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William J. Hughes Technical Center
Aviation Research Division
Atlantic City International Airport
New Jersey 08405

Overview of the Taxiway Centerline Deviation Study at Airplane Design Group III Airports

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Final Report

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16. Abstract
In 1999, a research team from the Federal Aviation Administration (FAA) Airport Technology Research and Development (R&D) Branch initiated the Taxiway Centerline Deviation Study. The purpose of this study was to determine whether airplane design group (ADG) VI aircraft, with wingspans of 214 to >262 ft (such as the New Large Aircraft (NLA) Airbus A380 and Boeing B747-8) could safely operate at civil airports with ADG V 75-ft-wide straight taxiway sections. Without this capability, airports could incur expensive and lengthy improvements to taxilanes, taxiways, and runways to accommodate ADG VI aircraft. It is expected that the results from the overall study will suggest that centerline separation standards between parallel taxiways or taxiways to fixed/movable objects can be reduced. This would allow larger aircraft to operate without imposed operational limitations, such as reduced speeds on smaller taxiways and centerline separations without a modification to standards or prior permission, which may increase airport capacity. In Phase I, conducted between 1999 and 2000, the research team determined how accurately a Boeing 747, which is an ADG V aircraft with wingspans of 171 to <214 ft and which closely resembled ADG VI aircraft, tracked the centerline of their corresponding ADG V taxiway. The study determined that ADG VI aircraft could safely operate on existing ADG V straight taxiway sections. Consequently, in 2003, the FAA published Engineering Brief (EB) 63, "Use of Non-Standard 75-Foot-Wide Straight Taxiway Sections for Airbus A380 Taxiing Operations." EB 63 also determined that ADG VI aircraft could operate on 75-ft-wide straight taxiway sections.

Based on the success of the original effort, it was decided to continue the Taxiway Centerline Deviation Study by collecting data at smaller ADG airports to focus on limited separations and object clearance standards. Phase II was conducted between 2008 and 2010 and collected ADG IV data from smaller ADG airports: Orlando International Airport (MCO), FL; Palm Beach International Airport (PBI), FL; Manchester-Boston Regional Airport (MHT), NH; and Chicago O'Hare International Airport (ORD), IL.

Phase III was conducted between 2009 and 2013 and collected data from four civil ADG III airports: Palm Beach International Airport (PBI), FL; Salisbury-Ocean City Wicomico Regional Airport (SBY), MD; Key West International Airport (EYW), FL; and Westchester County Airport (HPN), NY. Each airport met the criteria for this study, including 50-ft-wide straight taxiway sections built to ADG III standards and service to a strong mix of ADG III aircraft with wingspans of 79 to <118 ft, which are similar to an Airbus A320 and Boeing 737.

This document summarizes Phase III, which includes an overview of the taxiway deviation data collection system, the data collection and analysis process, an overview of the data collection systems installed at each ADG III airport, and recommendations to complete future data collection system installations. The data will be analyzed under a cooperative research and development agreement between the FAA Airport Technology R&D Branch and The Boeing Company. The analysis will determine the associated centerline wander risk for each evaluated ADG in relation to their standard taxiway width. This information will allow comparison of taxiing risk among the six ADGs. The results of the analysis will be disseminated as a supplement to this report at a later date.

17. Key Words
Airplane design group, Taxiway, Centerline, Deviation

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LIST OF ACRONYMS

ADG	Airplane design group
ATCT	Air Traffic Control Tower
EB	Engineering Brief
amp	Amperage
DS	Dataset
EYW	Key West International Airport
FAA	Federal Aviation Administration
FBO	Fixed-based operator
GA	General aviation
GFCI	Ground fault circuit interrupter
HPN	Westchester County Airport
IR	Infrared
LED	Light-emitting diode
MCO	Orlando International Airport
MHT	Manchester-Boston Regional Airport
NLA	New Large Aircraft
NPIAS	National Plan of Integrated Airport System
ORD	Chicago O'Hare International Airport
PBI	Palm Beach International Airport
PCC	Power control center
R&D	Research and development
RS	Recommended standard
SBY	Salisbury–Ocean City Wicomico Regional Airport
TOFA	Taxiway object-free area
TSA	Taxiway safety area
U.S.	United States
V AC	Volts of alternating current

EXECUTIVE SUMMARY

In 1999, a research team from the Federal Aviation Administration (FAA) Airport Technology Research and Development (R&D) Branch initiated the Taxiway Centerline Deviation Study. The purpose of this study was to determine whether airplane design group (ADG) VI aircraft, with wingspans of 214 to >262 ft, such as the New Large Aircraft (NLA) Airbus A380 and Boeing B747-8, could safely operate at civil airports with ADG V 75-ft-wide straight taxiways sections. Without this capability, airports could be faced with expensive and lengthy improvements to taxilanes, taxiways, and runways to accommodate ADG VI aircraft. It is expected that the results from the overall study will suggest that centerline separation standards between parallel taxiways or taxiways to fixed/movable objects can be reduced. This would allow larger aircraft to operate without imposed operational limitations, such as reduced speeds on smaller taxiways and centerline separations without modification to standards or prior permission, which may increase airport capacity. In Phase I, conducted between 1999 and 2000, the research team determined how accurately a Boeing 747, which is an ADG V aircraft with wingspans of 171 to <214 ft and which closely resembles ADG VI aircraft, tracked the centerline of their corresponding ADG V taxiway. Phase I determined that ADG VI aircraft could safely operate on existing ADG V straight taxiway sections. Consequently, in 2003, the FAA published Engineering Brief (EB) 63, "Use of Non-Standard 75-Foot-Wide Straight Taxiway Sections for Airbus A380 Taxiing Operations." EB 63 also determined that ADG VI aircraft could operate on 75-ft-wide straight taxiway sections.

Phase II was conducted between 2008 and 2010 and collected ADG IV data from smaller ADG airports: Orlando International Airport (MCO), FL; Palm Beach International Airport (PBI), FL; Manchester-Boston Regional Airport (MHT), NH; and Chicago O'Hare International Airport (ORD), IL.

Phase III was conducted between 2009 and 2013 and collected data from four civil ADG III airports across the United States: Palm Beach International Airport (PBI), FL; Salisbury-Ocean City Wicomico Regional Airport (SBY), MD; Key West International Airport (EYW), FL; and Westchester County Airport (HPN), NY. Each airport met the criteria for this study, including 50-ft-wide straight taxiway sections built to ADG III standards and service to a strong mix of ADG III aircraft with wingspans of 79 to <118 ft, which are similar to an Airbus A320 and Boeing 737.

This document summarizes Phase III, which includes an overview of the taxiway deviation data collection system, the data collection and analysis process, an overview of the data collection systems installed at each ADG III airport, and recommendations to complete future data collection system installations.

The Phase III data will be analyzed under a cooperative research and development agreement between the FAA Airport Technology R&D Branch and The Boeing Company. The statistical analysis will determine the associated centerline wander risk for each evaluated ADG in relation to their standard taxiway width. This information should permit a comparison of taxiing risk among the six ADGs. The results of the analysis will be disseminated as a supplement to this report at a later date.

1. INTRODUCTION.

In 1999, a research team from the Federal Aviation Administration (FAA) Airport Technology Research and Development (R&D) Branch initiated the Taxiway Centerline Deviation Study. The purpose of this study was to determine whether airplane design group (ADG) VI aircraft, with wingspans of 214 to >262 ft, such as the New Large Aircraft (NLA) Airbus A380 and Boeing B747-8, could safely operate at civil airports with ADG V 75-ft-wide straight taxiway sections. Without this capability, airports could incur expensive and lengthy improvements to taxilanes, taxiways, and runways to accommodate ADG VI aircraft.

During Phase I of the Taxiway Centerline Deviation Study, the research team determined how accurately Boeing 747 ADG V aircraft with wingspans of 171 to <214 ft, which closely resembles an NLA ADG VI aircraft, tracked the centerline of their corresponding ADG V taxiway width. Phase I determined that ADG VI aircraft could safely operate on existing ADG V straight taxiway sections [1]. Consequently, in 2003, the FAA published Engineering Brief (EB) 63, "Use of Non-Standard 75-Foot-Wide Straight Taxiway Sections for Airbus A380 Taxiing Operations." EB 63 also determined that ADG VI aircraft could operate on 75-ft-wide straight taxiway sections [1].

In Phase II, the data collection systems were relocated to four ADG IV airports: Orlando International Airport (MCO), FL; Palm Beach International Airport (PBI), FL; Manchester-Boston Regional Airport (MHT), NH; and Chicago O'Hare International Airport (ORD), IL.

After the completion of Phase II at ADG IV airports, the data collection systems were installed at four ADG III airports to begin Phase III: Palm Beach International Airport (PBI), FL; Salisbury-Ocean City Wicomico Regional Airport (SBY), MD; Key West International Airport (EYW), FL; and Westchester County Airport (HPN), NY.

It is expected that the results from the overall study will suggest that centerline separation standards between parallel taxiways or taxiways to fixed/moveable objects can be reduced. This would allow aircraft to operate without imposed operational limitations, such as reduced speeds on smaller taxiways without prior permission and centerline separations without modification to standards, which may increase airport capacity.

1.1 PURPOSE.

This report gives a summary of Phase III of the Federal Aviation Administration's (FAA) Taxiway Centerline Deviation Study at airplane design group (ADG) III airports.

1.2 OBJECTIVES.

The objectives of this report are to:

- identify system components of the taxiway centerline deviation data collection system.
- discuss the data collection and analysis process.
- provide an overview of the data collection systems installed at each ADG III airport.
- provide recommendations to complete future data collection system installations.
- determine the taxiing centerline risk for the ADG on straight taxiway sections.

2. OVERVIEW OF THE DATA COLLECTION SYSTEM.

During Phase III of the Taxiway Centerline Deviation Study, the research team used a data collection system to determine the distance of an aircraft's nose and outer main gears relative to a taxiway centerline. This data collection system was similar to the system used in Phase II. The components of this system included four industrial laser distance sensors, one high-definition camera with an infrared (IR) illuminator, one data collection box, and one power control center (PCC). The research team continued to work with Vector Airport Solutions (Vector), who was a major contributor to the success of Phases II and III. Vector owned, operated, and maintained the high-definition camera/IR illuminator and industrial server. In addition, Vector was a key participant in collecting, transmitting, and processing the data. The following sections provide the details of each system component.

2.1 LASER DISTANCE SENSORS.

Four industrial laser distance sensors were used to measure the distance of an aircraft's nose and outer main gears relative to a taxiway centerline, as shown in figure 1. During Phase II, the FAA procured several LD90-3300VHS-FLP (LD90-3-FLP) laser distance sensors from RIEGL Laser Measurement Systems to support this study. The laser distance sensors (herein referred to as laser) were reused during Phase III, as they were a proven technology and provided accurate distance measurements. To protect the lasers from outside elements, each laser was installed inside Pelco® EH4722 environmental enclosures, as shown in figure 2.

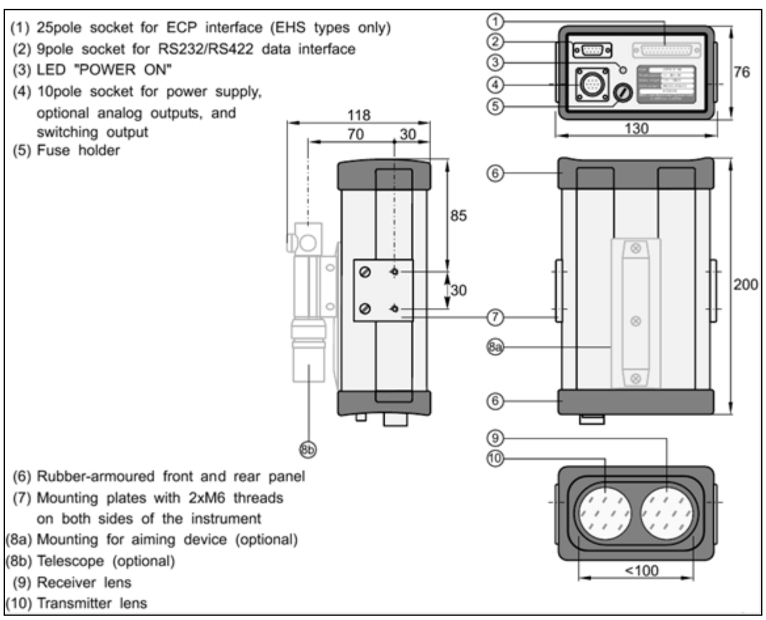

Figure 1. Laser Distance Sensor [2]

Figure 2. Laser Distance Sensor Installed in a Pelco EH4722 Environmental Enclosure [3]

As referenced in the LD90-3-FLP user's manual, the principle operation of the LD90-3300VHS-FLP laser distance sensor is that "an electrical pulse generator periodically drives a semiconductor laser diode sending out infrared light pulses, which are collimated and emitted by the transmitter lens. Via the receiver lens, part of the echo signal reflected by the target hits a photodiode, which generates an electrical receiver signal. The time interval between the transmitted and received pulses is counted by means of a quartz-stabilized clock frequency. The result is fed into the internal microcomputer, which processes the measured data and prepares it for the various data outputs." [2] A detailed flow diagram of the laser's principle operation is shown in figure 3.

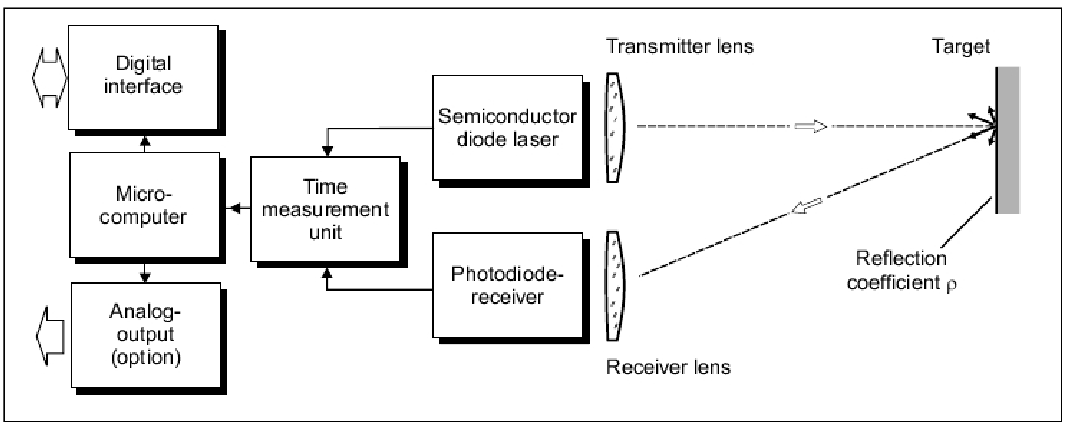

Figure 3. Laser Distance Sensor's Principle Operation [2]

Each laser constantly measures distances at a rate of 2000 hertz (measurements per second) and has a maximum range of 2296 ft with an accuracy of ±2 in. [2]. The laser's data interface is selectable between both recommended standard (RS)232 and RS422 data interfaces [2]. The lasers installed during Phase I were configured to RS232. However, of the four data collection systems installed in Phase III, the latter three systems were configured to RS422. The RS422 configuration was able to collect higher amounts of data compared to the RS232 configuration.

2.2 HIGH-DEFINITION CAMERA.

Each data collection system was equipped with one high-definition camera with an IR illuminator, as shown in figure 4. The high-definition camera took a picture of the tail (registration) number of each aircraft as it passed the data collection system. An internal process was used to compare the tail number pictures with the appropriate governing agency's aircraft registry (e.g., FAA, International Civil Aviation Organization, Transport Canada, etc.). Thereafter, the aircraft model (validation of the ADG aircraft) could be determined from the tail (registration) number. This information was stored in a database for later reporting.

An IR illuminator was located adjacent to the high-definition camera and aided in capturing images of aircraft tail numbers during nighttime hours. The IR illuminator was an ideal system component because it did not affect aircraft or vehicles that passed by the data collection system.

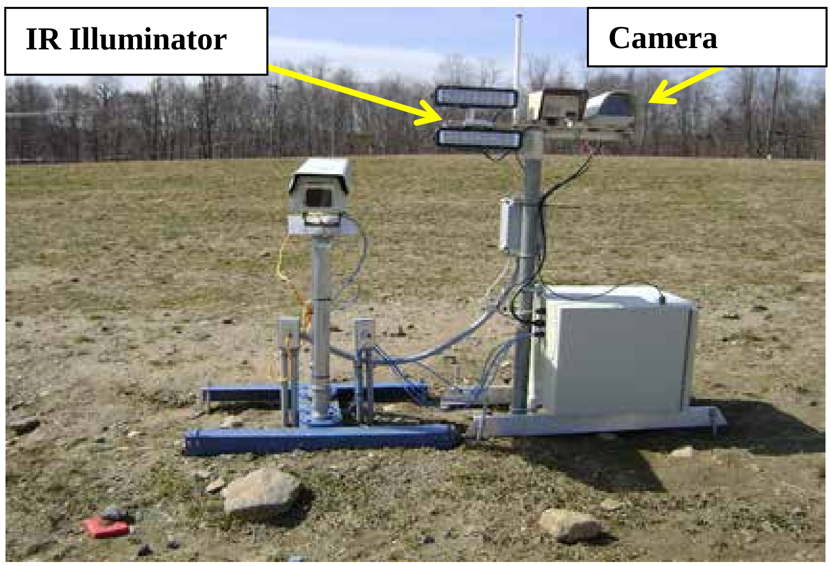

Figure 4. High-Definition Camera With IR Illuminator at Westchester County Airport

2.3 DATA COLLECTION BOX.

A weatherproof data collection box was installed with each system, as shown in figure 5. The data collection box contained an industrial server, wireless cellular router, marine battery, and battery charger.

Figure 5. Data Collection Box

2.3.1 Industrial Server.

An Advantech ARK-3381 industrial server was used to store data collected from the lasers and data high-definition camera. The server was mounted on the door of the data collection box, as shown in figure 6. This server was selected because it was compact and had the capability to operate in various climates [4]. In addition, the server had multiple serial ports [4], which allowed the lasers to be integrated into a single server rather than having multiple servers.

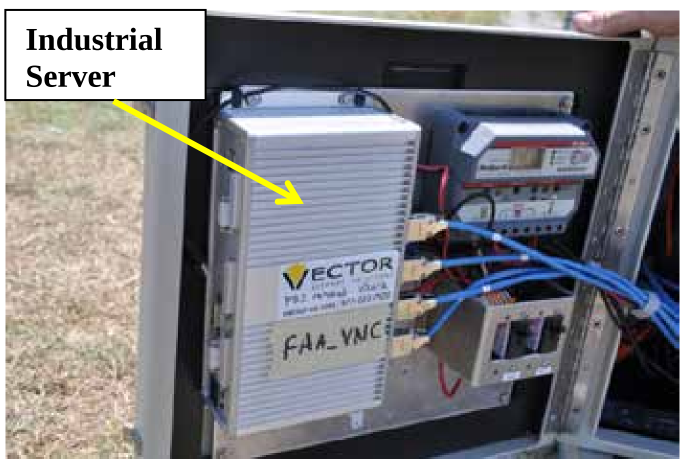

Figure 6. Industrial Server

2.3.2 Cellular Router.

A cellular router equipped with a 3G router was located inside the data collection box. The router transmitted data from the server in the data collection box to a central server for processing. The first data collection system in Phase III included a Digi® ConnectPort® Wan cellular router, shown in figure 7. The other three systems included a Proxicast® LAN-Cell 2™ cellular router, shown in figure 8, which performed better than the Digi ConnectPort Wan cellular router.

Figure 7. Digi ConnectPort Wan Cellular Router Installed at Palm Beach International Airport

Figure 8. Proxicast LAN-Cell 2 Cellular Router

2.3.3 Battery and Battery Charger.

The final component in the data collection box was a deep-cycle battery, commonly called a marine battery, shown on the left in figure 9. The battery powered both the industrial server and wireless router. The battery held a constant 12-volt charge via a battery charger, also located in the data collection box. The battery charger is shown on the right in figure 9.

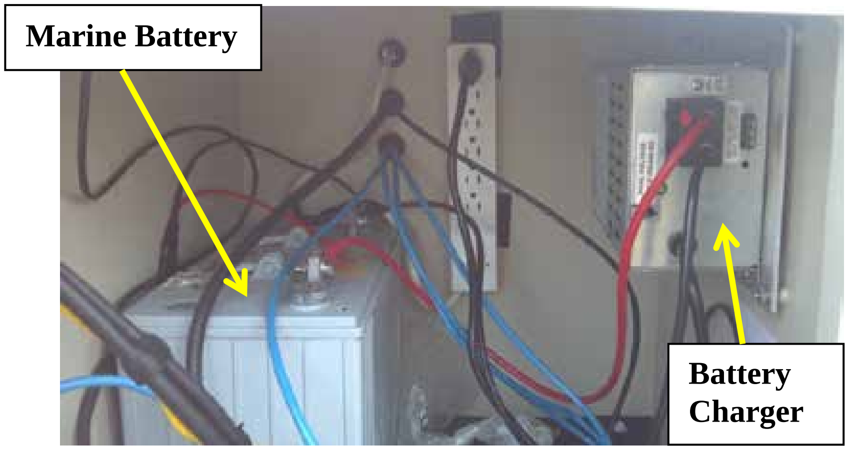

Figure 9. Battery and Battery Charger

2.4 POWER CONTROL CENTER.

A PCC was located near the data collection box, which acted as a circuit breaker panel for the data collection system, see figure 10. Except for the first airport in phase III (PBI), the remaining three airports had a PCC installed with the data collection system. The PCC was added to the data collection system in the event a laser(s) or data collection system experienced an overload. The PCC only took the respective laser(s) or data collection system offline instead of the entire system.

There were five circuit breakers on the PCC, one for each laser and one for the data collection box. Each laser was on a 5-amperage (amp) circuit, and the data collection box was on a 15-amp circuit. Located to the right of each circuit breaker was a green light-emitting diode (LED) light that indicated the status of the lasers and the data collection box. In normal operating conditions, each LED light was illuminated. In the event a laser(s) or data collection box experienced an overload, the respective circuit breaker would "pop," and the corresponding LED light would not be illuminated. To reset the circuit breaker, one had to simply push in the breaker that was overloaded.

Figure 10. Power Control Center

3. DATA COLLECTION SYSTEM INSTALLATION.

During Phase III, four taxiway deviation data collection systems were installed at four civil airports that have standard ADG III straight taxiway sections, which are 50 ft wide [5] and that serve ADG III aircraft that have a wingspan of 79 to <118 ft [5], such as an Airbus 320 and Boeing 737. The data collection systems were located outside the taxiway safety area (TSA) and taxiway object-free area (TOFA) of its corresponding ADG III taxiway standard designs.

Under a cooperative R&D agreement, the FAA Airport Technology R&D Branch is working with The Boeing Company (Boeing) to statistically analyze the data collected during this study. To obtain optimal results during the data collection period, Boeing selected the optimal distances between each laser. With the exception of the first data collection system, which was installed at PBI, the remaining three data collection systems followed the spacing parameters outlined in table 1 and figure 11. Because the PBI data collection system was installed concurrently with the final ADG IV system, the spacing of the lasers along the ADG III straight taxiway sections was the same as for the ADG IV data collection system installations. These distances are discussed in section 5.1.1.

Table 1. Optimal Distances Between Each Laser

Distance Between the Center of:	Feet
Laser 1 and 2	110
Laser 2 and 3	35
Laser 3 and 4	255

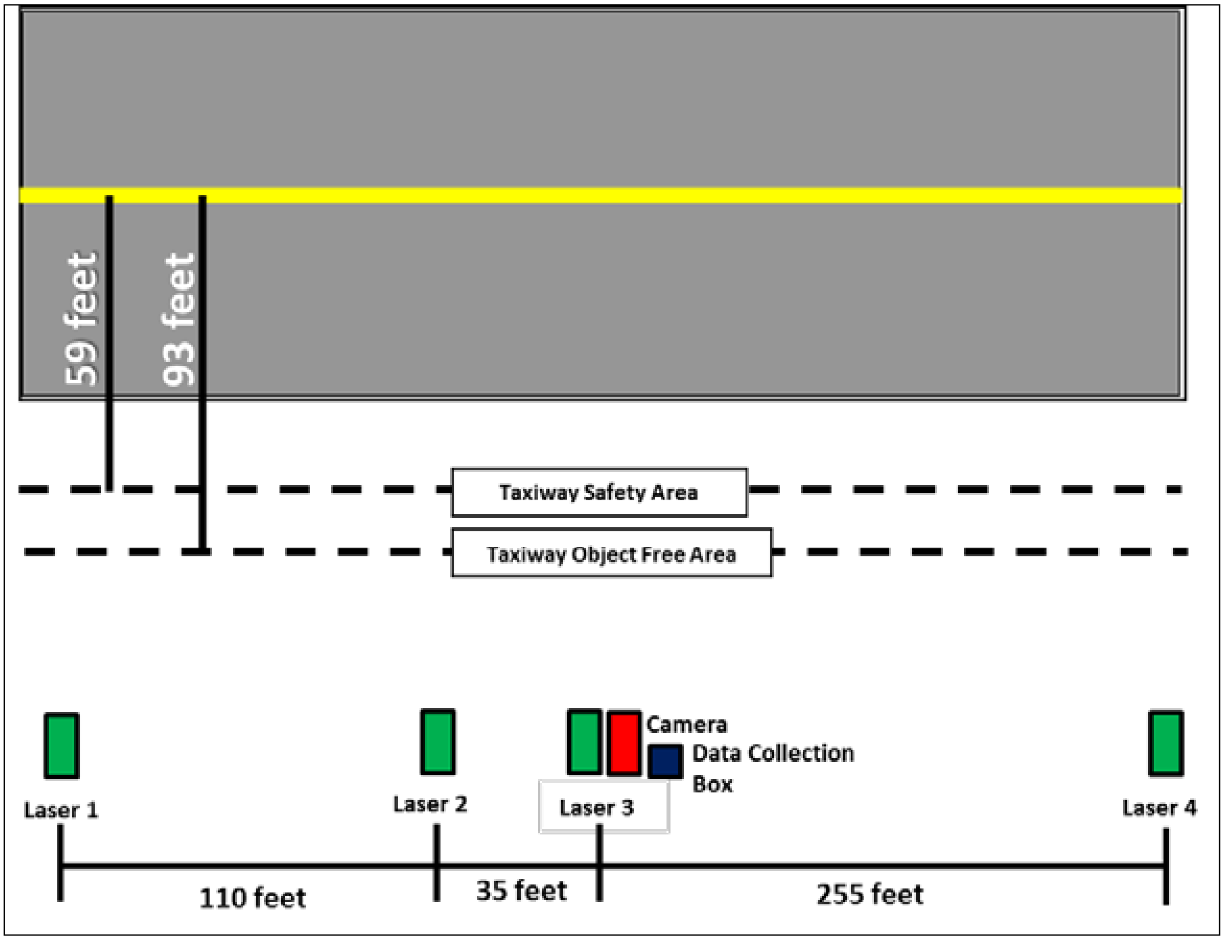

Figure 11. A Typical ADG III System Installation (not to scale)

As the study evolved, smaller ADG aircraft were tracked while taxiing in their corresponding ADG taxiway. These aircraft had smaller wheel bases[1] than the aircraft tracked during Phases I and II. Therefore, Boeing modified the distances between each laser. This modification allowed the data collection systems to be installed on smaller stretches of taxiway. Although Boeing selected the optimal distances between each laser, the exact distances varied slightly, and Boeing was informed of each variation. These distances are explained in detail in section 5.

Each laser was secured to two support legs and was frangible-mounted to either concrete pads, as shown in figure 12, or steel H-frames, as shown in figure 13. The lasers' support legs were between 2 and 4 ft high, varying from airport to airport, depending on the terrain. The lasers for the first two data collection systems installed in Phase III were mounted on concrete pads, as shown in figure 12. As the study progressed, steel H-frames were designed to mount the lasers, as shown in figure 13. The steel H-frames were portable, reusable, and more cost-effective than the concrete pads. The steel H-frames were leveled and secured to the ground with 8-ft ground rods. U-bolts were used to secure the ground rods to the steel H-frame. Each laser was aimed 12 in. above the centerline of the respective taxiway to capture the wheel hub of an aircraft's

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[1] Wheel base: the distance from the center of the nose gear to the center of the main gear of an aircraft.

main and nose gears. This allowed the laser's signal to terminate into the ground on the opposite side of the taxiway.

Figure 12. Lasers Mounted on Concrete Pad

Figure 13. Lasers Mounted on Steel H-Frame

The data collection box was also frangible-mounted to a pair of 3-in. rails with plastic nylon hardware. When concrete pads were used, the data collection box was secured to the pad with lead anchors and lag screws, as shown in figure 14. The data collection boxes that were installed concurrently with the lasers on steel H-frames were secured to the ground with 8-ft ground rods. U-bolts were used to secure the ground rods to the rails, as shown in figure 15.

Figure 14. Data Collection System Installed on a Concrete Pad

Figure 15. Data Collection System Installed on Rails

The data collection system was powered by 120 volts of alternating current (V AC) 20-amp power source via number 12 thermoplastic, high heat-resistant, nylon-coated wire. Electrical power was housed in conduit and was distributed from a designated power source to the laser closest to the power source. Thereafter, electrical power was housed in conduit and distributed to the remaining three lasers and the data collection box. The lasers at the first data collection system in Phase III were powered by ground fault circuit interrupter (GFCI) outlets. However, the GFCI outlets were found to trip due to condensation buildup in the outlet box. To avoid false tripping, the lasers at the other three data collection systems were hardwired from incoming power with junction boxes, weather-tight covers, and cable connectors. The junction boxes were approximately 12 to 18 in. above ground level.

A second line of conduit was run between the lasers and parallel to the conduit that housed the electrical power. The conduit housed communications cable used to transfer data from the lasers to the industrial server at the data collection box. An RS232 communications cable was used at the first data collection system in Phase III. The other three data collection systems were upgraded to RS422 communications cable, which increased the data transfer performance. Communications cable was fed from the data collection box, located near laser 3, to all four lasers. This communications cable was also hardwired via weatherproof junction boxes with weather-tight cable connectors.

Figure 16 shows the plan and profile views of the data collection system installation. The specific details of the installation are given in section 5.

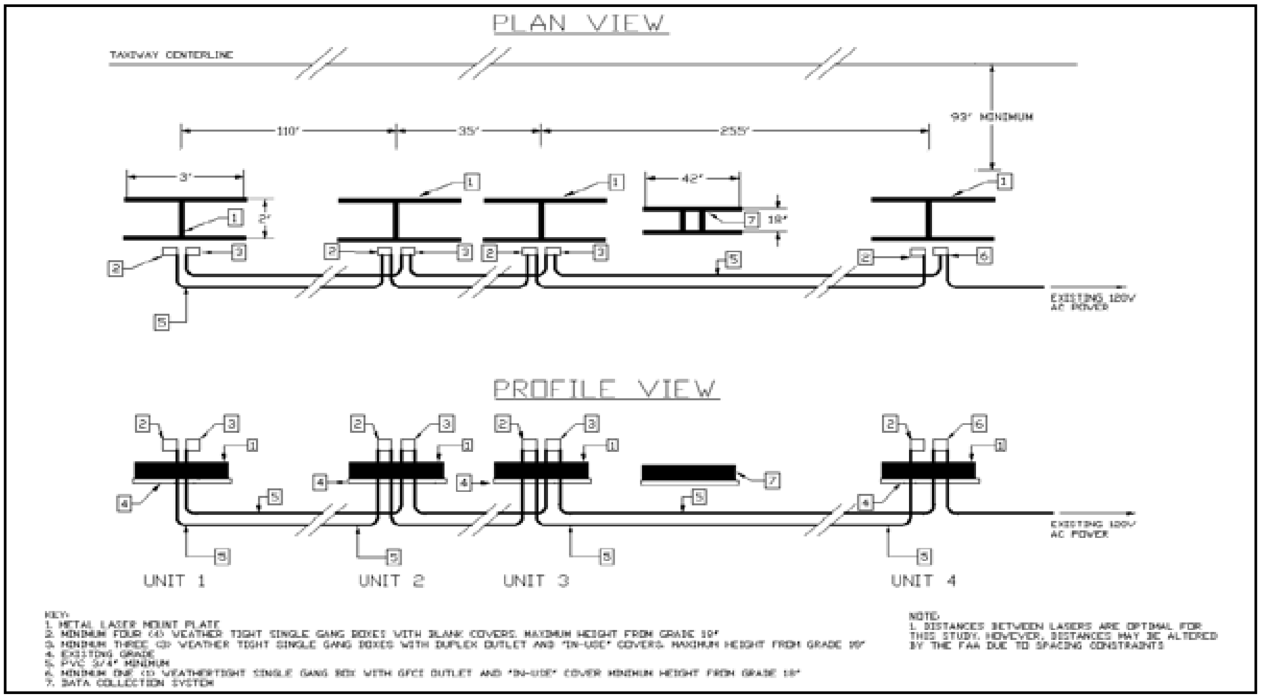

Figure 16. Plan and Profile Views of the Data Collection System

4. DATA COLLECTION SYSTEM OPERATION.

The data collection system operated continuously and collected data 24 hours a day, 7 days a week. The following is an example of a typical data collection scenario.

An aircraft will first taxi past laser 4, with data collection concluding at laser 1, as shown in figure 17. As an aircraft taxis past laser 4, the laser records multiple laser measurements of the distance between the aircraft's nose and outer main gears relative to the taxiway centerline. The multiple laser measurements are referred to as laser counts. The number of laser counts varies, depending on how fast an aircraft is taxiing. The laser counts range from as little as one to as many as a few hundred. The laser counts are then averaged together using an algorithm. An activity date and time is also correlated with each laser measurement. As the aircraft continues taxiing, the process repeats at laser 3, and the high-definition camera installed near laser 3 takes a picture of the aircraft's tail number. As the aircraft taxis past lasers 2 and 1, the lasers record the distance and time. Through a series of algorithms, the aircraft's tail number is linked to each laser measurement. The data collected from each laser is transferred to the server located in the data collection box near laser 3. Thereafter, the data are transferred to a central server for further processing.

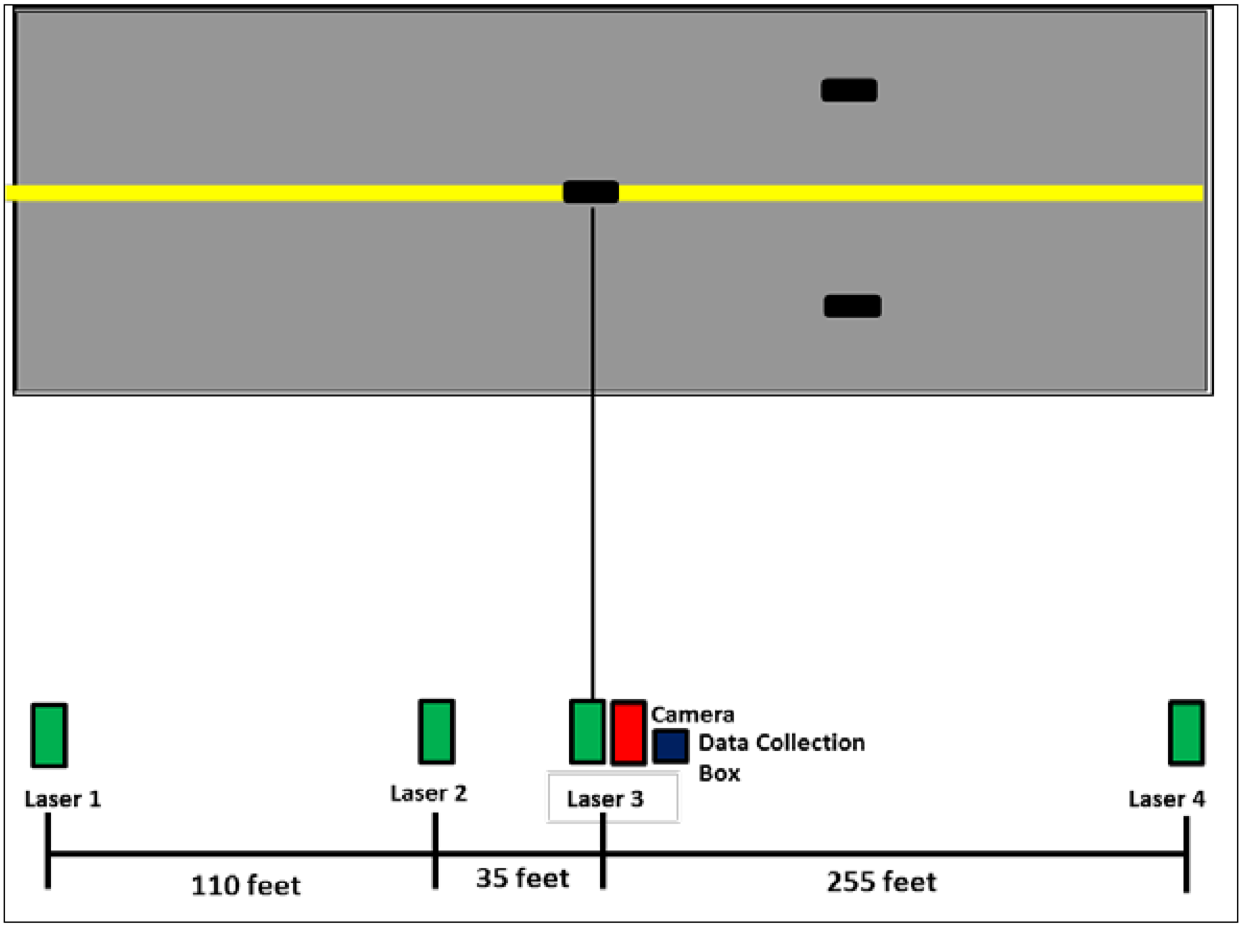

Figure 17. Aircraft Footprint on a Taxiway (not to scale)

4.1 DATA COLLECTION SYSTEM MONITORING.

During Phase III, the status of each data collection system was remotely monitored. Two web portals were used to monitor the systems: Log-Me-In Central and the Vector Portal Site. In the event the data collection system went offline, Log-Me-In Central sent an automated email alert message to the research team. The alert message indicated which system went offline and at what date and time. Figure 18 shows an example of the Log-Me-In Central, showing the status of each data collection system. Typically, the systems went offline due to poor internet connectivity, server malfunctions in the data collection box, and loss of power to the system.

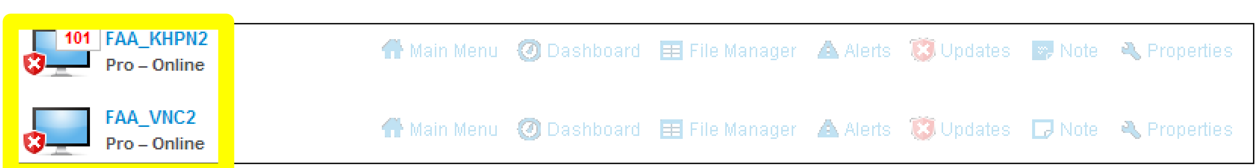

Figure 18. Log-Me-In Central—System Status

The Vector Portal Site showed the status of the individual lasers at each airport where a data collection system was installed. This site indicated whether the lasers were collecting data. If a laser(s) did not collect data within a 24-hour period, the respective laser(s) would be highlighted in orange, as shown in figure 19. This could be an indication that aircraft did not pass by the data collection system or that a particular laser(s) was offline. Alternatively, this condition could be an indication that the data transmission speed has been significantly reduced.

Laser Status

Airport Code	Laser Name	Activity Date
KHPN	L1	6/24/2013 1:08:02 PM
KHPN	L2	6/25/2013 8:22:04 AM
KHPN	L3	6/24/2013 9:33:27 PM
KHPN	L4	6/25/2013 8:21:56 AM
KVNC	L1	6/12/2013 8:01:48 AM
KVNC	L2	6/12/2013 7:15:34 AM
KVNC	L3	6/12/2013 7:15:35 AM
KVNC	L4	6/12/2013 7:15:44 AM

Figure 19. Vector Portal Site—Laser Status

In the event the data collection system went offline or a laser(s) was not collecting data, the research team would first troubleshoot remotely. If unsuccessful, the research team would work with Airport Operations/Maintenace departments to troubleshoot the system. If still unsuccessful, a member of the research team would travel to the airport to troubleshoot the system or laser(s).

4.2 DATA PROCESSING AND ANALYSIS.

The data collected from the system was transmitted to a central server. Figure 20 shows how the data is presented on the Vector Portal Site. The data presented includes the date and time of measurement, aircraft tail number, model type, the laser that took the measurement, the median and average measurements, and the number of laser counts.

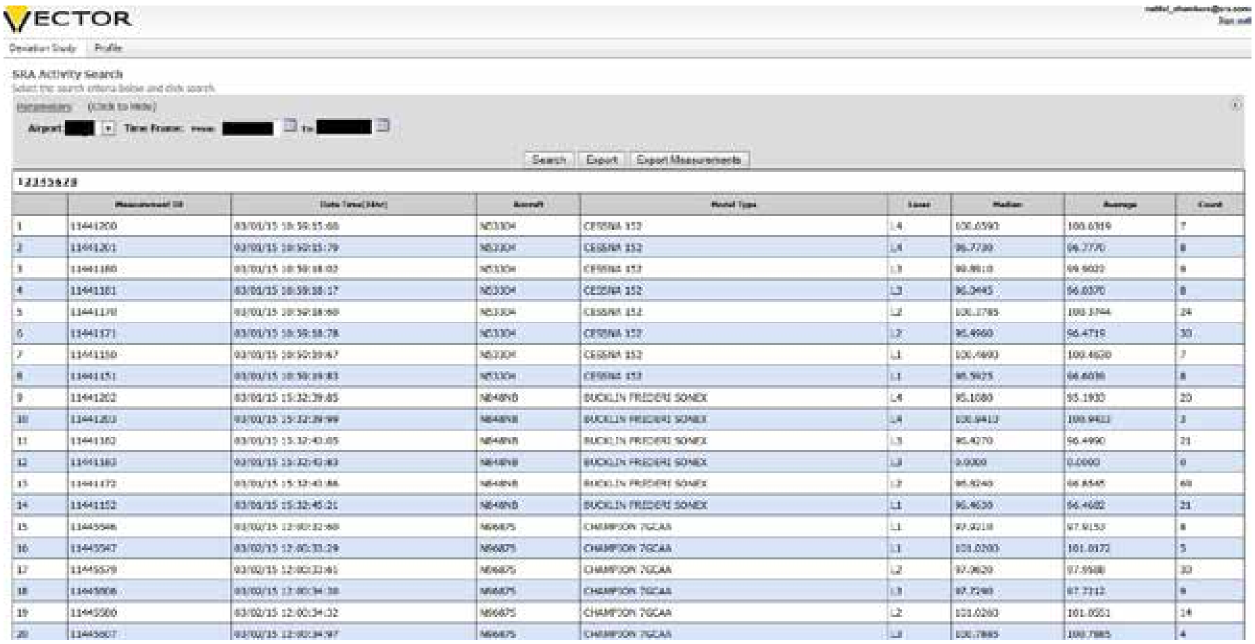

Figure 20. Vector Portal Site—Aircraft Activity Search

On a routine basis, the data from the Vector Portal Site was exported and run through an algorithm. This algorithm filtered for ADG III aircraft and associated the laser measurement as being a nose or main gear measurement. The data was analyzed for accuracy and sent to Boeing on a quarterly basis for statistical analysis. A sample dataset is shown in figure 21. The eight measurements comprise a complete dataset, including one nose wheel hub and one main gear wheel hub measurement for each laser.

ID	DateTime	DateTime	ActivityDateTime	AircraftNumber	ModelTypeDesignator	CommonName	DesignGroup	Laser	LaserGear	Distance	ExactDeviation	WholeNumberDeviation	Dataset	ActivityCount
1	7/9/2012 19:09	09:23.0	07/09/12 19:09:22:95	N800KS	BOEING 737-7BC	Boeing 737-700	III	L1	L1N	138.9482	1.1518	1	8	5
2	7/9/2012 19:09	09:23.6	07/09/12 19:09:24:11	N800KS	BOEING 737-7BC	Boeing 737-700	III	L1	L1M	128.4659	11.634	12	8	16
3	7/9/2012 19:09	09:26.1	07/09/12 19:09:26:08	N800KS	BOEING 737-7BC	Boeing 737-700	III	L2	L2N	138.7616	1.0384	1	8	8
4	7/9/2012 19:09	09:27.0	07/09/12 19:09:26:98	N800KS	BOEING 737-7BC	Boeing 737-700	III	L3	L3N	138.6163	1.1837	1	8	9
5	7/9/2012 19:09	09:27.3	07/09/12 19:09:27:30	N800KS	BOEING 737-7BC	Boeing 737-700	III	L2	L2M	128.372	11.428	11	8	15
6	7/9/2012 19:09	09:28.2	07/09/12 19:09:28:20	N800KS	BOEING 737-7BC	Boeing 737-700	III	L3	L3M	128.2293	11.5707	12	8	15
7	7/9/2012 19:09	09:34.6	07/09/12 19:09:34:59	N800KS	BOEING 737-7BC	Boeing 737-700	III	L4	L4N	140.3909	-0.5909	-1	8	10
8	7/9/2012 19:09	09:35.9	07/09/12 19:09:35:94	N800KS	BOEING 737-7BC	Boeing 737-700	III	L4	L4M	129.7843	10.0157	10	8	18

Figure 21. Sample Dataset

Occasionally, a dataset was incomplete and contained between one and seven laser measurements. An incomplete dataset was typically attributed to an obscure laser measurement(s) that was removed during data analysis, a laser(s) that went offline, or a laser(s) that failed to capture (measure) the wheel hub on the nose or main gears. Although some datasets were incomplete, Boeing was able to use the data for their statistical analysis.

5. AIRPLANE DESIGN GROUP III AIRPORTS.

During Phase III of the Taxiway Deviation Study, four data collection systems were installed at four civil airports, as shown in figure 22. Each airport met the criteria for this study, including straight taxiway sections designed to ADG III standards, which are 50 ft wide [5], and which serve a strong mix of ADG III aircraft with wingspans of 79 to <118 ft [5], similar to an Airbus 320 and Boeing 737. These airports were selected because they were located in different geographic regions of the United States (U.S.). Therefore, various weather conditions in these regions influenced the aircraft data collected during Phase III. The selected ADG III airports participating in the study included Palm Beach International Airport (PBI), FL; Salisbury-Ocean City Wicomico Regional Airport (SBY), MD; Key West International Airport (EYW), FL; and Westchester County Airport (HPN), NY. The airports are listed in the order in which the data collection systems were installed. Prior to each system installation, a project plan with the details of the system installation was approved by the respective airport and its corresponding FAA regional office. The specific details of each airport, the data collection system installation, and a summary of the data collected are given in the following sections.

Figure 22. Selected ADG III Airports

5.1 PALM BEACH INTERNATIONAL AIRPORT, WEST PALM BEACH, FL.

5.1.1 System Overview.

Palm Beach International Airport (PBI) was the first airport to have the data collection system installed. PBI was an ideal airport because of the high frequency and mix of ADG III aircraft that operate at the airport. At the time of this study, PBI was classified in the U.S. FAA National Plan of Integrated Airport System (NPIAS) as a primary[2] commercial service[3] medium-hub airport[4] [6].

With guidance from the management team at PBI, it was determined that the best location for the data collection system, based on the criteria, would be along Taxiway L, between Taxiways S and L1, as shown in figures 23 and 24. Taxiway L was built to ADG III standards with a 50-ft-wide taxiway and a 20-ft-wide paved shoulder (painted green). The taxiway markings on Taxiway L included continuous taxiway edge and centerline markings. In addition, an interim surface marking, "TAXIWAY," was located between lasers 3 and 4. This marking was applied so the taxiways were not mistaken for runways, as shown in figure 24. Taxiway L was also equipped with elevated taxiway edge lights; however, it did not have taxiway centerline lights. This was an ideal location for the data collection system because it captured the majority of traffic taxiing to and from the airport's general aviation (GA) hangars and fixed-based operators (FBO). The GA hangers and FBOs are located on the airport's south side adjacent to Runway 10L/28R, which is the airport's primary runway for arrivals and departures.

On April 23, 2009, the data collection system was installed at PBI on the north side of Taxiway L, between Taxiways S and L1, as shown in figures 23 and 24. The data collection system was installed approximately 109 ft from and parallel to the centerline of Taxiway L, which was clear of Taxiway L's TSA and TOFA. In addition, the data collection system was approximately 295 ft from Runway 10L/28R's centerline, which was clear of Runway 10L/28R's runway safety area and runway object-free area.

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[2] Primary airports are "receive an annual apportionment of at least $1 million in airport improvement program funds with the amount determined by the number of enplaned passengers." [9]

[3] Commercial service airports are "public airports receiving scheduled passenger service and having 2,500 or more enplaned passengers per year." [9]

[4] Medium-hub airports "account for between 0.25 percent and 1 percent of total U.S. passenger enplanements." [9]

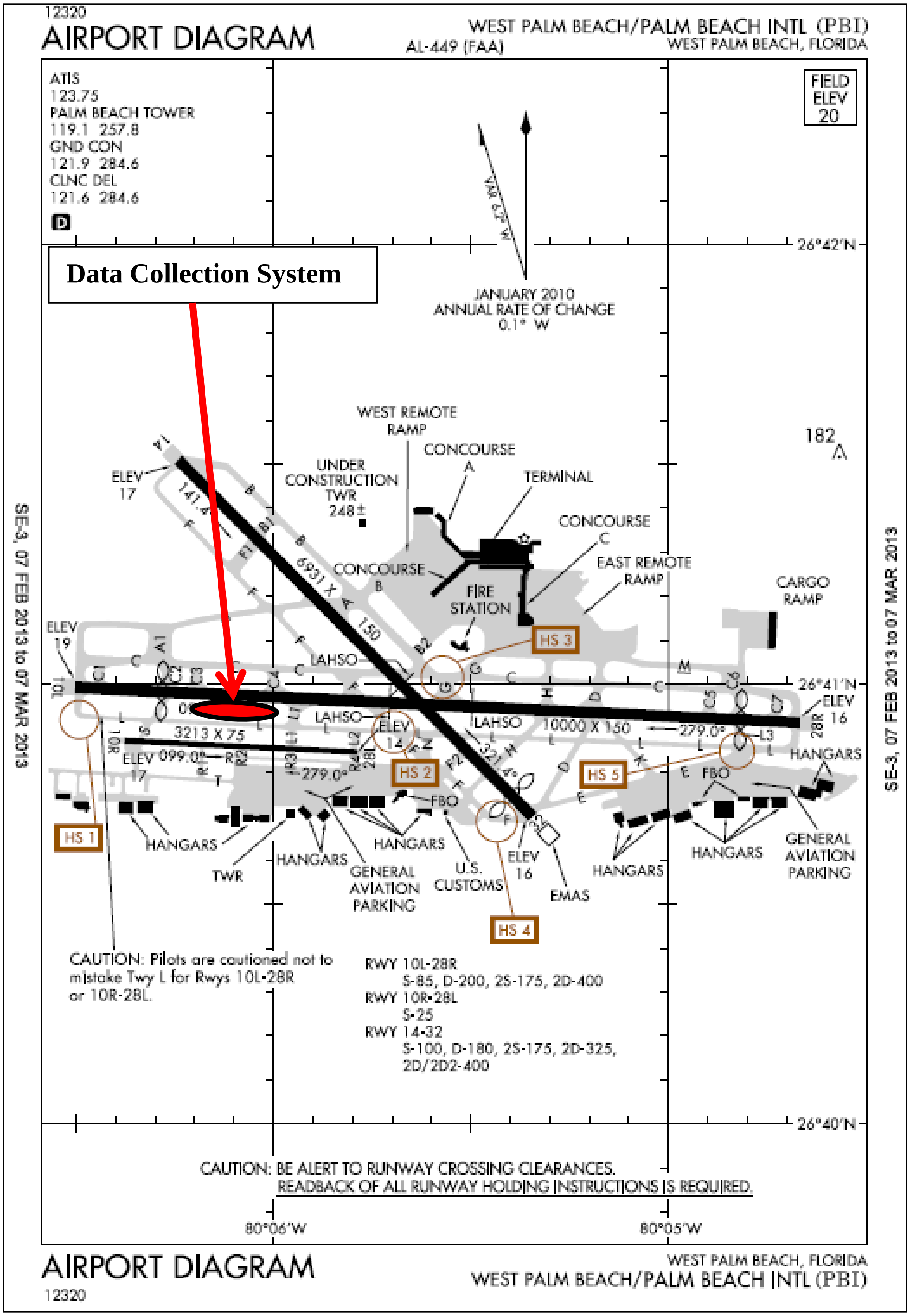

Figure 23. Data Collection System Location at PBI

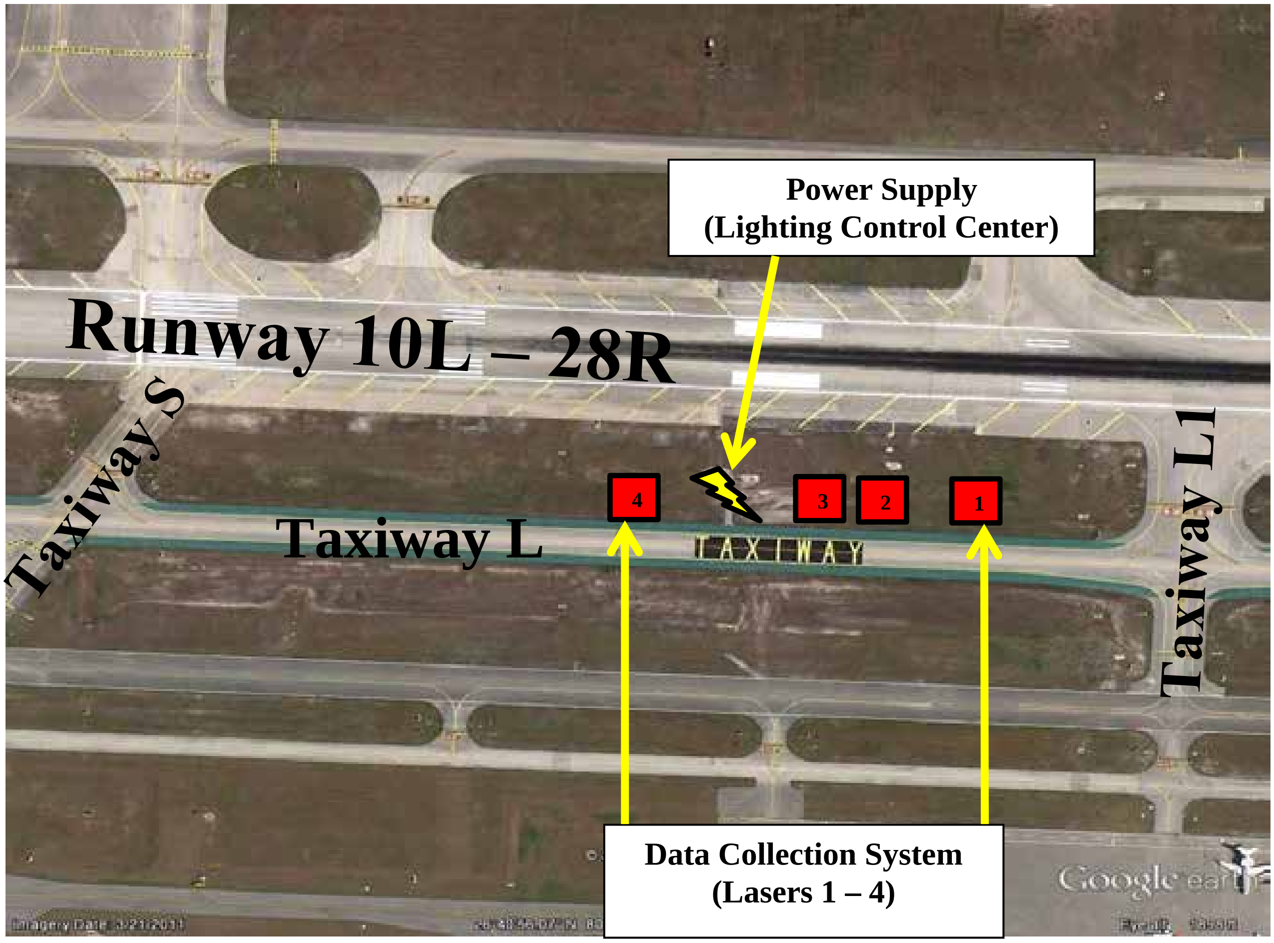

Figure 24. Aerial Photograph of the Data Collection System at PBI (not to scale)

A local electrical contractor installed the electrical infrastructure for the data collection system at PBI. This infrastructure included four concrete pads and two 3/4-in. conduit lines. The electrical contractor installed the concrete pads and conduit below ground level. Each laser was mounted to its associated concrete pad on two 4-ft support legs and was secured to the concrete pad with frangible couplings. The distance between lasers 1 and 2 was 161 ft; between lasers 2 and 3, 50 ft; and between lasers 3 and 4, 372 ft.

An FAA lighting control center located near the Runway 10L glide slope building provided 120 V AC 20-amp power to the data collection system, as shown in figure 25. The use of this power supply was coordinated with PBI's FAA Air Traffic Control Tower (ATCT) and FAA Technical Operations Managers. The lighting control center was located approximately 4 ft north of the conduit line between lasers 3 and 4. Power was distributed from the lighting control center to laser 4. A second power line was distributed from the lighting control center to lasers 3, 2, and 1.

Figure 25. Lighting Control Center at PBI

The data collection system was removed on July 9, 2012. Shortly thereafter, the concrete pads were removed by a local contractor. With permission from PBI, the abandon conduit from the system remained in place. An as-built drawing of the abandon conduit was provided to the airport.

5.1.2 Data Collected.

During the data collection period at PBI, the data collection system tracked 1211 ADG III aircraft movements, yielding 8876 laser measurements, as shown in table 2. Of the 1211 aircraft tracked by the data collection system, 69% were complete datasets (DS). The remaining 31% were incomplete; however, the incomplete datasets were still used by Boeing for their statistical analysis. As shown in table 3, Gulfstream V and Bombardier Global Express were the most common ADG III aircraft tracked by the data collection system.

Table 2. Summary of ADG III Data Collected at PBI (05/02/2009–04/12/2012)

Number of Aircraft Movements	Number of ADG III Laser Measurements	Dataset							
		DS 8	DS 7	DS 6	DS 5	DS 4	DS 3	DS 2	DS 1
1211	8876	837	57	271	12	12	4	17	1

Table 3. The ADG III Aircraft Tracked by the Data Collection System at PBI

Type of Aircraft	Number of Aircraft Movements	Percentage of ADG III Movements
Gulfstream V	732	60
Bombardier Global Express	408	34
Dassault Falcon 7x	22	2
DeHavilland Caribou	13	1
Boeing B737	12	<1
Boeing B727	8	<1
DC-9	7	<1
Convair 340	4	<1
Airbus A320	2	<1
DeHavilland Dash 8	1	<1
Airbus A319	1	<1
McDonnell Douglas MD-88	1	<1
Total	1211	100

5.2 KEY WEST INTERNATIONAL AIRPORT, KEY WEST, FL.

5.2.1 System Overview.

Key West International Airport (EYW) was the second airport selected for the study. At the time of this study, EYW received high-volume ADG III traffic. The airport has one runway, Runway 09/27, with one parallel taxiway, Taxiway A, as shown in figure 26. Regardless of the runway end in use, aircraft were forced to taxi past the data collection system prior to takeoff or after landing. Taxiway A was built to ADG III standards with a 50-ft-wide taxiway and no paved shoulder. The taxiway had a taxiway centerline marking but did not have continuous taxiway edge markings. In addition, Taxiway A was equipped with elevated taxiway edge lights; however, it did not have taxiway centerline lights. At the time of this study, EYW was classified in the U.S. FAA NPIAS as a non-hub[5] primary commercial service airport [7].

A data collection system was installed at EYW on November 16, 2011. The installation site was located south of Taxiway A, between Taxiways B and A1, as shown in figures 26 and 27. The data collection system was approximately 87 ft from Taxiway A's centerline and was clear of the TSA and just inside the TOFA (required 93 ft). Typically, the data collection system would be installed outside the TOFA of a respective taxiway; however, Taxiway A had a nonstandard TOFA. Therefore, the data collection system was installed south of Bunker Road, the airport's nonmovement area boundary line.

[5] Non-hub airport: "commercial service airports that enplane less than 0.05 percent of all commercial passenger enplanements but have more than 10,000 annual enplanements are categorized as non-hub primary airports." [9]

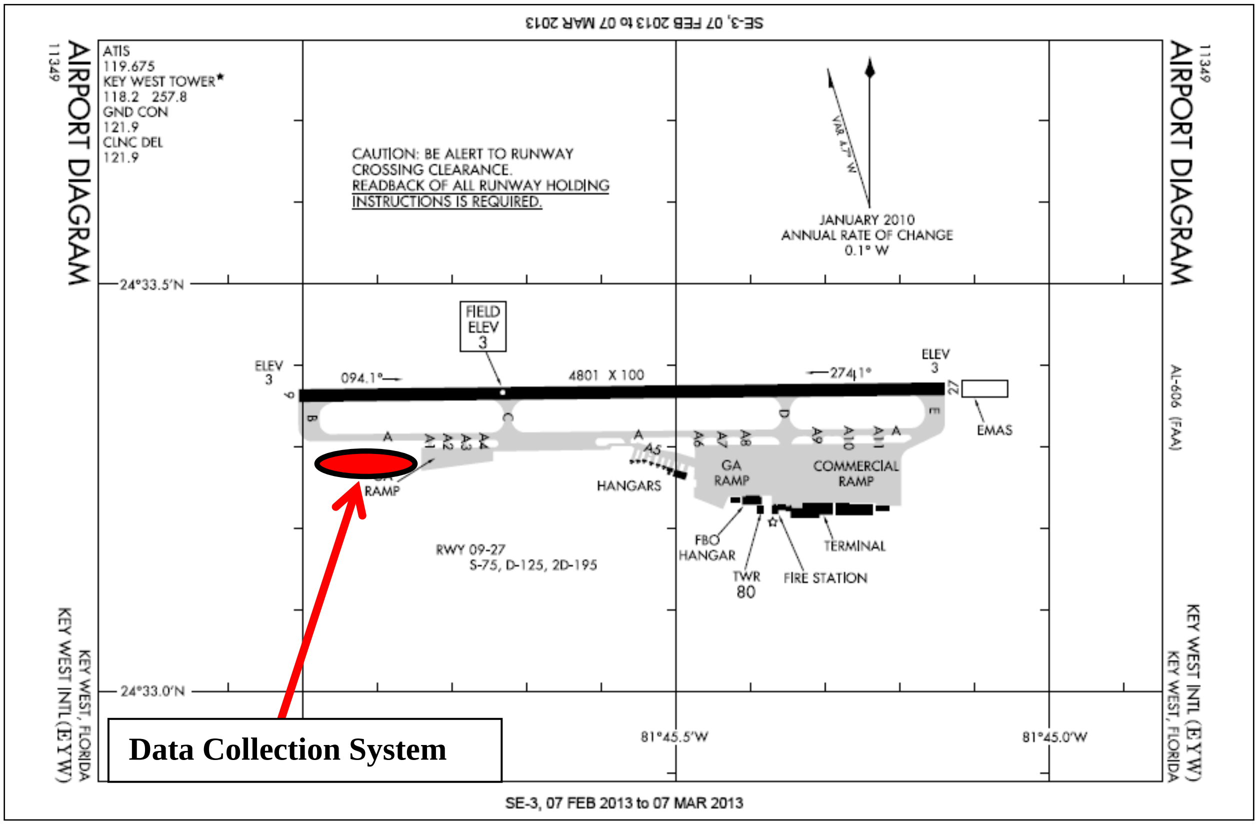

Figure 26. Data Collection System Location at EYW

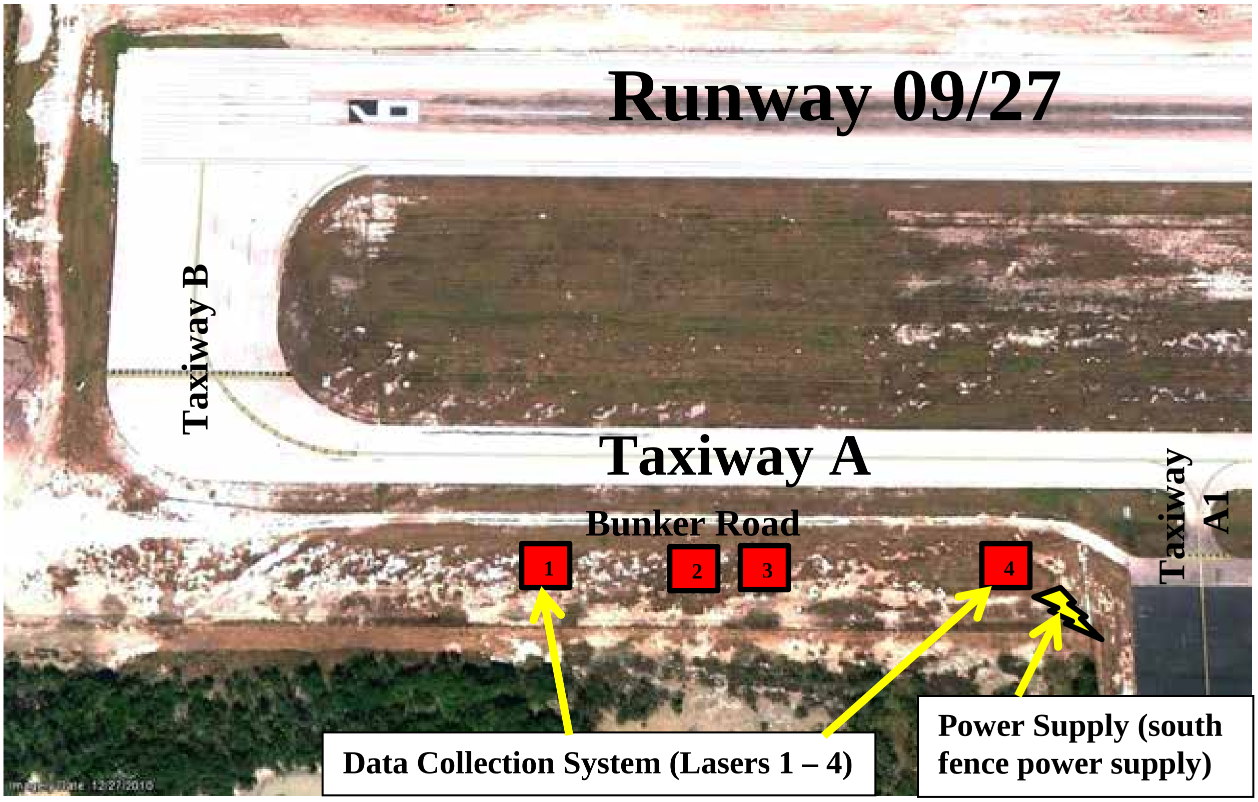

Figure 27. Aerial Photograph of the Data Collection System at EYW (not to scale)

The data collection system was installed on premade, portable concrete pads, which sat on top of the terrain south of Taxiway A. The conduit also rested on top of the terrain due to environmental concerns and makeup of the terrain, which restricted burying the conduit. Each laser was mounted to its associated concrete pad on two 3-ft support legs and was secured to the concrete pad with frangible couplings. The distance between lasers 1 and 2 was 110 ft; between lasers 2 and 3, 35 ft; and between lasers 3 and 4, 255 ft. Moreover, the distance from laser 1 to the curve of Taxiway B was 200 ft and from laser 4 to the curve of Taxiway A1, 96 ft.

Prior to installing the data collection system, EYW's electrician installed a 120 V AC 20-amp power supply called the "south fence power supply," as shown in figure 28, which was located approximately 85 ft southeast of laser 4. Power was supplied to laser 4 from this power supply; then from laser 4 to the data collection system and the remaining three lasers.

Figure 28. South Fence Power Supply

On January 16, 2013, the data collection system, concrete pads, conduit, and electrical and communications cables were removed.

5.2.2 Data Collected.

During the data collection period at EYW, the data collection system tracked 1801 ADG III aircraft movements, yielding 13,308 laser measurements, as shown in table 4. Of the 1801 ADG III aircraft tracked, nearly 62% had complete datasets, or datasets of 8, as shown in table 4. The remaining 38% were incomplete; however, the data were still used by Boeing for their statistical analysis. As shown in table 5, the ATR 72 and Boeing 737 were the most common ADG III aircraft tracked by the data collection system.

Table 4. Summary of ADG III Data Collected at EYW (02/23/2012–01/16/2013)

Number of Aircraft Movements	Number of ADG III Laser Measurements	Dataset							
		DS 8	DS 7	DS 6	DS 5	DS 4	DS 3	DS 2	DS 1
1801	13,308	1117	511	83	44	42	2	2	0

Table 5. The ADG III Aircraft Tracked by the Data Collection System at EYW

Type of Aircraft	Number of Aircraft Movements	Percentage of ADG III Movements
ATR 72	925	51
Boeing B737	676	38
Embraer E170	177	10
DeHavilland Dash 8	14	<1
Gulfstream V	6	<1
Airbus A319	2	<1
Global Express	1	<1
Total	1801	100

5.3 SALISBURY-OCEAN CITY WICOMICO REGIONAL AIRPORT, SALISBURY, MD.

5.3.1 System Overview.

The third data collection system was installed at Salisbury-Ocean City Wicomico Regional Airport (SBY). At the time of this study, SBY received a high volume of ADG III traffic and was classified by the U.S. FAA NPIAS as a non-hub primary commercial service airport [7].

Prior to installing the data collection system at SBY, a temporary aircraft identification system was installed southwest of Taxiway A, between Taxiways D and B, as shown in figure 29. The system was solar-powered and included a camera, IR illuminator, industrial server, and cellular router. The system was located outside Taxiway A's TSA and TOFA, and it monitored the mix and frequency of ADG III aircraft that taxied along Taxiway A. During the 32 days the aircraft identification system was in place, 191 ADG III aircraft passed by the system. Consequently, the data confirmed that Taxiway A would be an ideal location for a data collection system.

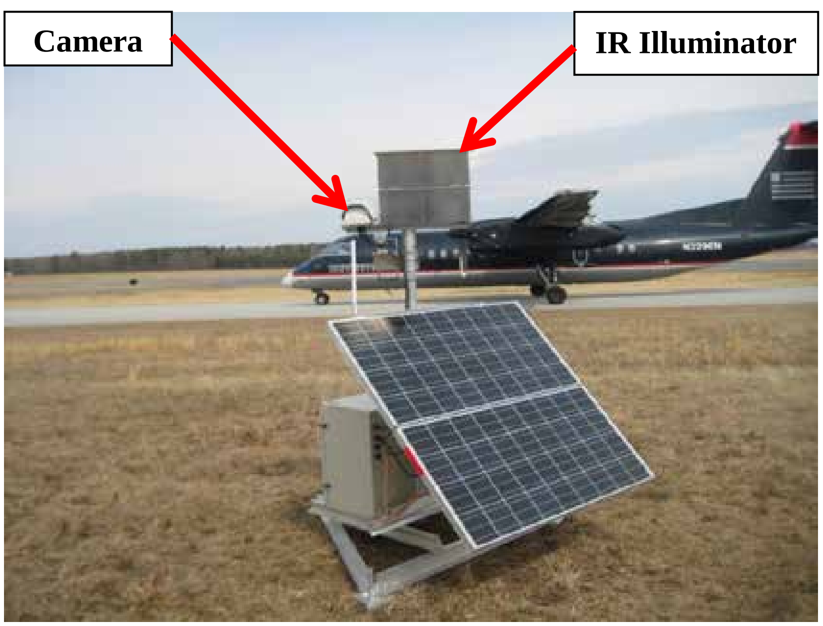

Figure 29. Temporary Aircraft Identification System

On July 6, 2011, the data collection system was installed at SBY on the southwest side of Taxiway A, between Taxiways B and D, as shown in figures 30 and 31. The data collection system was 99 ft from Taxiway A and was clear of Taxiway A's TSA and TOFA. Taxiway A was designed to ADG III standards with a 50-ft-wide taxiway and no paved shoulder. The taxiway had a taxiway centerline marking but did not have continuous taxiway edge markings. In addition, Taxiway A was equipped with elevated edge lights; however, it did not have taxiway centerline lights.

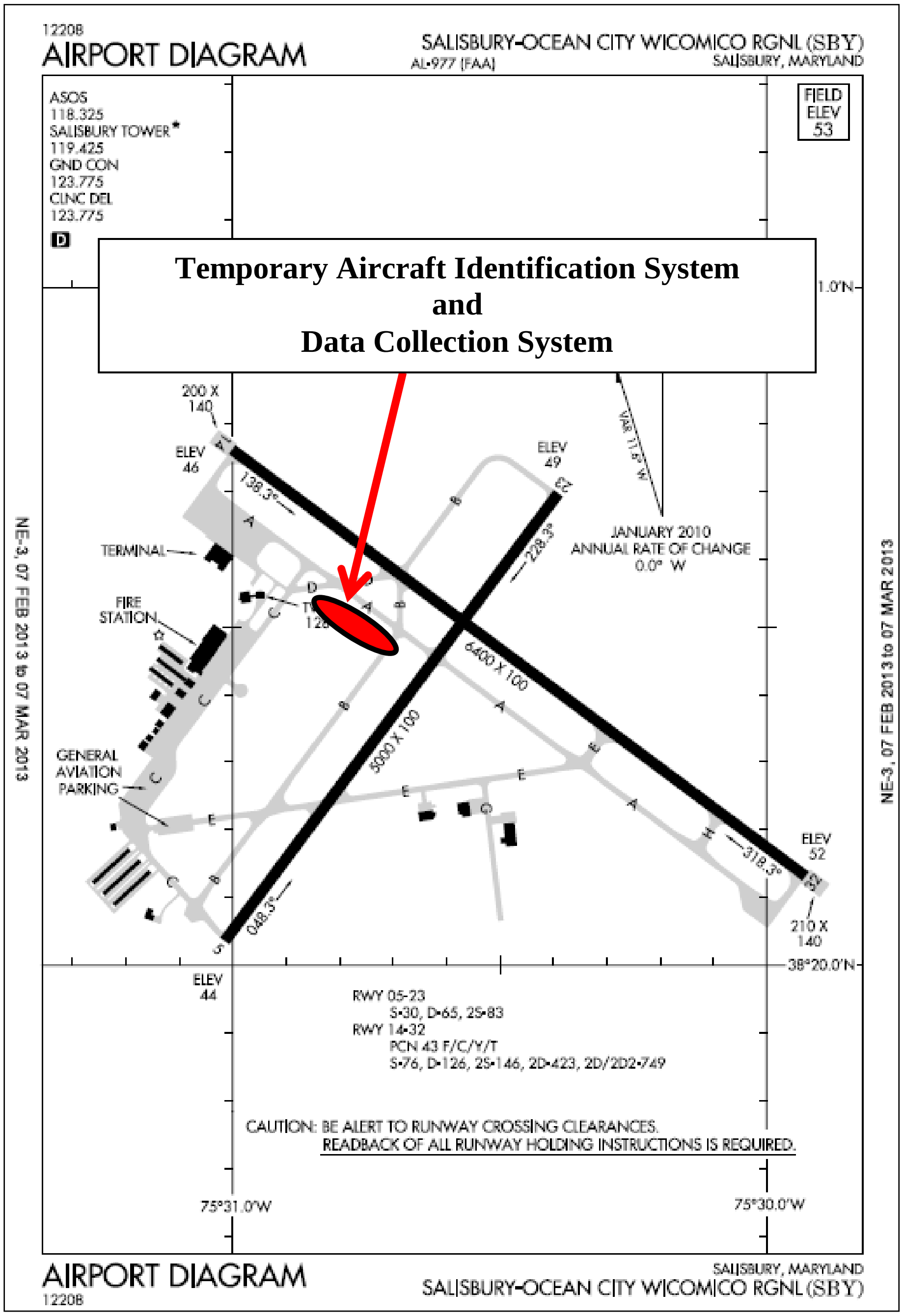

Figure 30. Data Collection System Location at SBY

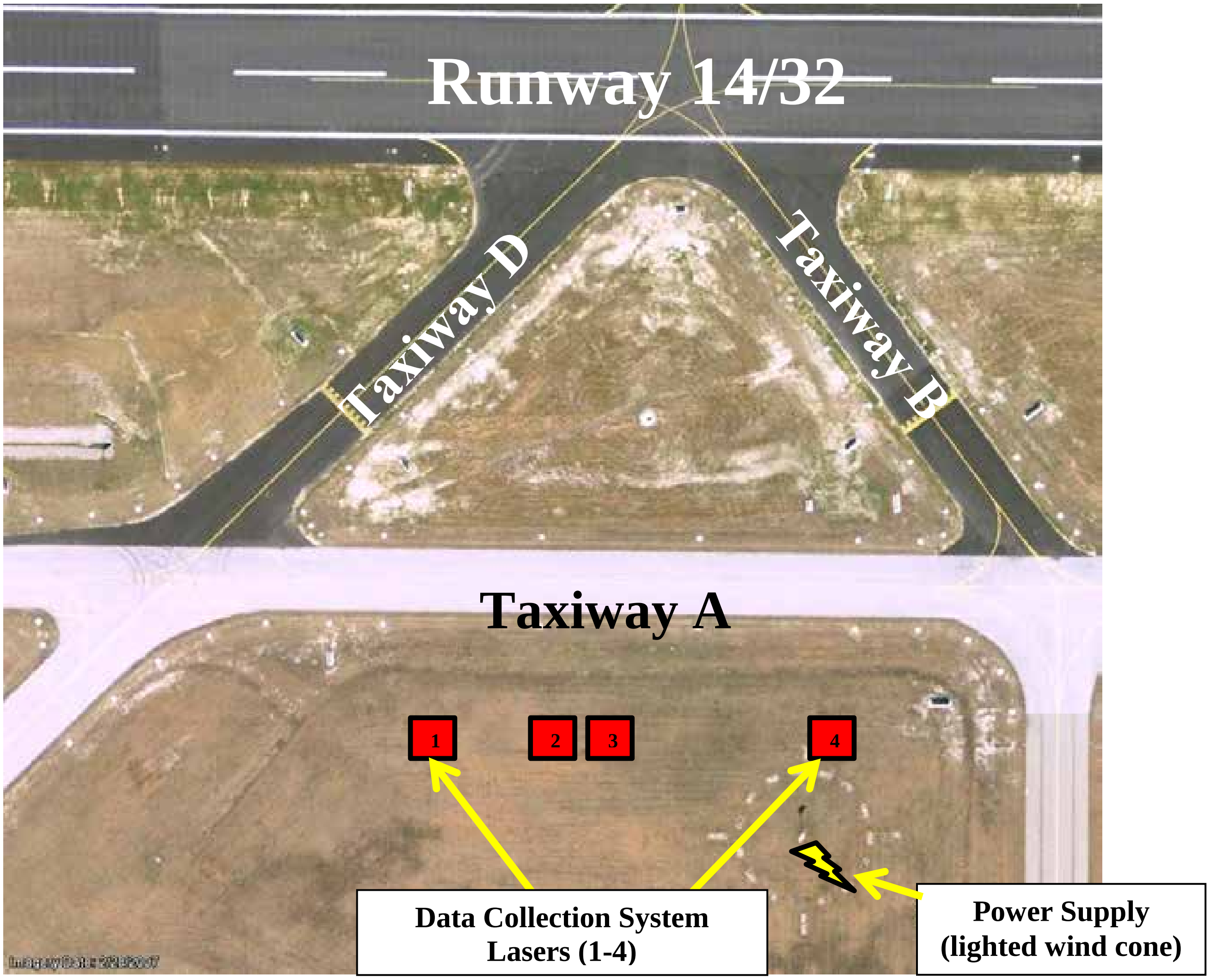

Figure 31. Aerial Photograph of the Data Collection System at SBY (not to scale)

The data collection system was installed on steel H-frames that sat on top of the terrain south of Taxiway A. Each laser was mounted to its associated steel H-frame on two 2-ft support legs and was secured to the steel H-frame with frangible couplings. The distance between lasers 1 and 2 was 110 ft; between lasers 2 and 3, 35 ft; and lasers 3 and 4, 225 ft. The distance from laser 1 to the curve of Taxiway D was 68 ft and from laser 4 to the curve of Taxiway B, 53 ft.

The data collection system was powered by a 120 V AC 20-amp power source from the airport's lighted wind cone. Prior to the installation, the wind cone was only illuminated at night and controlled by the ATCT. A local electrical contractor made modifications to the wind cone's power source to allow the wind cone to be constantly illuminated and removed the controls from the ATCT. A disconnect switch was installed at the base of the wind cone, as shown in figure 32. The disconnect switch allowed maintenance personnel to turn the power off to the wind cone while performing maintenance, which did not affect power to the data collection system. Power was fed from the wind cone to laser 3. The wind cone was located approximately 113 ft from laser 3. Power was distributed from laser 3 to the data collection system and the remaining three lasers.

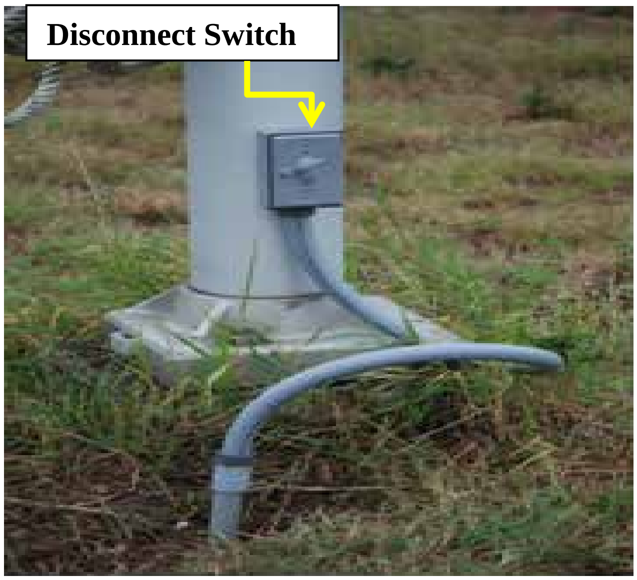

Figure 32. Disconnect Switch Installed at the Base of the Wind Cone

The data collection system was removed on September 5, 2012. All of the equipment and wiring was removed from this site; however, with the airport's approval, the conduit remained in place. An as-built drawing of the abandoned conduit was provided to the airport.

5.3.2 Data Collected.

During the data collection period, the data collection system tracked 1909 ADG III aircraft movements, yielding 14,442 laser measurements, as shown in table 6. Of the 1909 ADG III aircraft that were tracked, nearly 78% had complete datasets, or datasets of 8, as shown in table 6. The remaining 22% were incomplete; however, the data were still used by Boeing for their statistical analysis. As shown in table 7, the DeHavilland Dash 8 was the most common ADG III aircraft tracked by the data collection system.

Table 6. Summary of ADG III Data Collected at SBY (07/06/2011–09/05/2012)

Number of Aircraft Movements	Number of ADG III Data Measurements	Dataset							
		DS 8	DS 7	DS 6	DS 5	DS 4	DS 3	DS 2	DS 1
1909	14,442	1482	224	117	15	43	17	7	4

Table 7. The ADG III Aircraft Tracked by the Data Collection System at SBY

Type of Aircraft	Number of Aircraft Movements	Percentage of ADG III Movements
Dehavilland Dash 8 DHC-8	1882	99
McDonnell Douglas MD-80	25	1
Airbus A319	1	<1
Aerospatiale ATR 72	1	<1
Total	1909	100

5.4 WESTCHESTER COUNTY AIRPORT, WESTCHESTER, NY.

5.4.1 System Overview.

The final data collection system was installed at Westchester County Airport (HPN). At the time of this study, the airport received a strong mix and high frequency of ADG III aircraft and was classified by the U.S. FAA NPIAS as a small-hub[6] primary commercial service airport [7].

Prior to installing the data collection system, a temporary aircraft identification system was installed at two locations along Taxiway L, as shown in figure 33. The aircraft identification system was the same system installed at SBY. The data showed that the data collection system would be best suited at the Taxiway L north location because the majority of the traffic from GA hangars and FBOs on the airport's south side taxied past the data collection system when using Runway 16/34. Taxiway L was built to ADG III standards with a 50-ft-wide taxiway and no paved shoulder. Taxiway L had a taxiway centerline marking but did not have continuous taxiway edge markings. In addition, Taxiway L was equipped with elevated taxiway edge lights; however, it did not have taxiway centerline lights.

[6] Small-hub airport: "airports that enplane 0.05 percent to 0.25 percent of total U.S. passenger enplanements." [9]

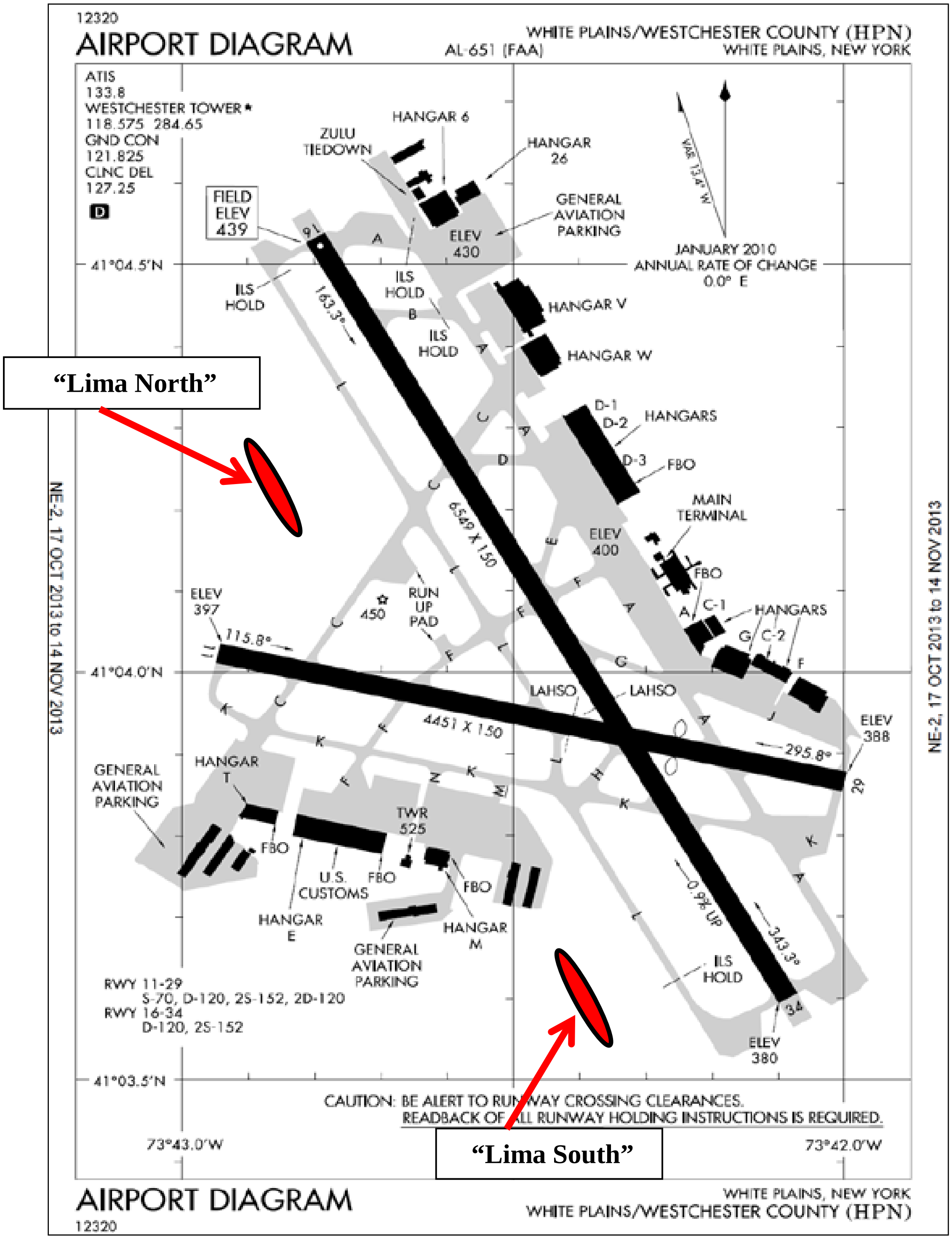

Figure 33. Location of Temporary Aircraft Identification System Along Taxiway L at HPN

Prior to installing the data collection system, HPN’s maintenance staff installed conduit at predetermined locations that housed power and communications cables to support the data collection system. On February 23, 2012, the data collection system was installed on steel H-frames on the west side of Taxiway L (Lima North), near the approach end of Runway 16, as shown in figure 34. Each laser was mounted to its associated steel H-frame on two 3-ft support legs and was secured to the steel H-frame with frangible couplings. The data collection system was installed approximately 140 ft from the centerline of Taxiway L, which was clear of Taxiway L's TSA and TOFA. The distance between lasers 1 and 2 was 108.5 ft; lasers 2 and 3, 32 ft; and lasers 3 and 4, 251 ft.

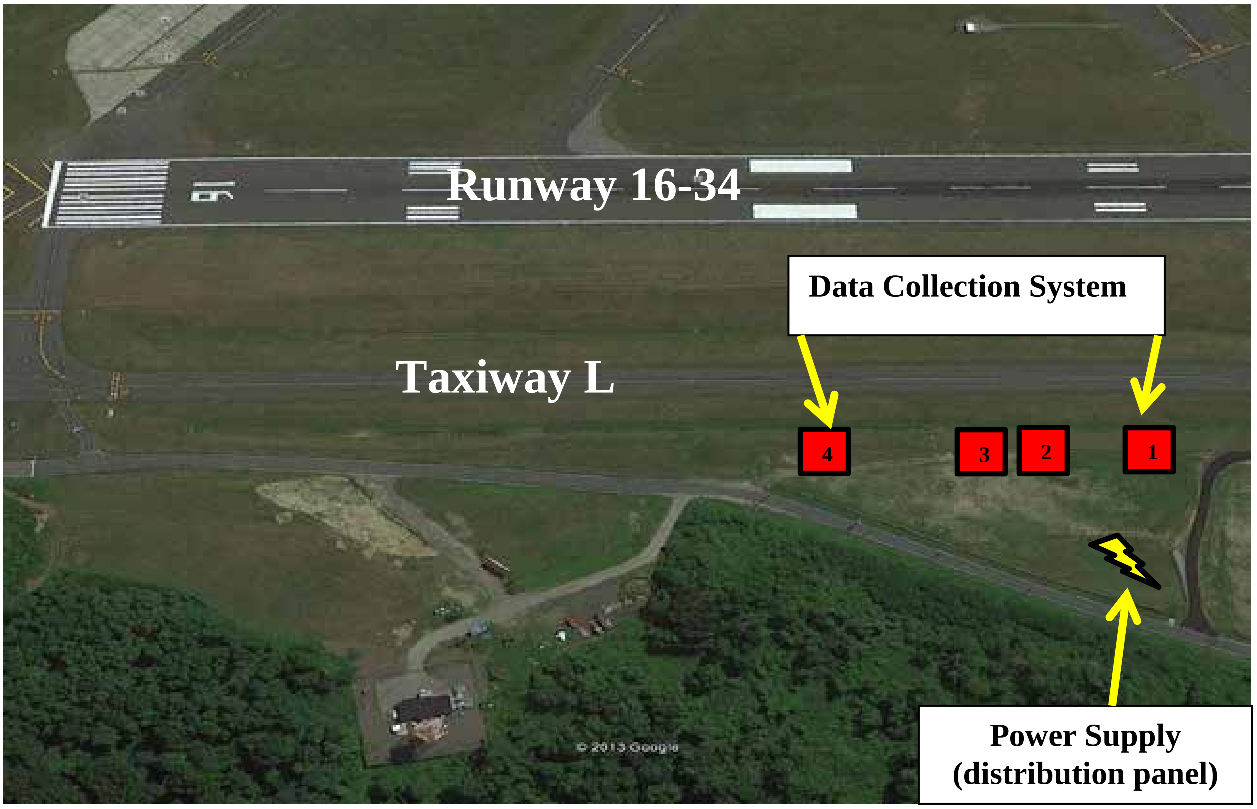

Figure 34. Aerial Photograph of the Data Collection System at HPN (not to scale)

The data collection system was powered by a 120 V AC 20-amp power source from an existing distribution panel, as shown in figure 35. Power was fed from the distribution panel to laser 1, which was approximately 210 ft south of laser 1. Power was then distributed from laser 1 to the data collection box and the remaining three lasers.

Figure 35. Power Supply—Existing Distribution Panel

The data collection system was removed from HPN on October 7, 2013. At the airport's request, the data collection system's conduit, junction boxes, and power/communication cables were left in place. The airport planned to use the existing electrical infrastructure for a future project.

5.4.2 Data Collected.

During the data collection period, the data collection system tracked 770 ADG III aircraft, yielding 5264 measurements, as shown in table 8. Of the 770 ADG III aircraft that were tracked, nearly 40% had complete datasets, or datasets of 8, as shown in table 8. The remaining 60% were incomplete; however, the data was still used by Boeing for their statistical analysis. As shown in table 9, the Gulfstream V and Bombardier Global Express accounted for nearly 70% of the ADG III aircraft tracked by the data collection system.

Table 8. Summary of ADG III Data Collected at HPN (02/27/2013–09/10/2013)

Number of Aircraft Movements	Number of ADG III Data Measurements	Dataset							
		DS 8	DS 7	DS 6	DS 5	DS 4	DS 3	DS 2	DS 1
770	5264	307	211	128	79	35	8	2	0

Table 9. The ADG III Aircraft Tracked by the Data Collection System at HPN

Type of Aircraft	Number of Aircraft Movements	Percentage of ADG III Movements
Gulfstream V	336	44
Bombardier Global Express	197	26
Embraer E190	58	8
Dassault Falcon 7x	42	4
Boeing B737	35	4
DeHavilland Dash 8	30	4
Boeing B717	22	3
DeHavilland Twin Otter	18	2
Airbus A319	17	2
Embraer E170	9	1
Airbus A320	5	<1
Bombardier Global 5000	1	<1
Total	770	100

6. SUMMARY.

The data collection period for phase III extended from April 23, 2009 through October 7, 2013. The four data collection systems installed at participating airports tracked 5691 ADG III aircraft, yielding 41,991 laser measurements, as shown in table 10. Of the 5691 ADG III aircraft that were tracked, nearly 66% had complete datasets, or datasets of 8, as shown in table 10. The remaining 34% was incomplete; however, the data will still be used by Boeing for their statistical analysis. In addition, the data collection systems tracked nearly 20 different types of aircraft, including turboprop and jet aircraft, as shown in table 11. The most common aircraft tracked included De Havilland Dash 8, Gulfstream V, Aerospatiale ATR 72, Boeing B737, and Bombardier Global Express, as shown in table 11. Table 12 provides a summary of the ADG III aircraft and movements tracked by the data collection system at ADG III airports.

A statistical analysis of the data collected in Phase III will be completed by The Boeing Company. The results from the statistical analysis will be added as a supplement to this report at a later date.

Table 10. Summary of ADG III Data Collected at ADG III Airports (04/23/2009–09/10/2013)

Airport	Number of Aircraft Movements	Number of ADG III Data Measurements	Dataset							
			DS 8	DS 7	DS 6	DS 5	DS 4	DS 3	DS 2	DS 1
SBY	1909	14,442	1482	224	117	15	43	17	7	4
EYW	1801	13,409	1117	511	83	44	42	2	2	0
PBI	1211	8,876	837	57	271	12	12	4	17	1
HPN	770	5,264	307	211	128	79	35	8	2	0
Total	5691	41,991	3743	1003	599	150	132	31	28	5

Table 11. Summary of ADG III Aircraft Tracked by the Data Collection System (04/23/2009–09/10/2013)

Type of Aircraft	Number of Aircraft Movements	Percentage of ADG III Movements
De Havilland Dash 8	1927	34
Gulfstream V	1074	19
Aerospatiale ATR 72	926	16
Boeing B737	730	13
Bombardier Global Express	607	10
Embraer E170	186	3
Dassault Falcon 7x	64	1
Embraer E190	58	1
McDonnell Douglas MD-80	25	<1
Boeing B717	22	<1
Airbus A319	20	<1
De Havilland Twin Otter	18	<1
DeHavilland Caribou	13	<1
Boeing B727	8	<1
McDonnell Douglas DC-9	7	<1
Airbus A320	7	<1
Convair 340	4	<1
Bombardier Global 5000	1	<1
McDonnell Douglas MD-88	1	<1
Total	5691	100

Table 12. Summary of ADG III Aircraft Tracked by the Data Collection System at ADG III Airports (04/23/2009–09/10/2013)

Type of Aircraft	Number of Aircraft Movements	Percentage of ADG III Movements
Salisbury Ocean City Wicomico Regional Airport (SBY), MD		
DeHavilland Dash 8 DHC-8	1882	99
McDonnell Douglas MD-80	25	1
Airbus A319	1	<1
ATR 72	1	<1
Total	1909	100
Key West International Airport (EYW), FL		
ATR 72	925	51
Boeing B737	676	38
Embraer E170	177	10
DeHavilland Dash 8	14	<1
Gulfstream V	6	<1
Airbus A319	2	<1
Global Express	1	<1
Total	1801	100
Palm Beach International Airport (PBI), FL		
Gulfstream V	732	60
Bombardier Global Express	408	34
Dassault Falcon 7x	22	2
DeHavilland Caribou	13	1
Boeing B737	12	<1
Boeing B727	8	<1
DC-9	7	<1
Convair 340	4	<1
Airbus A320	2	<1
DeHavilland Dash 8	1	<1
Airbus A319	1	<1
McDonnell Douglas MD-88	1	<1
Total	1211	100

Table 12. Summary of ADG III Aircraft Tracked by the Data Collection System at ADG III Airports (04/23/2009–09/10/2013) (Continued)

Type of Aircraft	Number of Aircraft Movements	Percentage of ADG III Movements
Westchester County Airport (HPN), NY		
Gulfstream V	336	44
Bombardier Global Express	197	26
Embraer E190	58	8
Dassault Falcon 7x	42	5
Boeing B737	35	5
DeHavilland Dash 8	30	4
Boeing B717	22	3
DeHavilland Twin Otter	18	2
Airbus A319	17	2
Embraer E170	9	1
Airbus A320	5	<1
Bombardier Global 5000	1	<1
Total	770	100

7. RECOMMENDATIONS.

The FAA's taxiway deviation data collection system and system installations have evolved from the inception of this study. Phase III tracked a total of 5691 aircraft and collected 41,991 laser measurements. Data were obtained from 19 different types of aircraft, including turboprop, turbojet, and turbo fan aircraft. The data collection systems were installed in four geographic regions, all of which presented a different meteorological dynamic to the study (snow, ice, rain, fog, etc.). The data collection systems were installed on taxiways with different combinations of visual aids. For example, some taxiways were only equipped with taxiway centerline markings and taxiway edge lights, while others had taxiway centerline and edge markings, taxiway centerline lights and edge lights, and surface painted markings.

However, three recommendations could improve the effectiveness of future system installations. These recommendations include (1) reducing the data collection systems' footprint, (2) equipping the data collection systems with radio networks, and (3) powering the data collection systems with solar energy.

During Phases I through III of this study, data was collected from ADG V-III aircraft that have wheel bases ranging from approximately 89 ft (Boeing 747) to 28 ft (Airbus A319) [8]. In future studies, data will be collected from ADG II and I aircraft that have wheel bases less than ADG V-III aircraft. Therefore, it is recommended that the overall footprint of the system be reduced to less than 400 ft, which is the current system footprint length. Reducing the footprint will allow the data collection system to be installed on smaller stretches of straight taxiway, broadening the number of potential airports to be considered for the study.

During Phases II and III (ADGs IV and III, respectively), aircraft data were transferred from the data collection system to a central server via a cellular router. The cellular router was effective;

however, the amount of data the system collected slowed down the data transfer rate. In addition, the cellular router's signal strength was reduced because of interference with various radio frequencies at the airports. In future studies, it is recommended using a radio network in place of the cellular router. The radio network will link off an independent wireless internet signal, typically from the airport's terminal building, and uses the signal to transfer the data collected by the system. The radio network will increase the data transfer rate from the data collection system to the central server.

The final recommendation for future data collection systems is to investigate the possibility of using solar energy to power the data collection systems. Upgrading the data collection system to solar energy would broaden the number of airports to be considered for future studies to those that may have limited sources of continuous power.

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