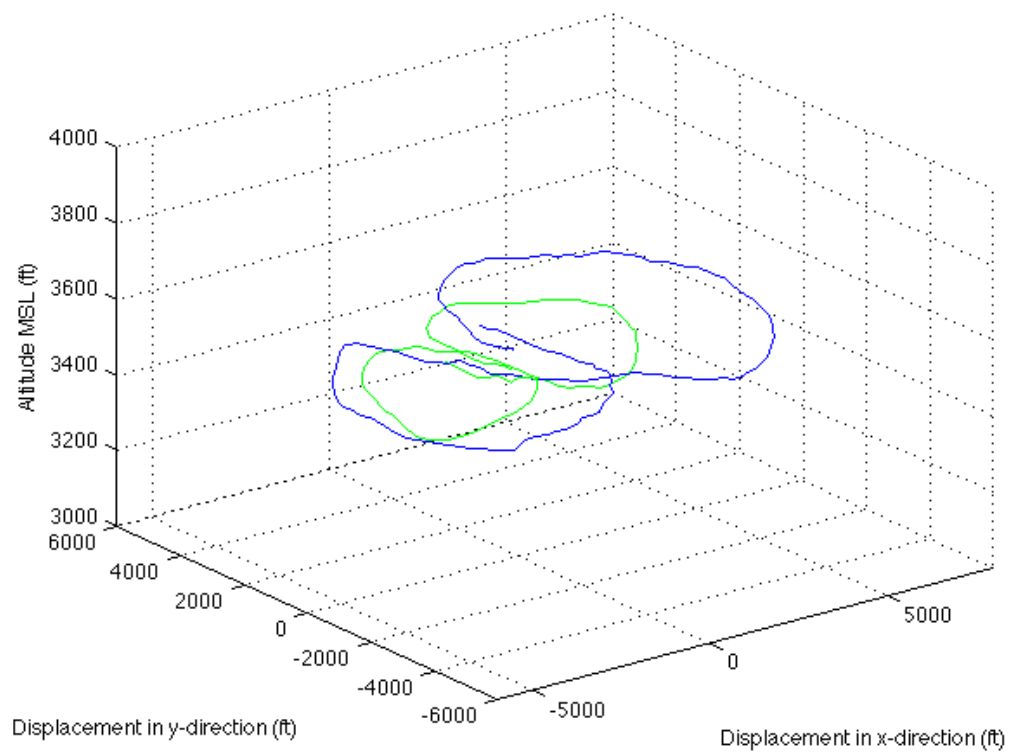


Figure 43. Performance turns (3D view).

Figure 44 shows the top view of the maneuver, executed by *Student A* at  $45^\circ$  (blue) and  $60^\circ$  (green) of bank angle. As expected, the iPhone tracks two pairs of circular patterns with different radii. Based on the steeper bank angle, the pilot achieves a faster turn rate and a smaller turn radius. The profile view shown in Figure 45 clearly shows the altitude range in which this maneuver was performed. This view also indicates minor fluctuations in altitude, which are well within acceptable limits. Keeping in mind the absence of any artificial control systems, these disturbances are mostly the result of pilot under or over compensation to the motion of the ambient atmosphere.

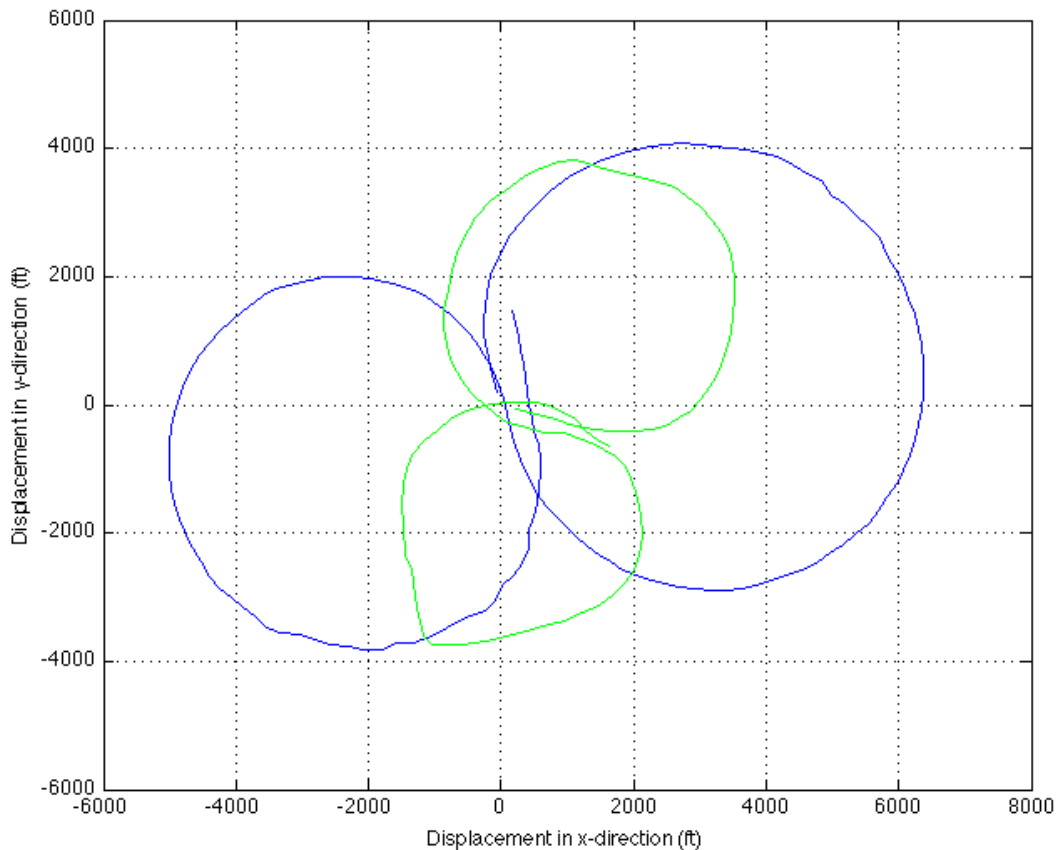


Figure 44. Performance turns (top view).

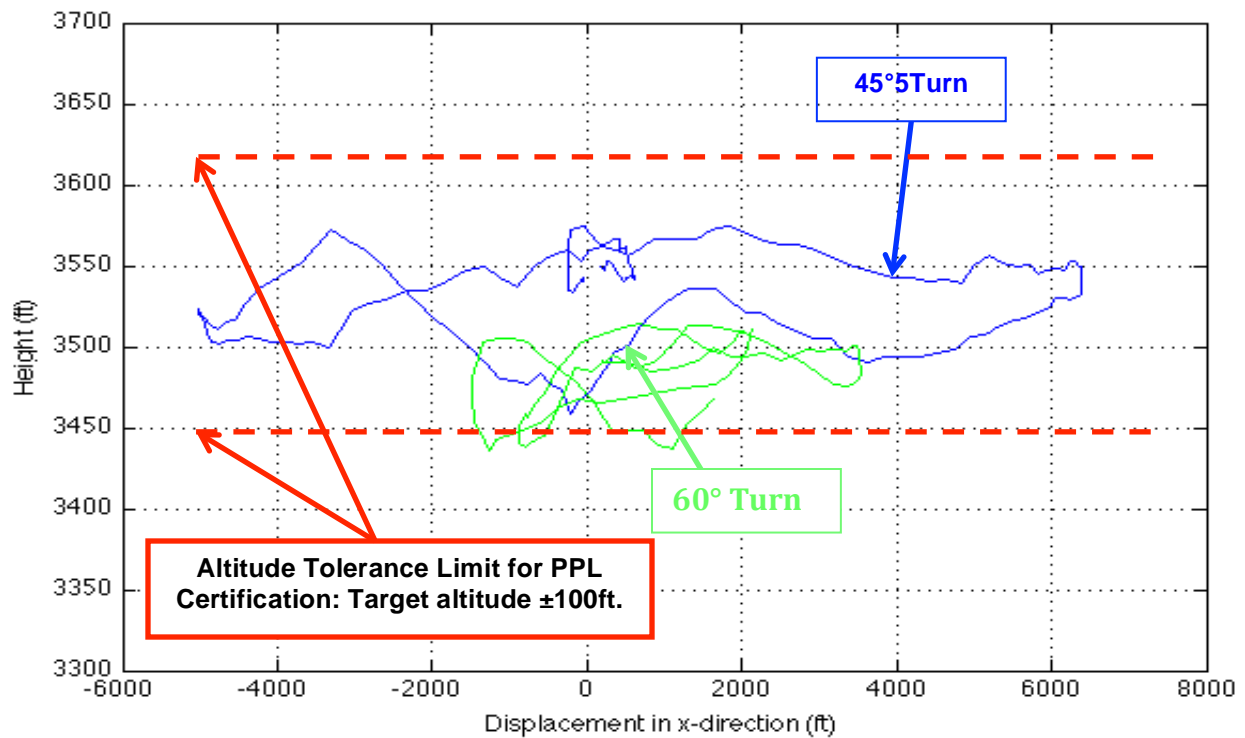


Figure 45. Performance turns (profile view).

Figures 46 to 49 represent the actual bank and heading angles tracked by the iPhone during performance turn maneuvers. The illustrated results show data pairs of bank and heading information for *Pilots A, B, and C*, performing turns at 45° and 60° bank angles. The desired target values for the bank angle are shown in green in accordance with private pilot and commercial pilot practical test standards (PTS). The resulting curves not only illustrate the quality of the turns but also show which test pilot would have passed a check ride under private or commercial test standards.

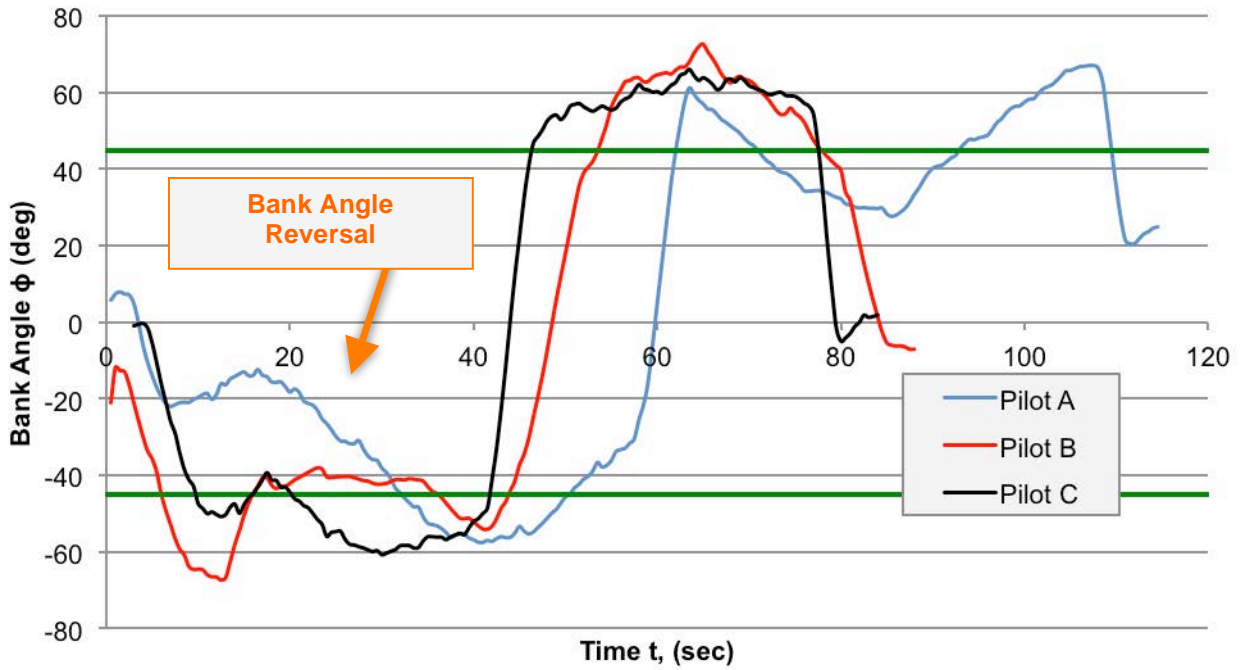


Figure 46. Bank angle during pair of 45° performance turns (steep turns).

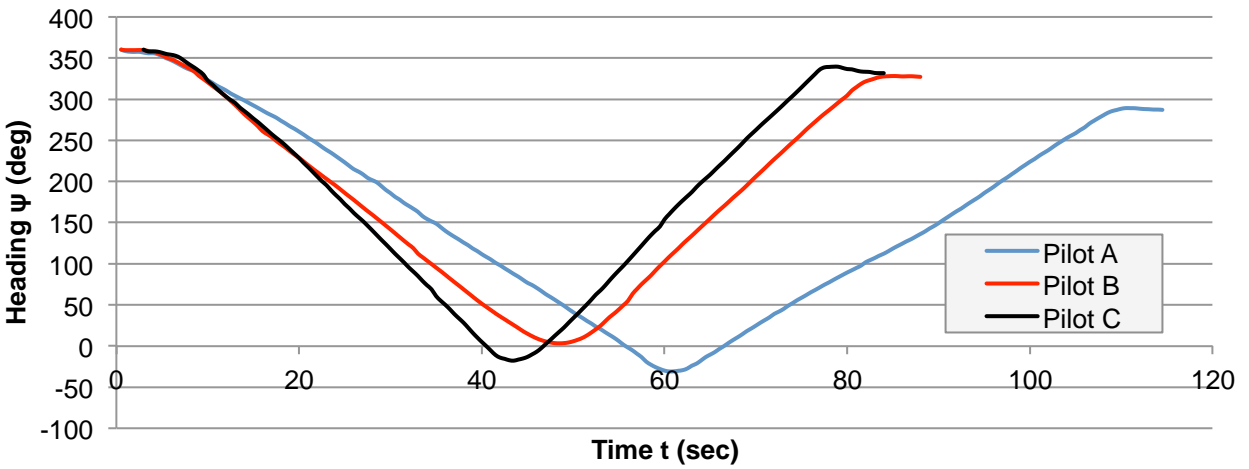


Figure 47. Heading angle during pair of 45° performance turns (steep turns).

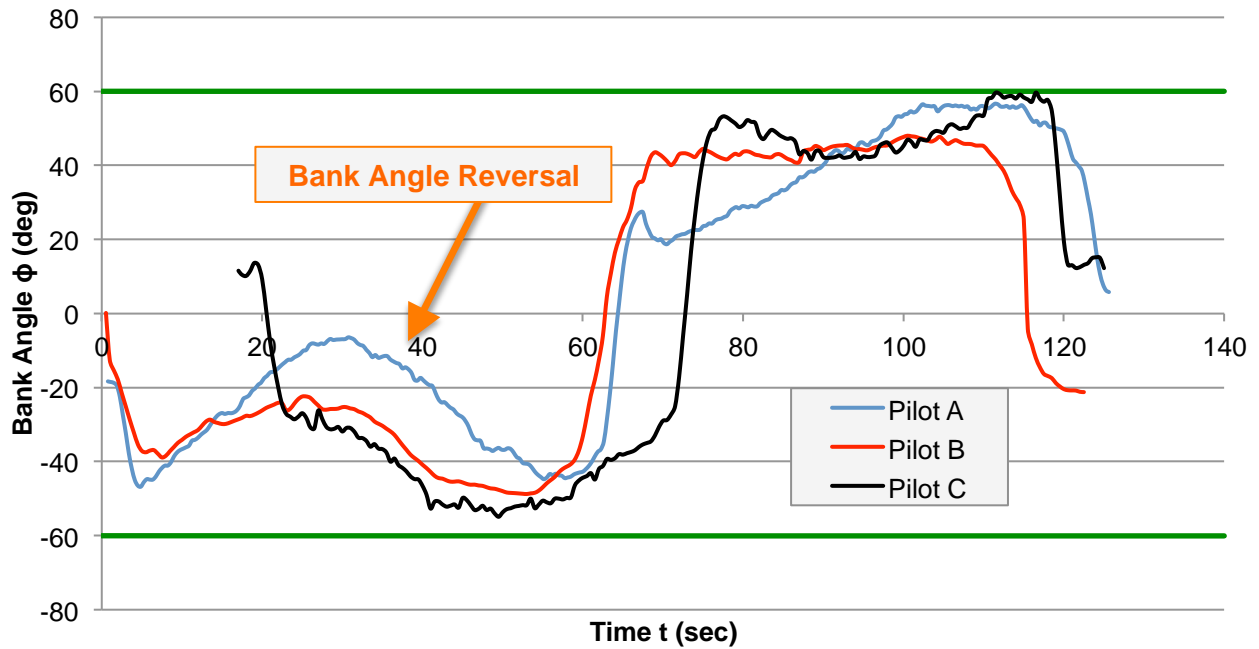


Figure 48. Bank angle during pair of 45° performance turns (steep turns).

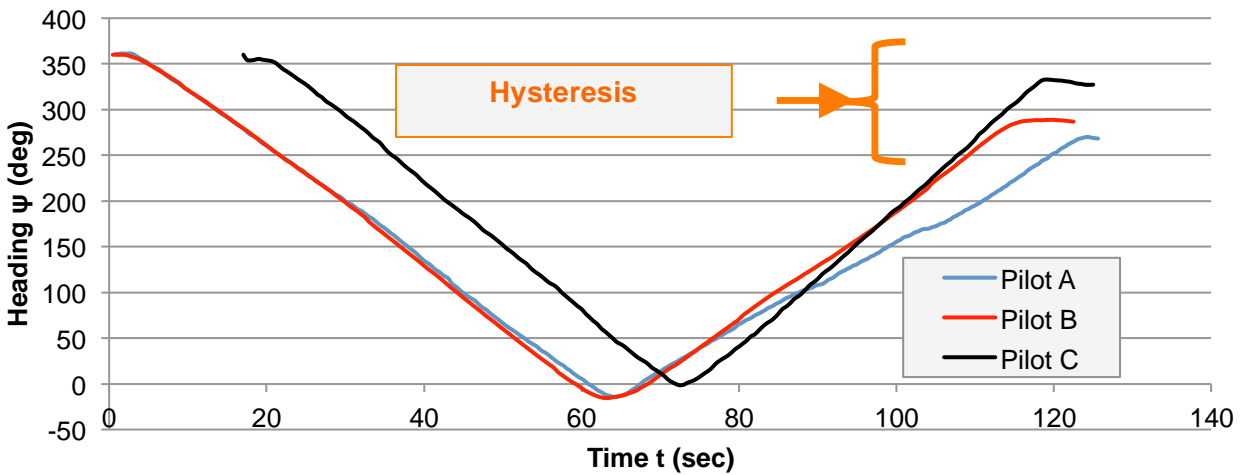


Figure 49. Heading angle during pair of 45° performance turns (steep turns).

Based on the student performance shown, Student C would have likely passed the performance test maneuver in a practical test. The tolerable margin of error for the pilots is  $\pm 10^\circ$  of bank angle. For Student A the data for the 45° and 60° performance maneuvers fall mostly within that range. Note that all graphs show a very distinct changeover from a left turn (negative

roll) to a right turn (positive roll). Also, the heading data for all three pilots and in both 45° and 60° maneuvers show a hysteresis. This hysteresis seems to be related to X-Plane since roll and heading displayed directly on the iPhone screen appear very accurate. The discrepancy in roll-in and rollout heading corrects itself after several minutes. Pilots A and C show an initial bank reversal shortly after initiating the turn. This is likely due to a perceived feeling of discomfort in performing this maneuver and is most prominent during the 60° banked turn, as shown in Figure 49. As shown in Table 9, the three pilots evaluated their performance during the maneuver to mitigate human error in determining the accuracy of system. The self-evaluation mostly matches the expectations derived from the plots.

TABLE 9

SELF EVALUATION DURING PERFORMANCE TURNS

Item	Student A	Student B	Student C
Airspeed	3	2	2
Altitude	4	3	2
Roll-Out Heading	3	1	1
Bank Angle	5	3	2
Score: 1 (Excellent) 2 (Good) 3 (Fair) 4 (Marginal) 5 (Deficient)			

#### 5.4 Cross-Country Cruise Performance

To ensure reliability during cross-country flights, a flight was tracked to KAAO (Colonel James Jabara Airport), departing KEWK (Newton City County Airport). Figure 50 shows the track of the flight as it was received and displayed by X-Plane.

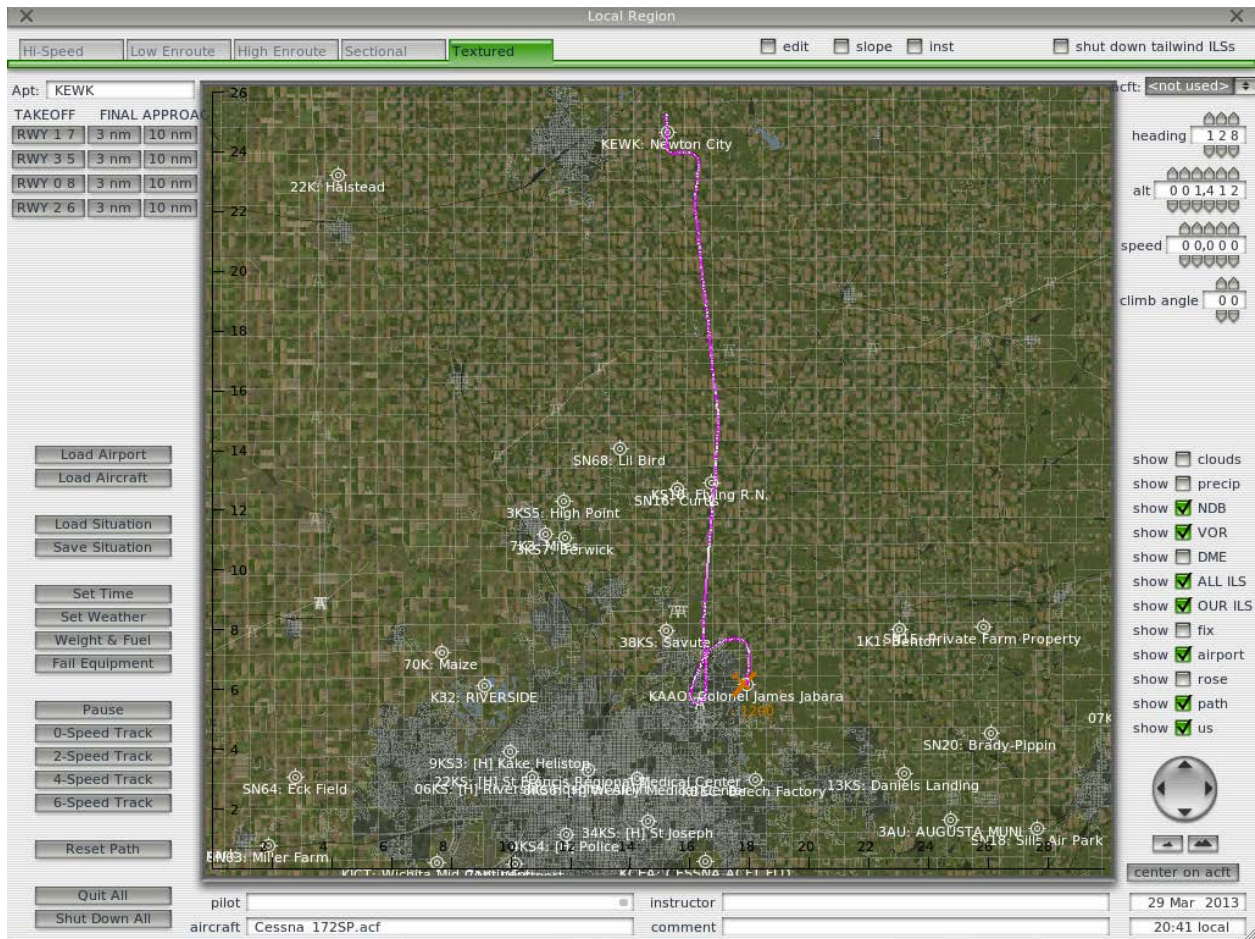


Figure 50. Flight track during cross-country flight from KEWK to KAAO.

Table 10 shows the pilot’s self evaluation with regards to the desired flight regime. Throughout the flight, several waypoints were identified by the ground station and verified by the pilot. All points were within a short distance from the aircraft proving the integrity of position data during long range/cruise flight.

TABLE 10

SELF EVALUATION DURING PERFORMANCE OF CROSS-COUNTRY FLIGHT

Item	Score
Airspeed	3
Altitude	3
On-Course Heading	4
Bank Angle	2
<i>Score: 1 (Excellent) 2 (Good) 3 (Fair) 4 (Marginal) 5 (Deficient)</i>	

Figure 51 shows the altitude profile during the cruise flight. The data was received continuously without delay or interruption. The final altitude indication to the ground station at the time of arrival was 1,418.38 feet (MSL). The published elevation surveyed at the runway threshold was 1,421 feet (MSL).

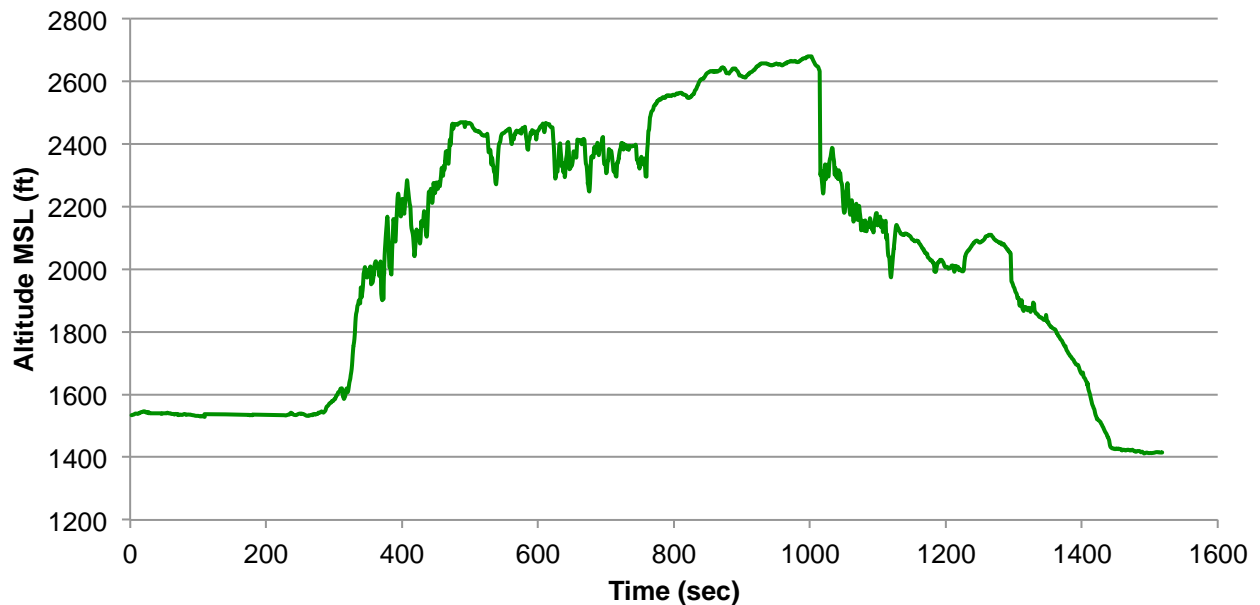


Figure 51. Altitude profile during cross-country test flight.

An interesting side note: As the test pilot arrived in the vicinity of Jabara airport, he accidentally began to execute an incorrect approach towards Runway 36, mistaking the upwind leg for the downwind leg. I was monitoring his flight, and informed him via Skype that based on the southerly wind direction at the time he was about to enter opposing traffic and land downwind instead of upwind. He immediately corrected by flying southwest, reentering the traffic pattern for a correct approach onto Runway 18 (Figure 52). Note that this was not a planned component of the test as it imposed a risk to the pilot; however, it provides a valuable demonstration and testimony to the system's ability to track flights accurately.

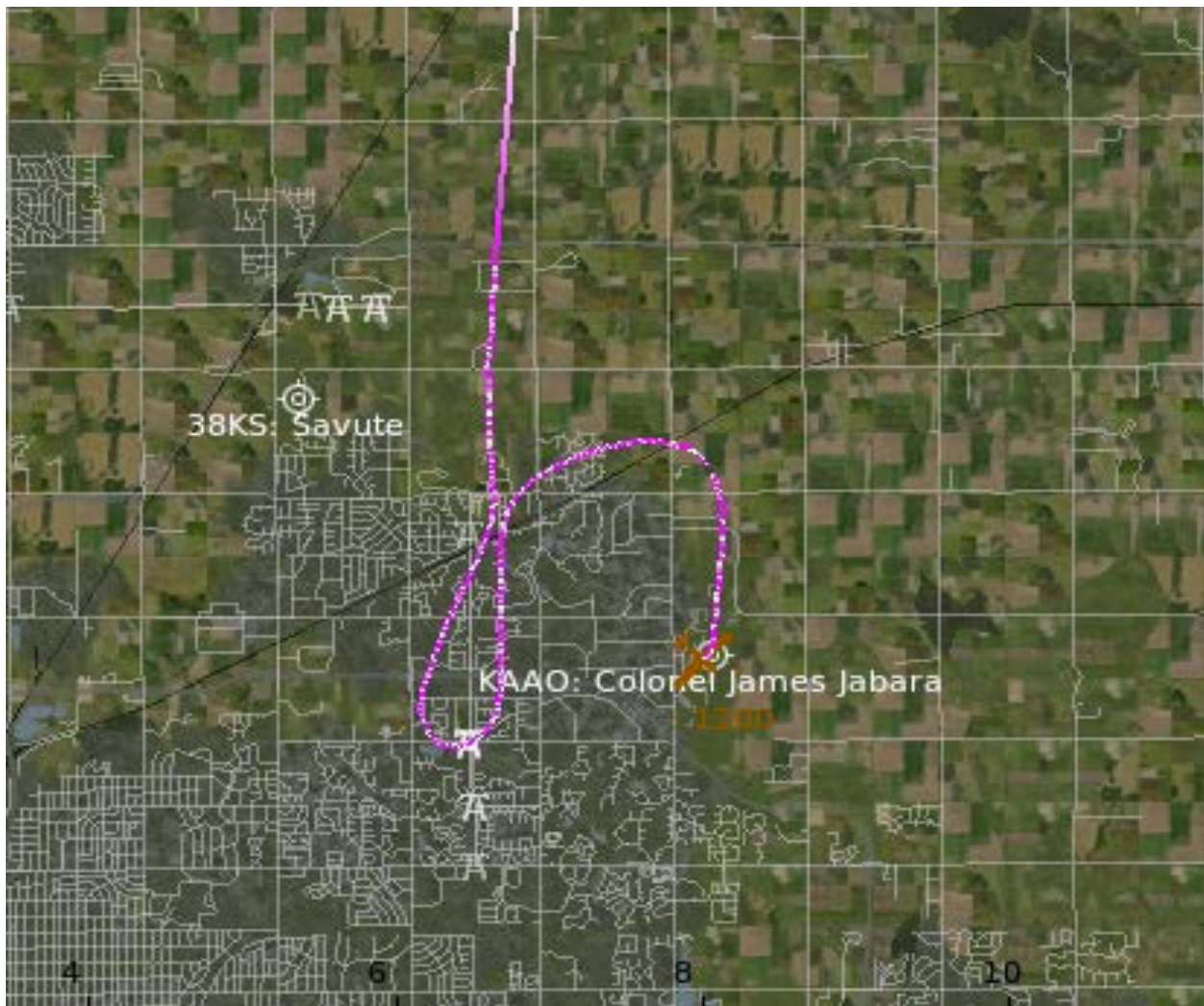


Figure 52. Instructor intervention during false-pattern entry.

## 5.5 Precision Instrument Approach

Testing CFiTrack on a published instrument approach allowed for performance evaluation of the system by comparing output data to a calibrated reference. The test was started at the final approach fix (FAF) and focused on the accurate representation of a glideslope, as it was flown by the test pilot. The ILS 17 approach into the Newton airport was flown twice. The first test allowed the pilot to use outside references along with instrumentation indications. The second test was flown under the hood with a view-limiting device, restricting the pilots view to include only the aircraft instruments.

### ILS 17 Visual with Outside References

Figure 53 shows the descent over time for the ILS 17 approach without a view-limiting device. This curve describes an initial disturbance during the capture of the glideslope, followed by a smooth descent down to the touchdown zone.

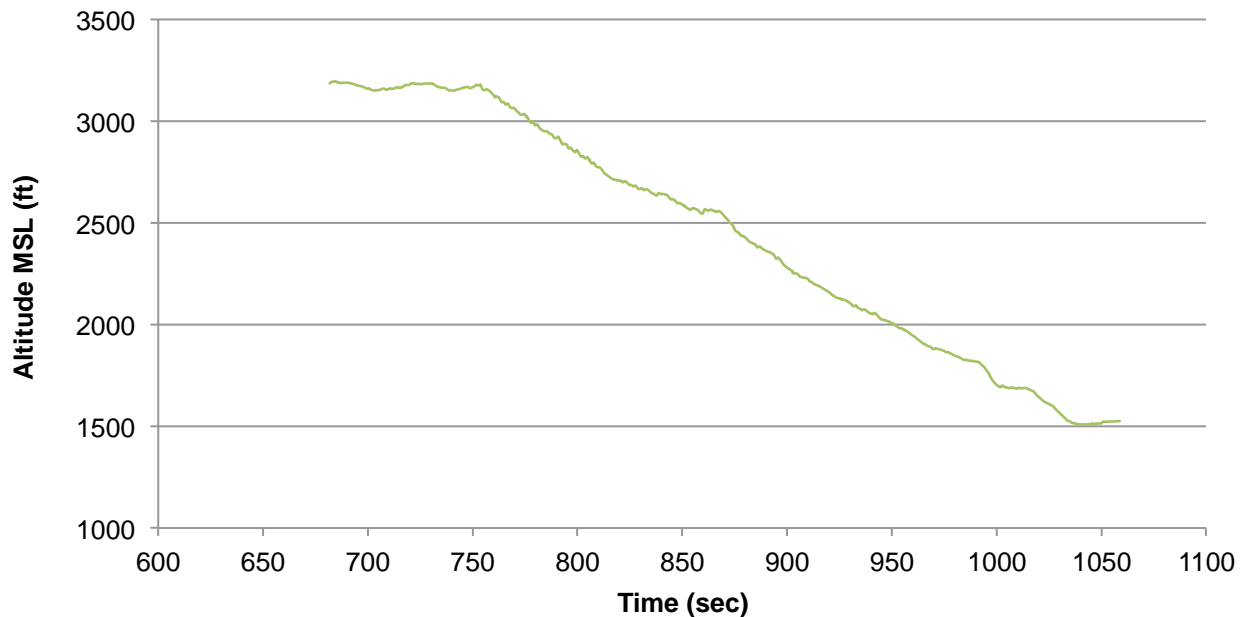


Figure 53. Rate of descent during ILS 17 approach, flown visually with outside references

Figure 54 depicts a similar trend but provides qualitative information on the glideslope angle. The target approach path is shown in green and represents the published glideslope angle of 3°. Also shown is the lateral displacement from the approach path, which suggests a very precise approach.

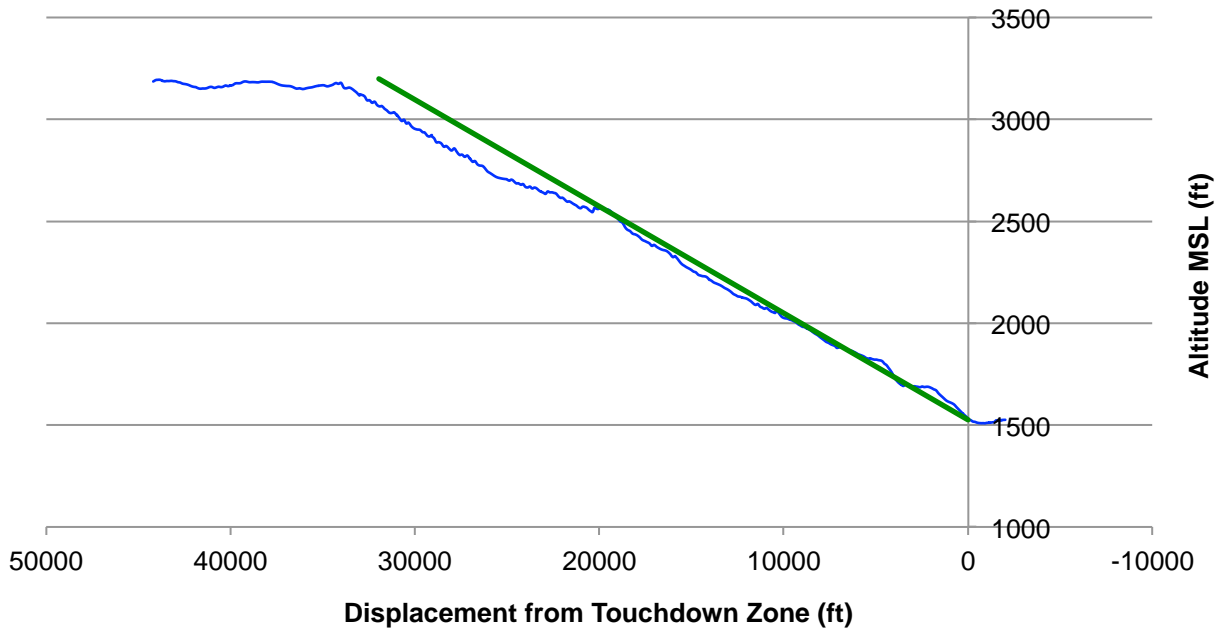


Figure 54. Glideslope track during ILS 17 approach, flown visually with outside references

### **ILS 17 with View-Limiting Device (Simulated Instrument Approach)**

When flying under simulated vs. actual instrument conditions, the task of piloting an aircraft becomes significantly more difficult. This becomes apparent when viewing Figure 55. Under simulated IFR conditions, the approach path now shows more disturbances. CFiTrack successfully detected the disturbances that were caused by the pilot as he attempted to remain on a proper glide path.

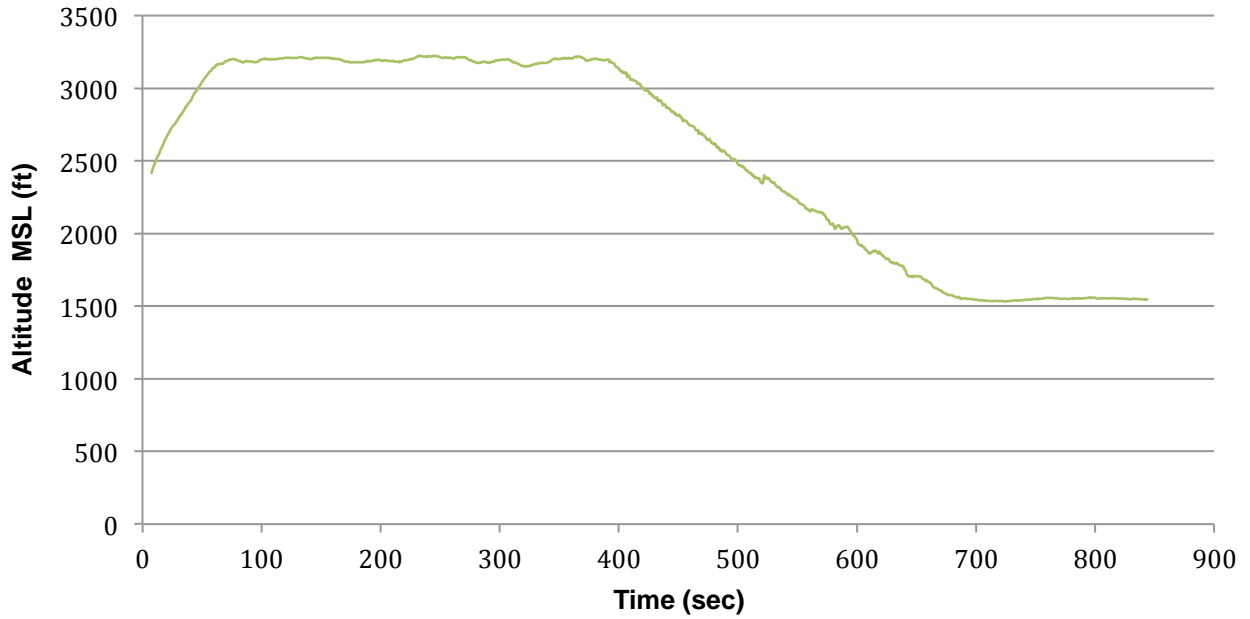


Figure 55. Rate of descent during ILS 17 approach, flown under simulated instrument conditions

Figure 56 shows that the pilot has fallen slightly below the glide path. This trend was also verified by the safety pilot onboard the aircraft

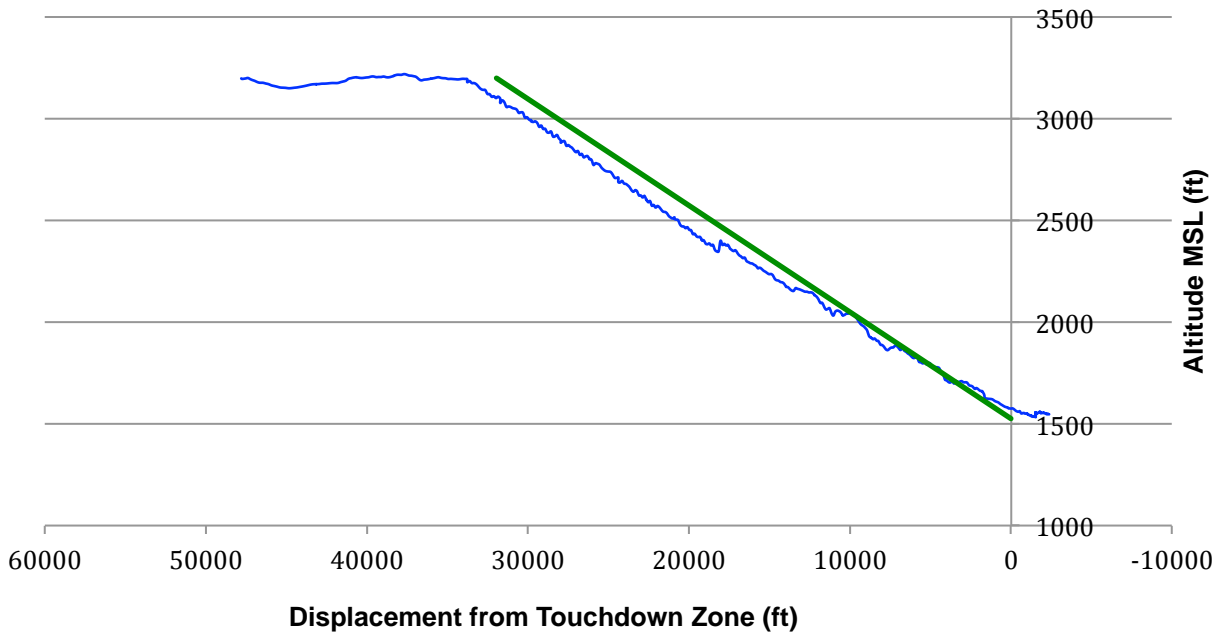


Figure 56. Glideslope track during ILS 17 approach, flown under simulated instrument conditions

Figures 57 and 58 show the lateral track of the ILS approach, flown visually and flown solely by reference to the instruments with the use of a view-limiting device, respectively. Similar to the results for the altitude tracking, the plot for lateral tracking shows a better pilot performance when piloting the aircraft visually without a view-limiting device. Accordingly, the lateral tracking of the approach indicates a significant offset until successfully established on the localizer. The safety pilot on board the aircraft reviewed and confirmed the integrity of the plotted data.



Figure 57. Lateral track during ILS 17 instrument approach, visual



Figure 58. Lateral track during ILS 17 approach, simulated instrument condition

The testing that was conducted throughout this research was invaluable in evaluating the performance of both the iPhone and the CFiTrack. A conclusion is drawn in Chapter 6, and opportunities for future research, reflecting on the results that were provided in this chapter, are also discussed.

## CHAPTER 6

### CONCLUSIONS AND FUTURE DEVELOPMENT

Findings in the previous chapters have provided a promising outlook for the future development of this smartphone-based flight-tracking system using an CFiTrack prototype. Society's exposure to new technology and the lack of innovative flight instruction methods, discussed in Chapter 1, suggest a need and a market for such a system. This chapter critically reflects on the test results that were obtained in Chapter 5, and discusses evidence that suggests the feasibility of such a system.

#### 6.1 Conclusions

The results of Chapter 5 clearly point out the strengths and potential weaknesses of the smartphone-based flight-tracking system in its current development stage. Generally speaking, the iPhone 5 performed well during testing of the preliminary device and the final prototype testing.

During the taxi test, location representation was accurate within +/- 10 feet of vertical displacement and less +/- 5 feet of lateral displacement. Validation and comparison of elevation at known checkpoints with tracked altitude, however, suggests a possible mapping error within X-Plane rather than an error with the iPhone or CFiTrack. A slight location error in the scenery development of X-Plane could explain the faulty altitude and even location. The X-Plane model seemed to be displayed more accurately at some locations than others, hence supporting the presumption of a possible mapping error in the X-Plane scenery engine. For terminal operations at affected airports, this altitude and position error results in undesirable inaccuracies; however, this only becomes a relevant issue in the immediate vicinity of the touchdown zone. For

operations at altitudes greater than 50+ feet, this error quickly approaches zero and becomes negligible.

The results that were obtained in the traffic pattern show satisfactory precision in terms of location data. The pilot maneuvered the airplane along the desired course in the traffic pattern. Any altitude discrepancies were minor and can mostly be attributed to wind gusts and pilot error, rather than faulty flight tracking. Weaknesses during this test were mainly seen during turns and show a slight lag in bank and heading along with hysteresis in restoring level flight after turns. This hysteresis also showed up during the performance turn maneuvers. It is noteworthy to mention that indications taken directly from the iPhone (CFiTrack UI) did not show this hysteresis in bank recovery, hence, suggesting again an issue within X-Plane. As with every test flight, maneuvers such as performance turns were performed without the use of an autopilot or any other artificial controller, suggesting the presence of control input error in the execution of all maneuvers. This could very well be the single most significant contributor to any disturbances seen in the test data. These disturbances were found in almost every test flight but almost always remained well within acceptable performance margins.

Testing CFiTrack during a simulated cross-country flight gave testimony to the functionality of the system. At any given time, the instructor was aware of the exact location of the student and was able to intervene.

Results of the instrument approach clearly show a difference in pilot performance and accuracy when the approach is executed under the hood as opposed to executed visually. This test proves the successful implementation of such a system, even in advanced flight training. The overall accuracy of the CFiTrack prototype is satisfactory. Any increase in precision as a result of further development is welcomed; however, for the purpose of remote flight instruction, it is

not required. The performance of CFiTrack as it was evaluated throughout extensive testing shows, beyond a doubt, the usefulness of such a system and its proven feasibility.

## **6.2 Future Development**

The described concept provides unique opportunities for further development and the addition of technology, ranging from communication standards to the utilization of information that is broadcast to the ground station. The next step in future development is a corresponding client application for the flight instructor on the ground. Using the *Map Kit Framework* within the iOS software, the instructor would be capable of tracking the student from anywhere on an iPhone device without having to use a stationary computer. Future work could include the transmission of flight data into the secondary radar signal, which is part of the conventional radar system that is already in existence and covers most of the continental United States. With the current prototype of CFiTrack, each flight instructor (client) wishing to obtain flight data must have a public IP address and share this address with the student (host). Without this information, communication between student and instructor can be challenging. In the future, the host could stream flight data to a web-based database. End users (i.e., flight instructors) would obtain a live data feed from anywhere in the world of multiple students by subscribing to a service that allows access to that database.

In conclusion, it can be said that with ongoing progress in the development of consumer electronics, one can expect that smartphone technology will continue to advance quickly. Critical system components such as sensors and transmitters are likely to become faster and more accurate. With faster and more reliable communication standards, the data transmission in remote areas and at altitude should improve, making this system faster and even more reliable.

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