The Role of Flight Simulation in NTSB Accident Investigations

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Abstract

Simulation is one of the tools the NTSB uses to understand the physics governing the motion of an aircraft during an accident. Today, the NTSB's engineering desktop simulation program is *MATLAB* based, and includes a "mathematical pilot" that can compute a set of flight control and throttle inputs required to match a given flight trajectory (as determined by recorded radar or GNSS data, for example). Mathematical models describing the airplanes must be obtained from manufacturers or otherwise estimated. This tool has been used to reproduce and analyze the recorded flight paths for several recent general aviation accidents.

However, the NTSB also uses other kinds of simulation when appropriate. This paper will discuss three different levels of simulation used by the NTSB: 1) Full-flight pilot training simulators, 2) desktop engineering simulations with no pilot interface, and 3) simulator visuals and cockpit cabs used as "media players" for accident data. These different levels will be further illustrated through case studies of the 2009 "Miracle on the Hudson" ditching on the Hudson River (US1549), the 2001 American Airlines flight 587 accident in New York (AA587), a 2017 spatial disorientation accident involving a Pilatus PC-12, and a 2015 midair collision between an F-16 fighter jet and a Cessna 150. Simulators were used in the investigation of these events as follows:

● The Airbus A320 full-flight engineering simulator was used to evaluate the landing options available to the pilots of US1549, which ditched in the Hudson River following the loss of thrust to both engines due to bird strikes. In addition, the simulator was used to evaluate the operational feasibility of achieving prescribed ditching touchdown criteria.

● The mathematical aerodynamic and propulsion models underlying the Airbus A300 full-flight simulator were incorporated into a desktop engineering simulator (with no pilot interface) to analyze the aircraft motions recorded on the AAL587 Flight Data Recorder. This analysis served to identify the relative importance of pilot flight control inputs and external atmospheric disturbances (resulting from a wake penetration) on the motion of and loads on the airplane. In addition, the NASA Ames "Vertical Motion Simulator" (VMS) was used to re-create the AA587 scenario, duplicating the visual scene, cockpit control motions, instrument displays, load factors (within limits), and sounds (including Cockpit Voice Recorder audio) during the event. This "back-drive" of the VMS allowed investigators to evaluate how the aircraft accelerations might have affected the First Officer's reactions on the rudder pedals and other flight controls.

● A simulation model for the Pilatus PC-12 was used in a desktop engineering simulator to compute a set of flight control and throttle inputs that result in a match of recorded radar data.

● Finally, for the midair collision case, *Microsoft Flight Simulator X* was used to depict the visual scene from the cockpit of each aircraft, including the appearance of the conflicting airplane from each pilot's point of view. This animation allowed investigators to determine the visibility of each airplane in the minutes before the collision, and helped to illustrate the limitations of the "see-and-avoid" concept of collision avoidance, as well as the benefits of cockpit displays of traffic information.

Introduction

Today (2021), computer-based flight simulation is ubiquitous. The world's airline pilots are trained in simulators; pilots of high-performance general aviation aircraft can also seek high-fidelity simulator training, and even novice pilots working on obtaining an instrument rating can log some of their training time using ground-based flight training devices. Moreover, it might well be that the largest group of people exercising flight simulation software today are not pilots at all, but thousands of individuals in love with aviation who have vicariously "slipped the surly bonds of earth" through the spectacular scenery and cockpit realism offered by "games" such as *X-Plane* and *Microsoft Flight Simulator*. While flight simulation is perhaps used most commonly for both serious pilot training and leisurely entertainment, simulation is also a valuable engineering tool used by aircraft manufacturers in the development and testing of their products. As described in this paper, simulation is also useful for analyzing and communicating the circumstances and causes of aircraft accidents.

The United States National Transportation Safety Board (NTSB) has used simulation in the investigation of numerous aviation accidents, including United Airlines flight 585 (Colorado Springs, Colorado, 1991), USAir flight 427 (Hopewell Township, Pennsylvania, 1994), TWA flight 800 (East Moriches, New York, 1996), American Airlines flight 587 (Belle Harbor, New York, 2001), US Airways flight 1549 (Weehawken, New Jersey, 2009), and UPS flight 1354 (Birmingham, Alabama, 2013), among many others. In several of these investigations, to recreate and evaluate the accident scenario, simulators were used in the usual way: pilots in a cockpit cab manipulated the flight controls, and the simulator computed the response of the airplane and updated the visual scene, sound and motion cues, and cockpit instruments accordingly.

In many NTSB cases, however, simulators have been used in unusual ways, including as a device for recreating the accident airplane's motion, flight control movements, and instrument displays, without any pilot involvement or solution of the equations of motion, using data recorded by or derived from Flight Data Recorder (FDR) information. In addition, the aircraft aerodynamic and systems models underlying full-flight simulators have been exercised on a desktop computer (without a cockpit cab or pilot-in-the-loop) to determine the set of flight control inputs required to produce a recorded aircraft trajectory, or to analyze the effects of recorded pilot control inputs and external disturbances, such as wake encounters. The NTSB has even used *Microsoft Flight Simulator X* (*FSX*) to visualize the motion of aircraft and the view out of the cockpit windows during mid-air collisions.

This paper describes these different uses of flight simulation for accident investigation, and illustrates each through case studies of the 2009 US Airways flight 1549 "Miracle on the Hudson" ditching on the Hudson River (US1549), the 2001 American Airlines flight 587 accident (AA587), a 2017 spatial disorientation accident involving a Pilatus PC-12, and a 2015 midair collision between an F-16 fighter jet and a Cessna 150.

What is "simulation?"

For the purposes of this paper, "simulation" refers to the methods and devices used to compute an aircraft's response to thrust and control inputs and to recreate (as far as possible), in a ground-based facility, the experience of operating that aircraft. The aircraft's response is computed by

using mathematical models of the forces and moments acting on the aircraft in the solution of the aircraft equations of motion. The corresponding “experience” of flight is recreated through a cockpit mockup (a “cab”), which can include flight controls, flight instruments, a visual display (to depict the view through the aircraft windows), and a motion system. A given simulator’s cab or other pilot interface might only include some of these components.

Overview of the computational flow in a full-flight simulator

The different ways of using flight simulation for accident investigation introduced above can be better understood by reviewing how a full-flight simulator (FFS) works, and by describing the different components and computational tasks involved. Figure 1 is a flow chart depicting the logic and data flow in a typical FFS incorporating a cockpit cab, visual display, and motion system. The boxes with thicker lines and non-italicized text represent simulation models, that is, units of computer code and data that describe the behavior of a part of the airplane or its systems mathematically. The boxes with thinner lines and italicized text represent physical quantities or values computed by the simulation models. The arrows indicate which simulator models compute the various physical quantities, and how these quantities are in turn used as inputs by other models.

Starting with the box labeled “Human Pilot,” we see that by manipulating the simulator cab controls the pilot can generate inputs to the column, wheel, throttles, speedbrake handle, flaps, gear, and other cockpit controls duplicated in the cab. He can also provide inputs to the Flight Management Computer, Autopilot, and other cockpit systems. In the case of “desktop” engineering simulations, which run on a computer without a cab (and are described further below), these “pilot” inputs are accomplished by computer code. For both desktop and cab-based simulations, the pilot inputs are eventually processed by the simulator flight controls model that calculates the appropriate response of the airplane control surfaces, and by the propulsion model that computes the response of the airplane’s engines and the resulting thrust forces and moments. The aerodynamic model then uses the control surface positions along with the motion state of the airplane (airspeed, altitude, etc.) to calculate aerodynamic forces and moments on the airplane. Ground reaction forces are computed by the gear model. The total forces and moments are used along with quantities calculated by the mass properties model in the solution of the equations of motion that determine the motion states, both angular and linear. Angular states are the airplane’s yaw, pitch and roll angles, and their time derivatives (angular rates and accelerations). Linear states are the components of the three dimensional position of the airplane in space and their time derivatives (velocities and accelerations). These states are also used as inputs in the various mathematical models that compute the quantities that eventually affect the forces and moments.

In the case of cab-based simulations, information about the airplane motion states and from the propulsion model are used to drive the visual displays and cockpit instruments in the cab. For simulator cabs on a motion base (such as Level-D training simulators), the motion information can be used to maneuver the base to duplicate, within limits, the acceleration cues (“G forces”) felt by the pilots. In the case of “animations” or “backdrive” simulations (described further below), the aircraft states that drive the visual scene, cockpit instruments, and cab motion are not computed by solving the equations of motion or by exercising the simulator aerodynamic and other models, but are defined *a priori* from recorded or pre-computed data.

Three "tiers" of simulation

Referring to Figure 1, we can define three "tiers" of simulation, differentiated by the elements of an FFS that each incorporates.[1] From the most to the least complex, these simulation tiers are described below.

Tier 1: Full-flight simulations (physics, graphics, and pilot)

Tier 1 simulations incorporate all the simulator elements depicted in Figure 1. The equations of motion are solved based on forces and moments computed by the mathematical models of the aircraft's aerodynamics and systems (physics); the resulting visual scene, audio environment, and cab motion are presented to the pilot (graphics); and the pilot interacts with the simulation in real-time through the cockpit controls and interfaces (pilot).[2]

Tier 1 simulations are used when aircraft operational and human performance questions are of primary interest. These simulations help investigators to define and experience the circumstances faced by a flight crew during an accident, and to understand and evaluate the decisions and actions the crew took in response to those circumstances. Investigators can experience the accident scenario (for example, a flight control problem or a loss of thrust), and evaluate the urgency of the situation and the effectiveness of existing emergency procedures, and explore different strategies for coping with the emergency. In addition, if the accident crew made an error (such as mis-configuring the autoflight or navigation systems), investigators can evaluate the context in which the error was made and gain insight into possible reasons for the error. To address these kinds of questions, the pilot interface elements shown in Figure 1 are fundamental, driving the need for an FFS.

Tier 1 simulations are generally only available at commercial training providers, large Part 121 operators' training departments, or at aircraft manufacturers' facilities. Consequently, investigators will need to partner with these organizations (usually through an organization's role as a party to the investigation, or in the case of commercial providers, through contracts) to access these devices.

Tier 2: "Desktop" simulations (physics only)

This tier of simulation solves the equations of motion based on forces and moments computed by the mathematical models of the aircraft's aerodynamics and systems, but does not incorporate the elements used to present the state of the airplane to a pilot (visuals, audio, motion, cockpit instruments), or to receive inputs to the simulation from the pilot (cab controls and system interfaces). The flight control and other inputs required by the simulation to exercise the models and solve the equations of motion are generated by computer algorithms or read from data files. The aircraft state parameters computed by the simulation are saved to a data file and / or plotted on a computer screen. Since these operations can be performed using only a personal computer, Tier 2 simulations can be referred to as "desktop" simulations.

Tier 2 simulations are used when the physical performance of the aircraft is of primary interest, and the interface between the pilot and the airplane is irrelevant or pre-defined (for example, when the pilot's flight control inputs are recorded by an FDR). Tier 2 simulations can be used to evaluate

the effect of different environmental conditions or flight control inputs on the performance of the aircraft, or to compute a set of flight control and throttle inputs that reproduce the flight track recorded by surveillance systems (such as ADS-B or radar data).

Tier 2 simulations can also be limited in scope so as to evaluate the performance of individual aircraft systems, without having to simulate the entire aircraft.[3] Similarly, depending on the problem, a Tier 2 simulation might not require the complete set of aerodynamic and systems models underlying an FFS, but only those corresponding to the flight condition of interest. For example, simulations of the landing roll of an airplane (to determine the effect of different runway conditions and / or deceleration devices on the required stopping distance) can be done with a very small subset of the aerodynamic and thrust data underlying an FFS.

Because Tier 2 simulations can be run on a desktop computer without the pilot interface hardware required by an FFS, the NTSB has developed its own simulation software with which to perform Tier 2 simulations. However, obtaining the aircraft models and data needed to address a particular problem can be challenging, given aircraft manufacturers' concerns about divulging intellectual property. This challenge is discussed below in the "Access to devices and models" section of this paper, but here it suffices to say that the NTSB has obtained partial to full aircraft models from different aircraft manufacturers during the course of investigations involving those manufacturers' products, and has obtained full aircraft models under licensing agreements with some simulator manufacturers and aircraft model developers, both for free and at cost.

Tier 3: "Backdrive" simulations and "animations" (graphics only)

Tier 3 "simulations" only incorporate the data output elements of the FFS illustrated in Figure 1: the generation of the visual scene and the simulator cab instrument displays and motion. The state of the aircraft that drives these elements is not computed by exercising the simulator models and solving the equations of motion, but is defined beforehand based on data obtained from an FDR or computed some other way. In essence, the simulator visuals and / or cab are used to "replay" pre-existing data. The simulator becomes a "media player," and the "channels" this player exercises can include the visual scene, cab motion, cab instruments, and even the cab flight control and throttle positions. In an "animation," only the visual scene (from the interior and / or exterior of the aircraft) is generated. In a "backdrive simulation," one or more elements of the cockpit cab are driven with pre-recorded data.

Tier 3 simulations and animations are used to visualize pre-existing data in the most intuitive context possible. An animation that presents a video of the aircraft position and attitude throughout an accident sequence is much easier for investigators, managers, and the public to understand than engineering plots of performance parameters vs. time. Even for engineers, the presentation of the aircraft's motion in *real time* can help to impress the pace of events in a way that data plots cannot.

Backdrive simulations allow investigators to "re-live" an accident scenario from the pilots' seats. Like Tier 1 FFS simulations, backdrive simulations help investigators to define and experience the circumstances faced by a flight crew during an accident; but unlike Tier 1 simulations, in which the investigators are in control of the simulation, backdrive simulations allow investigators to witness the exact flight control inputs employed by the accident crew, and the exact aircraft

response that resulted. In special cases, Cockpit Voice Recorder (CVR) audio from the accident can by synchronized with the backdrive, so that the accident crew's recorded conversation can be monitored while their actions on the flight controls are visualized. In essence, investigators become spectators in the cockpit at a high-fidelity reenactment of the accident.

Like Tier 1 simulations, backdrive simulations require a cockpit cab and the other pilot interface elements shown in Figure 1. Consequently, full backdrive simulations can only be performed using an FFS. In addition, the FFS must have the ability to be programmed to accept input data from a file to drive the cockpit cab controls, visual display, motion system, and other elements, as opposed to the normal way of operating, in which the simulation computes these data in response to inputs made by pilots using the cab controls. Training simulators operated by commercial pilot training providers are not likely to be easily programmed in this way, and investigators will likely have to rely on aircraft manufacturers' "engineering" simulators that are designed to accommodate programing changes as part of aircraft development and testing cycles. On occasion, engineers in an airline's training department may be able to reprogram their training simulators to support a backdrive scenario. As described below, for the AA587 investigation, the NTSB used the NASA Ames Vertical Motion Simulator (VMS) to accommodate a backdrive simulation that could reproduce a larger range of load factors than that possible with a training simulator; a trade-off in this case was that the VMS cockpit cab did not represent an Airbus A300 (the accident model) as well as an A300 training simulator would have.

As noted above, Tier 3 simulations also include animations, consisting of video images of the airplane's motion from different points of view, such as from the pilot's seat (depicting the view out the window and the instrument panel) and / or an external view from a "chase plane."[4] Animations are not really simulations at all, but only graphic representations of pre-existing data. Many NTSB animations (for aviation accidents and accidents in other transportation modes) have been created using general 3D modelling software unrelated to simulation. However, animations are included here as "Tier 3 simulations" because, once the underlying aircraft position and orientation data is defined, an animation of an aviation accident can be created in a matter of minutes with flight simulation software such as *X-Plane* or *Microsoft Flight Simulator*,[5] vs. the many hours required using general-purpose 3D modelling software.[6]

The NTSB has used all three tiers of simulation in the investigation of different aircraft accidents; sometimes, a single investigation itself requires the use of all three tiers. In many cases (in aviation and other transportation modes), an animation depicting an exterior view of the aircraft (or other vehicle) driven by data generated during the investigation will be used to present the circumstances of an accident most intuitively to NTSB Board Members and to the public.

Examples of the use of the three simulation tiers in several NTSB accident investigations are presented below. Before describing the details of these simulations, however, it is helpful to provide brief descriptions of the accidents themselves.

Summaries of the aircraft accidents discussed in this paper

The simulation case studies below concern the following aviation accidents investigated by the NTSB:

- American Airlines flight 587 (Belle Harbor, New York, 2001)
- US Airways flight 1549 (Weehawken, New Jersey, 2009)
- Mid-air collision between an F-16 and a Cessna 150 (Moncks Corner, South Carolina, 2015)
- PC-12 (N933DC) crash after takeoff (Amarillo, Texas, 2017)

These accidents and the resulting investigations are further described as follows.
NTSB #DCA02MA001: American Airlines flight 587, Belle Harbor, NY, 11/12/2001

The "Executive Summary" on the NTSB's webpage for this accident (linked below) states:

> On November 12, 2001, about 09:16:15 eastern standard time, American Airlines flight 587, an Airbus Industrie A300-605R, N14053, crashed into a residential area of Belle Harbor, New York, shortly after takeoff from John F. Kennedy International Airport, Jamaica, New York. Flight 587 was a regularly scheduled passenger flight to Las Americas International Airport, Santo Domingo, Dominican Republic, with 2 flight crewmembers, 7 flight attendants, and 251 passengers aboard the airplane. The airplane's vertical stabilizer and rudder separated in flight and were found in Jamaica Bay, about 1 mile north of the main wreckage site. The airplane's engines subsequently separated in flight and were found several blocks north and east of the main wreckage site. All 260 people aboard the airplane and 5 people on the ground were killed, and the airplane was destroyed by impact forces and a postcrash fire. Flight 587 was operating under the provisions of 14 Code of Federal Regulations Part 121 on an instrument flight rules flight plan. Visual meteorological conditions prevailed at the time of the accident.
>
> The safety issues discussed in this report focus on characteristics of the A300-600 rudder control system design, A300-600 rudder pedal inputs at high airspeeds, aircraft-pilot coupling, flight operations at or below an airplane's design maneuvering speed, and upset recovery training programs. Safety recommendations concerning these issues are addressed to the Federal Aviation Administration and the Direction Général de l'Aviation Civile.

On October 26, 2004 the NTSB determined that the probable cause of this accident was:

> The in-flight separation of the vertical stabilizer as a result of the loads beyond ultimate design that were created by the first officer's unnecessary and excessive rudder pedal inputs. Contributing to these rudder pedal inputs were characteristics of the Airbus A300-600 rudder system design and elements of the American Airlines Advanced Aircraft Maneuvering Program.

The NTSB issued fifteen safety recommendations as a result of this accident. The accident report, accident animation, accident docket, safety recommendation correspondence, and aircraft performance and simulation reports can be accessed at the following links:

Accident webpage / final report / safety recommendations:
https://www.ntsb.gov/investigations/AccidentReports/Pages/AAR0404.aspx

Animation: https://www.youtube.com/watch?v=4-xj5YON88Y

Docket: https://data.ntsb.gov/Docket?NTSBNumber=DCA02MA001

Aircraft Performance Study:
https://data.ntsb.gov/Docket/Document/docBLOB?ID=40168982&FileExtension=.PDF&FileName=Aircraft%20Performance%2013%20-%20Factual%20Report%20of%20Group%20Chairman-Master.PDF

Simulation Study:
https://data.ntsb.gov/Docket/Document/docBLOB?ID=40198619&FileExtension=.PDF&FileName=Aircraft%20Performance%2013%20-%20Addendum%201-Master.PDF

Human Performance Study Report: American Airlines Simulator Exercise:
https://data.ntsb.gov/Docket/Document/docBLOB?ID=40197540&FileExtension=.PDF&FileName=Human%20Performance%2014%20-20Study%20Report,%20American%20Airlines%20Simulator%20Exercise-Master.PDF

Human Performance Study Report: Vertical Motion Simulator Activities Phase I: Backdrive of Accident Flight:
https://data.ntsb.gov/Docket/Document/docBLOB?ID=40168576&FileExtension=.PDF&FileName=Human%20Performance%2014%20-%20Study%20Report,%20Vertical%20Motion%20Simulator%20Activities,%20Phase%20I%3A%20Backdrive%20of%20Accident%20Flight-Master.PDF

NTSB #DCA09MA026: US Airways flight 1549, Weehawken, NJ, 12/10/2009

The "Executive Summary" on the NTSB's webpage for this accident (linked below) states:

> On January 15, 2009, about 15:27 eastern standard time, US Airways flight 1549, an Airbus Industrie A320-214, N106US, experienced an almost complete loss of thrust in both engines after encountering a flock of birds and was subsequently ditched on the Hudson River about 8.5 miles from LaGuardia Airport (LGA), New York City, New York. The flight was en route to Charlotte Douglas International Airport, Charlotte, North Carolina, and had departed LGA about 2 minutes before the in-flight event occurred. The 150 passengers, including a lap-held child, and 5 crewmembers evacuated the airplane via the forward and overwing exits. One flight attendant and four passengers were seriously injured, and the airplane was substantially damaged. The scheduled, domestic passenger flight was operating under the provisions of 14 Code of Federal Regulations Part 121 on an instrument flight rules flight plan. Visual meteorological conditions prevailed at the time of the accident.
>
> Contributing to the survivability of the accident was (1) the decision-making of the flight crewmembers and their crew resource management during the accident sequence; (2) the fortuitous use of an airplane that was equipped for an extended overwater flight, including the availability of the forward slide/rafts, even though it was not required to be so equipped; (3) the performance of the cabin crewmembers while expediting the evacuation of the airplane; and (4) the proximity of the emergency responders to the accident site and their immediate and appropriate response to the accident.
>
> The safety issues discussed in this report relate to the following: in-flight engine diagnostics, engine bird-ingestion certification testing, emergency and abnormal checklist design, dual-engine failure and ditching training, training on the effects of flight envelope limitations on airplane response to pilot inputs, validation of operational procedures and requirements for airplane ditching certification, and wildlife hazard mitigation. The report also discusses survival-related issues, including passenger brace positions; slide/raft stowage; passenger immersion protection; life line usage; life vest stowage, retrieval, and donning; preflight safety briefings; and passenger education. Safety recommendations concerning these issues are addressed to the FAA, the U.S. Department of Agriculture, and the European Aviation Safety Agency.

On May 4, 2010, the NTSB determined that the probable cause of this accident was:

> the ingestion of large birds into each engine, which resulted in an almost total loss of thrust in both engines and the subsequent ditching on the Hudson River. Contributing to the fuselage damage and resulting unavailability of the aft slide/rafts were (1) the Federal Aviation Administration's (FAA) approval of ditching certification without determining whether pilots could attain the ditching parameters without engine thrust, (2) the lack of industry flight crew training and guidance on ditching techniques, and (3) the captain's resulting difficulty maintaining his intended airspeed on final approach due to the task saturation resulting from the emergency situation.

Thirty-five safety recommendations were issued as a result of this accident. The accident report, accident animation, accident docket, safety recommendation correspondence, and aircraft performance and simulation reports can be accessed at the following links:

Accident webpage / final report / safety recommendations:
https://www.ntsb.gov/investigations/AccidentReports/Pages/AAR1003.aspx

Animation: https://www.youtube.com/watch?v=z70mT0h8ooA

Docket: https://data.ntsb.gov/Docket?NTSBNumber=DCA09MA026

Aircraft Performance Study:
https://data.ntsb.gov/Docket/Document/docBLOB?ID=40322563&FileExtension=.PDF&FileName=Aircraft%20Performance%2013%20-%20Factual%20Report%20of%20Group%20Chairman-Master.PDF

Simulation test report:
https://data.ntsb.gov/Docket/Document/docBLOB?ID=40314093&FileExtension=.PDF&FileName=Operations%2FHuman%20Performance%202DD%20-%20Attachment%2028%3A%20Simulator%20Results%20Document-Master.PDF

NTSB #ERA15MA259: F-16/C150 midair collision, Moncks Corner, SC, 07/15/2015

On July 7, 2015, about 11:01 eastern daylight time, a Cessna 150M, N3601V, and a Lockheed Martin F-16CM, operated by the US Air Force, collided in midair near Moncks Corner, South Carolina. The private pilot and passenger aboard the Cessna died, and the Cessna was destroyed during the collision. The damaged F-16 continued to fly for about 2.5 minutes, during which the pilot activated the airplane’s ejection system. The F-16 pilot ejected safely and incurred minor injuries, and the F-16 was destroyed after its subsequent collision with terrain and postimpact fire. Visual meteorological conditions prevailed at the time of the accident. No flight plan was filed for the Cessna, which departed from Berkeley County Airport, Moncks Corner, South Carolina (KMKS), about 10:57, and was destined for Grand Strand Airport, North Myrtle Beach, South Carolina. The personal flight was conducted under the provisions of 14 Code of Federal Regulations (CFR) Part 91. The F-16 was operating on an instrument flight rules (IFR) flight plan and had departed from Shaw Air Force Base, Sumter, South Carolina, about 10:20.

On November 15, 2016 the NTSB determined that the probable cause of this accident was:

> The approach controller's failure to provide an appropriate resolution to the conflict between the F-16 and the Cessna. Contributing to the accident were the inherent limitations of the see-and-avoid concept, resulting in both pilots' inability to take evasive action in time to avert the collision.

A safety recommendation and a safety alert were issued as a result of this accident. The accident report, accident animation, accident docket, safety recommendation correspondence, and aircraft performance / cockpit visibility study can be accessed at the following links:

Final report: https://data.ntsb.gov/carol-repgen/api/Aviation/ReportMain/GenerateNewestReport/91508/pdf

Accident webpage / animation links / safety alert / safety recommendation:
https://www.ntsb.gov/news/events/Pages/2016-midair-presentations.aspx

Docket: https://data.ntsb.gov/Docket?ProjectID=91508

Aircraft Performance & Cockpit Visibility Study:
https://data.ntsb.gov/Docket/Document/docBLOB?ID=40445948&FileExtension=.PDF&FileName=Aircraft%20Performance%20Radar%20%26%20Cockpit%20Visibility%20Study-Master.PDF

NTSB #CEN17FA168: PC-12 (N933DC), Amarillo, Texas, 04/28/2017

On April 28, 2017, about 23:48 central daylight time, a Pilatus PC-12 airplane, N933DC, impacted terrain near Rick Husband Amarillo International Airport (KAMA), Amarillo, Texas. The airline transport pilot and two flight crew were fatally injured. The airplane was destroyed. The airplane was registered to and operated by Rico Aviation LLC, under the provisions of 14 Code of Federal Regulations Part 135 as an air ambulance flight. Instrument meteorological conditions (IMC) prevailed at the time of the accident and the flight was operated on an instrument flight rules (IFR) flight plan. The flight was originating at the time of the accident and was en route to Clovis Municipal Airport (KCVN), Clovis, New Mexico.

At 23:46:54, the pilot contacted AMA departure control and reported "with you at 6,000 [ft msl]." The departure controller radar-identified the airplane. At 23:48:12, the departure controller advised the pilot that he was no longer receiving the airplane's transponder; the pilot did not respond. The departure controller made three more transmissions to the pilot without response. There were no further recorded transmissions to or from the airplane. The local controller reported to the departure controller that he had observed a fireball and reported a potential crash.

On September 4, 2018 the NTSB determined that the probable cause of this accident was:

> The pilot's loss of airplane control due to spatial disorientation during the initial climb after takeoff in night instrument meteorological conditions and moderate turbulence.

No safety recommendations were issued as a result of this accident. The accident report, docket, and aircraft performance and simulation study can be accessed at the following links:

Final report: https://data.ntsb.gov/carol-repgen/api/Aviation/ReportMain/GenerateNewestReport/95076/pdf

Docket: https://data.ntsb.gov/Docket?ProjectID=95076

Aircraft Performance Radar & Simulation Study:
https://data.ntsb.gov/Docket/Document/docBLOB?ID=40461657&FileExtension=.PDF&FileName=Aircraft%20Performance%20Radar%20and%20Simulation%20Study-Master.PDF

Examples of Tier 1 (FFS) simulations used in accident investigations

Tier 1 Full-Flight Simulators were used in the investigations of both the AA587 and the US1549 accidents.

American Airlines flight 587

The *Human Performance Study Report: American Airlines Simulator Exercise* (linked above) describes the purpose of an exercise conducted in an American Airlines' Airbus A-310/300 FFS:

> On December 4, 2002, the Human Performance Group conducted a study in the A-310/300 training simulator as part of its meeting at the American Airlines Training Academy, DFW Airport, TX. The purpose of the study was to examine the Advanced Aircraft Maneuvering Program (AAMP) excessive bank angle recovery exercise, a simulator scenario in which the instructor induced an excessive bank angle in a wake turbulence context. Following initial ground training and simulator briefings, six pilots from the Human Performance Group performed the scenario multiple times using different pilot rudder input strategies to evaluate whether the scenario encouraged particular pilot inputs.

The report goes on to describe the procedures used to experience the AAMP "excessive bank angle" upset training in the simulator:

> For purposes of the study, the instructor was asked to initiate the roll event at about 240 knots airspeed but, otherwise, to introduce the scenario as a normal AAMP simulator exercise. The instructor set up the exercise as a departure behind a Boeing 747 airplane, in this case having each pilot execute a normal takeoff on runway 31L at JFK airport in day, visual conditions. During a climb to 5,000 feet, the instructor cautioned that the airplane was following behind a large aircraft, directed the pilot to turn, and initiated the roll event while the airplane was banked at an altitude between 2,000 to 2,500 feet. The simulated airplane exhibited an uncommanded roll in one direction (either left or right determined arbitrarily by the computer) followed immediately by a substantial uncommanded roll in the opposite direction. The simulator scenario was programmed to momentarily inhibit the aircraft response to pilot inputs in roll and yaw during the event to allow the simulated airplane to reach a substantial bank angle before recovery began. Each pilot was instructed to recover the airplane according to the AAMP training they received from the training tape and simulator instructors. After recovery, the simulator trial ended and the pilot provided verbal evaluations on structured interview questions.
>
> This procedure was repeated for 5 additional trials that were identical to the first except that the roll maneuver was initiated during level flight after the pilot indicated his readiness. During the successive trials, the pilot was instructed to respond using one of five specific recovery strategies:
>
> • Partial Wheel, No Rudder (Strategy A)
> • Full Wheel, No Rudder (Strategy B)
> • Full Wheel, Partial Rudder (Strategy C)
> • Full Wheel, Full Rudder (Strategy D)
> • Pilot's own preference

The report then presents the results of the study in terms of pilot responses to interview questions and a record of the maximum bank angle achieved during the exercises. Among other results, the report notes that

> Strategies A to D provided a range of potential recovery strategies and pilots reported definite preferences. Three pilots selected strategy A as the worst strategy, and all six pilots questioned whether Strategy A provided sufficient control authority to achieve recovery. Two pilots selected Strategy D as the worst one, with several pilots indicating there was a possibility of overcontrol. Based on pilot evaluations and pilot actions on the first and last trial, pilots appeared to prefer a strategy of full wheel and limited rudder in response to the scenario.
>
> Contrary to pilot evaluations, the four recovery strategies showed little difference in terms of maximum bank angle reached. Each recovery strategy showed an average maximum bank angle between 104 and 107 degrees and none of the individual recoveries by any subject was achieved at less than 100 degrees despite the widely varying nature of the inputs provided under the four strategies.

US Airways flight 1549

The simulation test report for the US Airways flight 1549 (linked above) describes exercises conducted in Airbus' "S31" A320 FFS (with a motion base) and "S22" Engineering simulator (with a fixed base). As stated in the report, the objectives of the exercises were:

> 1. To allow the NTSB Operations/Human Performance Group to familiarize themselves with the A320 cockpit, instrument displays, controls, systems, and normal takeoff/landing and emergency procedures.
>
> 2. To identify and evaluate the operational and airplane performance implications of the various options available to a flight crew following the loss of thrust on both engines. This will apply to the context of US Airways Flight 1549 and other relevant options.
>
> 3. To evaluate the A320 ENG DUAL FAILURE checklists/procedures.
>
> 4. To evaluate the operational feasibility of achieving minimum vertical speed at touchdown.

The report goes on to describe the simulation participants and procedures as follows:

> Four airline transport pilot members of the operational factors/human performance group, three of whom [were] type-rated on the A320, and one of whom was an A320-rated Airbus test pilot, participated in an observational study at the Airbus Training Center in Toulouse, France, on April 14-16, 2009. The simulators used for the observations were an S22 engineering test simulator and a S31 motion-based training simulator ….
>
> The purpose of the simulations [was] to identify and evaluate the various options available to the flight crew of US Airways Flight 1549 following the bird strike (e.g., land at an airport or land on the Hudson River) and to determine the implications of each of those options. Additionally, the group expanded beyond the context of Flight 1549 in order to understand the implications of a dual engine failure in which the aircraft is in the EMER ELEC mode (no green or yellow hydraulics). Finally, the group evaluated the checklists and procedures made available to flight crews, as well as the operational feasibility of achieving minimum vertical speed at touchdown.
>
> Each pilot was fully briefed on the maneuver before it was attempted. The autopilot was off for all tests. Flight scenarios were flown from zero groundspeed on the takeoff runway 4 in LGA, from a pre-programmed point shortly before the bird-strike and loss of thrust, and from 1500' above the river on approach to landing.

> Initial conditions duplicated as closely as possible those of the accident flight. They were programmed into the simulator (winds, temp, altimeter, weight and balance). The profile flown duplicated as closely as possible the accident profile (airplane position, thrust setting, altitude at beginning of turns, thrust reduction and clean-up altitudes, speeds, and altitude/speed combination) up until the time of bird ingestion and dual engine failure. Following the failure, pilots followed the US Airways QRH ENG DUAL FAILURE checklist and relied on their training and experience to complete the test conditions. An observer was present to document observations, times, etc. Data from the S22 engineering simulator was recorded electronically for later review and analysis. In addition, the runs flown in the S31 motion-based simulator were recorded with a video camera mounted so as to approximate the point of view of an observer in the jumpseat.
>
> At the completion of each condition, the pilot flying was asked to rate the difficulty of the landing on a scale of 1-7 (1 being very easy, 7 being very difficult) and to provide any comments about observations made during the scenario. In addition, one A320 test pilot and one A320 type-rated pilot completed the Cooper Harper Rating Scale at the end of each condition they performed.

It should be noted that the purpose of the evaluation of the flight crew's options following the loss of engine thrust was not to "second-guess" or call into question the crew's (wise) decision to ditch the airplane in the Hudson River, rather than to attempt to glide to a runway. Instead, the purpose was to "evaluate the operational and airplane performance implications of the various options," and to determine whether a return to LGA was even possible (a question that would certainly be asked both within and outside of the investigation). The test conditions for the attempted glides back to a runway included both immediate turns towards a runway following the loss of thrust, and a 35 second delay before initiating any turns to account for the time required for the crew to assess the situation and decide upon a course of action.

The conditions tested during the attempts to glide back to a runway are listed in Table 1 of the simulation report, duplicated here:

Condition #	Airport	Runway	Timing	Turn	Flaps	Simulator
2.1	LGA	22	Immediate	Right	Available/Pilot's discretion	S31/Motion
2.1a	LGA	22	Immediate	Right	Available/Pilot's discretion	S22/Fixed
2.1b*	LGA	22	Immediate	Right	Flaps 3/Slats only^	S22/Fixed
2.2	LGA	13	Immediate	Left	Available/Pilot's discretion	S31/Motion
2.2a	LGA	13	Immediate	Left	Available/Pilot's discretion	S22/Fixed
2.2b†	LGA	13	Immediate	Left	Flaps 3/Slats only^	S22/Fixed
2.2c†	LGA	13	35 seconds	Left	Available/Pilot's discretion	S22/Fixed
2.3	TEB	19/24	Immediate	Left	Available/Pilot's discretion	S31/Motion
2.3a	TEB	19/24	Immediate	Left	Available/Pilot's discretion	S22/Fixed
2.3b§	TEB	19/24	Immediate	Left	Flaps3/Slats only^	S22/Fixed
2.3c§	TEB	19/24	35 seconds	Right	Available/Pilot's discretion	S22/Fixed

Table 1. Conditions tested during the attempts to glide back to a runway following the loss of engine thrust. **Notes**: Conditions 2.1, 2.2 and 2.3 performed only once with a different pilot in each condition to provide them with the physical/motion-based cues associated with an immediate turn to an airport; * Condition performed only if Condition 2.1a is successful; † Condition performed only if Condition 2.2a is successful; § Condition performed only if Condition 2.3a is successful; ^ Condition assumes EMER ELEC with APU started.

The results of the attempts to glide back to a runway are reported as follows:

> A total of 20 runs were performed in the S22 simulator in which pilots attempted to return to LGA runways 13 or 22, or attempted to land at TEB runway 19. Five of 20 runs (25%) were discarded

> due to poor data or simulator malfunctions, leaving 15 runs for analysis (6 runs to LGA runway 22, 7 runs to LGA runway 13, and 2 runs to TEB runway 19). Eight of 15 runs (53%) made successful landings. The 8 successful runs were made following an immediate turn to an airport after the bird strike. See Table 1 for details of each run.
>
> Specifically, six runs were made to return to LGA runway 22 immediately following the bird strike. Of those six, two (33%) resulted in a successful runway landing – one using flaps at the pilot's discretion (condition 2.1a; one additional attempt was unsuccessful) and one using slats only (condition 2.1b; four additional attempts were unsuccessful). Due to inadequate successful landing attempts following an immediate turn after the bird strike, attempts to land at LGA runway 22 after a 35 second delay (condition 2.1c) were not performed.
>
> Additionally, pilots attempted to land at LGA on runway 13. All four pilots successfully landed (100%) on LGA runway 13 following an immediate left turn to the airport following the bird strike (condition 2.2a). Two runs were attempted in which the pilot was required to use slats only on landing on runway 13 (condition 2.2b). One landing (50%) was successful and one landing was not successful, requiring the pilot to ditch in the waters adjacent to LGA. The one attempt to return to LGA runway 13 following a 35 second delay (condition 2.2c) was not successful. No additional attempts were made to return to LGA runway 13.
>
> Finally, two runs were attempted to determine the ability of the airplane to land at TEB runway 19 immediately after the bird strike. In both runs, pilots were able to use flaps at their discretion (condition 2.3a). One attempt (50%) was successful and one attempt was unsuccessful. Due to inadequate successful landing attempts following an immediate turn, conditions 2.3b and 2.3c were not attempted.

These results vindicate the flight crew's decision to ditch the airplane in the Hudson River instead of attempting to glide the airplane back to LGA over a densely populated city.

The Airbus simulators were also used to "to evaluate the operational feasibility of achieving minimum vertical speed at touchdown." The investigation determined that in order to prevent a rupture of the aft fuselage upon contact with the water (as occurred in the flight 1549 accident), a flight path angle of -0.5° or shallower had to be achieved.[7] On flight 1549, the touchdown flight path angle was -3.4°, which resulted in a vertical speed at touchdown of about -750 ft/min, beyond what the skin of the fuselage could withstand. The resulting fuselage breach and water penetration into the cargo hold and aft cabin submerged the aft door sills below the level of the river, rendering the life rafts attached to the aft doors unusable. As a result, there was insufficient raft space available for all the passengers, and some passengers had to stand on the wings of the airplane to await rescue.

The Airbus simulators were used to evaluate pilots' abilities to touch down within the -0.5° flight path angle constraint. The simulation test report describes this task as follows:

> All conditions started at a predetermined location of 1500' above the Hudson River and 200 knots which closely replicates the location and airspeed of the accident flight. The left seat pilot was at control when the simulator was 'released' and the right seat pilot performed the US Airways QRH ENG DUAL FAILURE checklist and other duties as assigned by the pilot flying. The left seat pilot attempted to land on the river following guidance in the QRH ("touchdown with approximately 11 degrees of pitch and minimum vertical speed").

Ditching tests were conducted using flaps 2, flaps 3, and flaps 3 with slats only. The results of the tests are reported as follows:

> A total of 16 runs were performed in the S22 simulator in which pilots attempted to ditch the airplane, of which two were discarded due to poor data. Each of the four pilots attempted a landing under each of the three conditions – using CONF 2 (condition 3.2), using CONF 3 (condition 3.3) and using CONF 3/Slats only (condition 3.4). The flight path angles of each of these runs are presented in [Figure 2]. See [Table 2] for details of each run.
>
> In addition, two runs were attempted in which the pilot flying was instructed to fly within the flight envelope protection range (i.e., alpha protection) to understand the impact of such conditions on the flight path angle. The flight path angles at touchdown for the landings were -6.5 and -6.3 degrees.

Condition #	Heading	Speed±	Flaps	Simulator
3.1*	Left to 220	Green Dot	Flaps 2	S31/Motion
3.2	Left to 220	Green Dot	Flaps 2	S22/Fixed
3.3	Left to 220	Green Dot	Flaps 3	S22/Fixed
3.4	Left to 220	Green Dot	Flaps 3/Slats only^	S22/Fixed

Table 2: Conditions for the US1549 simulated ditching tests.
Notes: *Condition 3.1 will "recreate" the accident flight; ± Per the QRH, pilots will maintain green dot speed until configuring for landing at which time they will assume F speed on the speed tape; ^Condition assumes EMER ELEC with APU started.

The test results plotted in Figure 2 indicate that only one of the twelve landings on the water achieved a flight path angle within the -0.5° target at touchdown, and that all but one landing achieved a flight path angle shallower than the -3.4° of flight 1549. In addition, the Figure indicates that the -0.5° target is shallower than that achieved by the four simulator pilots during their normal landings on a runway.

Examples of Tier 2 (desktop) simulations used in accident investigations

Not counting Tier 3 animations, Tier 2 (desktop) simulations are those most frequently used by the NTSB, since all that they require is a desktop computer, a simulation program (or "engine"), and a mathematical model of the aircraft of the scope and fidelity[8] required for the problem at hand. Some problems can be addressed with very simple, low-fidelity models – for example, when the simulator is used to create a physically realistic, smooth flight path through noisy radar data, and only the motion of the aircraft's center of gravity is of interest. Such simulations can produce aircraft speeds and accelerations that are more realistic than those obtained by filtering or otherwise mathematically smoothing the radar data. Other problems, however, require more complex and higher-fidelity models, because the particular handling qualities and other physical characteristics of the aircraft are of primary concern.

For the AA587 accident, a Tier 2 desktop simulation was used to determine the relative significance of the encounter with the Boeing 747 wake, and of the First Officer's control inputs in response to that encounter, on the subsequent motion of the airplane. For the Amarillo PC-12 accident, a desktop simulation was used to determine a set of flight control inputs, and the associated control forces, that would result in a match of the airplane's flight track as recorded by

radar. Both of these simulations required high-fidelity mathematical models of the airplanes involved, and are described further below.

American Airlines flight 587

Airbus and the NTSB both conducted Tier 2 desktop simulations of the final seconds of flight of AA587. The Airbus simulation computed the expected response of the A300 to the flight control inputs recorded on the FDR, without any external forces or moments associated with the encounter with the Boeing 747 wake applied; only vertical and horizontal wind gusts were used in the simulation to account for wake effects. The resulting simulator output matches the aircraft motion recorded on FDR well, but not perfectly; as stated in the NTSB *Aircraft Performance Study* (lined above),

> The simulator match of the accident event … is good, but not perfect. Factors that can cause the simulator to calculate motion that differs from that measured in flight include:
>
> 1. Errors in the flight sensors or other measuring/recording equipment.
> 2. Inaccuracies in the simulator aerodynamic and/or other mathematical models.
> 3. Improper simulator initialization or matching technique.
> 4. External forces or moments not modeled in the simulator.
>
> The external winds needed to obtain the match of vane angle of attack and normal load factor indicate that the air surrounding the airplane is not quiet, which makes the atmosphere hard to model and a very precise match of the FDR data hard to obtain. The disturbance in the atmosphere is likely due to a second encounter with the wake from the JAL 747 that preceded the accident airplane out of JFK (see Appendix B [of the *Performance* Study] for information about work performed by the NASA Langley Research Center to model the wake from the 747).
>
> While a better match of the FDR data could probably be obtained by trial-and-error with external winds or other effects attributable to a wake encounter, the match in hand does provide important information about the accident sequence. The simulator results indicate that the motion of the airplane, and most importantly, the buildup of the sideslip angle, is consistent with and principally the result of the movements of the airplane's control surfaces, especially the rudder.

The NTSB desktop simulation used mathematically applied "external" rolling, pitching, and yawing moments (in addition to horizontal and vertical wind gusts) to force a better match between the simulator response and the motion recorded on the FDR. The NTSB simulation and its results are discussed in the *Aircraft Performance Study Addendum #1* (linked as the AA587 "simulation study" above):

> As discussed in the Aircraft Performance Study, crew comments recorded on the CVR, a NASA analysis of the wake of the Boeing 747 that departed JFK ahead of AAL587, and the AAL587 FDR data all indicate that AAL587 encountered the 747 wake twice shortly before the accident. The Airbus and NTSB simulations of the accident start just before the second wake encounter, at about 09:15:47 EST.
>
> As described in Appendix B to the Aircraft Performance Study, the trailing vortices in the wake of the B747 produce significant disturbances in the direction and velocity of the surrounding air. In fact, the vortices may induce updrafts of 20 knots in one place, and downdrafts of 20 knots only 30 feet away. Similar differences in horizontal gusts are also possible. Depending on the geometry of

how the airplane encounters the wake, these changes in wind speed and direction can cause the angle of attack to increase on one wing and decrease on the other, creating a rolling moment. Changes in the local flow angles over the horizontal stabilizer can produce pitching moments, and changes in flow over the vertical stabilizer can produce yawing moments. These “vortex-induced” rolling, pitching, and yawing moments are not modeled in the baseline A300 simulator, and so if they not accounted for in some way, the simulator will not be able to duplicate all the forces and moments acting on the actual airplane, and the simulator motion will not match that recorded on the FDR.

The load factor and engine N1 data fluctuations recorded on the FDR between about 09:15:50 and 09:15:54 suggest that the second wake encounter occurred during this time, and that the motion of the airplane was affected by the wind gusts induced by the wake. To account for these effects, during this 4 second period the NTSB simulation incorporates external rolling, pitching, and yawing moments that make the simulator motion more closely match the motion recorded on the FDR. After the 4 second period, the airplane is assumed to be free of the wake, and the external moments are removed.

In addition to external moments, the wake can induce forces on the airplane that can be accounted for by changes in the velocity of the airmass surrounding the airplane (as opposed to differential changes in the flow at various points). These gross effects are modeled in the simulator as vertical wind gusts and changes in the horizontal wind speed and direction.

Throughout the simulation, the simulator cockpit control positions and aerodynamic surface positions are driven so as to match the positions recorded on the FDR as closely as possible without sacrificing the match of the motion recorded by the FDR. Because of the effects of the SDAC filter (see Section D-IV of the *Aircraft Performance Study*), the *filtered* simulator control surface positions are matched to the FDR positions.

To get a sense of the magnitude of the effects of the vortex-induced external moments and vertical and horizontal wind gusts, the simulator match is repeated, but without any cockpit control or control surface movements. The simulator then computes the response of the airplane solely to the forces and moments induced by the wake encounter.

The NTSB simulator match of the Euler angles (heading, pitch, and roll) recorded on the AA587 FDR is shown here in Figure 3, for the case in which the simulation is driven with both the flight control inputs recorded on the FDR and with the wind gusts and external moments required to force a better match. The NTSB simulator match of the Euler angles for the case in which the simulation is driven *only* with the wind gusts and external moments (and the flight controls are left in their trim positions) is shown here as Figure 4. The *Aircraft Performance Study Addendum #1* concludes that

> The simulator match of the accident maneuver … indicates that while external winds and moments, assumed to be attributable to the wake encounter, are required to match the motion recorded on the FDR, the large roll and yaw oscillations, lateral load factors, and sideslip angles achieved during the maneuver are the result of wheel and rudder inputs. By themselves, the external winds and moments only produce an initial 10° deviation in bank angle and only subtle changes in heading, resulting in sideslip angles of less than 2.5°.

PC-12 (N933DC), Amarillo, Texas

The *Aircraft Performance Radar & Simulation Study* for the Amarillo PC-12 accident (linked above) describes the simulation used during the investigation as follows:

> … a computer simulation of the accident flight was performed in order to generate a trajectory that is consistent with both the recorded radar data and crash site location, and the performance capabilities of the airplane. The simulation also yields a set of control and throttle inputs that are consistent with the simulated trajectory (though it should be noted that other inputs, which produce similar but slightly different trajectories, could also be generally consistent with the recorded radar data).
>
> The following information sources define the "target" trajectory and airplane model used in the simulation, and provide criteria by which to measure the quality of the simulation match:
>
> Radar data: For the simulation to "match" the radar data, the position of the airplane in the simulation solution should lie within the uncertainty boxes of the radar returns at the times corresponding to those returns, and the altitude should fall between the ± 50 ft. uncertainty band of the corrected Mode C data at those times.
>
> Crash site data: The simulation and actual crash sites should coincide.
>
> Performance data: The simulation should be representative of the Pilatus PC-12 aerodynamics and engine thrust capabilities. Airplane aerodynamics and engine simulation models provided by Pilatus were used for this *Study*. These models were developed by Pilatus for SimCom (a flight simulator manufacturer), and were largely complete, except for the flight control system. For this system, Pilatus provided system description reports (including control gearing ratios and aerodynamic surface hinge moments) from which a flight control system model could be constructed. As described further below, the resulting model yielded reasonable control forces in the pitch and yaw axes, but did not yield reasonable control forces in the roll axis. For the roll control forces, a simpler, linearized model provided to the NTSB for a previous PC-12 accident investigation was used, and this model did yield reasonable roll control forces.
>
> Wind data: The winds and temperatures aloft as a function of altitude, based on the … FDR data [from a Boeing 737 that preceded N933DC out of KAMA], were used in the simulation.
>
> The simulation uses a "math pilot" to generate control system and throttle inputs to produce pitch and roll angles and engine thrust that result in an approximate match of the "target" trajectory defined by the radar data and the impact point. Since the aerodynamic characteristics of the simulation are representative of the airplane, the engine power, angle of attack, Euler angles (pitch, roll, and heading), and control inputs and forces computed by the simulation to match the target track are relevant and of interest.
>
> The flaps and gear up configuration is used throughout the simulation, which starts at 23:45:13 with the airplane climbing at about 600 ft/min through 3640 ft. MSL (about 40 ft. AGL) and accelerating through 100 kt. This configuration is consistent with the normal takeoff procedure outlined in the AFM, which states that the gear should be raised after liftoff and positive rate of climb is established, and the flaps should be raised to 0° above 100 kt. The flaps and gear up configuration at the start of the simulation may be a little early (i.e., occur earlier than in the actual flight), which could account for the less than full thrust required at the start of the simulation …. The simulation thrust increases to max power at 23:45:20, so it is likely that the clean configuration was achieved by that time.

> The simulation results … satisfy the match criteria outlined above well, though not perfectly; as shown in [Figure 5], the position of the airplane is within or close to the edge the uncertainty boxes of the radar data at the radar return times, and the impact is close to (about 130 ft from) the crash site. In general, the airplane positions are within about 200 ft of the corresponding radar returns. The attitude of the airplane at impact is: heading 301° true, pitch 42° down, roll 76° left. In this attitude, the projection of the leading edge of the wing along the ground is a line oriented southeast to northwest from 141° to 321°, which matches the general orientation of the ground scar of the left wing leading edge in the wreckage. The left-wing-low impact attitude is also consistent with the deeper impact crater created by the left wing than the right wing ….

The *Study* states the following concerning the flight control positions computed by the simulation's "math pilot:"[9]

> Figures [6, 7, and 8] present the simulation flight control inputs, aerodynamic control surface positions, and flight control forces, respectively. The travel limits of the flight controls and aerodynamic surfaces are also shown in the plots, to provide a sense of the scale of the movements. To provide a scale for the control forces, the short-term force application limits specified in the certification standards for Part 23 airplanes[10] (§23.143) are also shown in Figure [8]. §23.143 specifies both 1- and 2-handed force limits for the pitch and roll axes.

Examples of Tier 3 ("backdrive") simulations and animations for accident investigations

The two types of Tier 3 "simulations" described in this paper are not really simulations at all, but only "media players" of pre-existing data defining an aircraft's position and attitude, and the state of its various systems, as a function of time. In a "backdrive" simulation using a simulator cab, the visual scene, cab motion, cab instruments, and flight control and throttle positions are all driven by (set according to) pre-defined data read from a file. Animations are simpler, driving only one channel of information: the visual scene (from the interior and / or exterior of the aircraft).[11]

The NASA Ames VMS was used to create a backdrive simulation for the AA587 accident, and the Moncks Corner midair collision is a powerful example of how animations can help communicate critical information about accidents and safety issues, such as the inherent limitations of the "see and avoid" concept that serves as the philosophical basis for avoiding collisions in visual meteorological conditions. These examples are discussed further below.

American Airlines flight 587

The motivations for creating a backdrive simulation during the AA587 investigation, and the reasons the NASA Ames VMS was selected for this task, are described in the AA587 *Aircraft Performance Study* (linked above):

> The information recorded on the FDR and CVR can be used together with a motion-base simulator to recreate, within limits, the "experience" of the accident from the point of view of the flight crew. The Human Performance Group is particularly interested in such a representation, as it may provide insights about the environment surrounding the crew and the situation presented to them.
>
> The representation of the accident in a simulator for human performance evaluation purposes requires that simulator recreation be as accurate and as "real" as can be. This means that every

> element of the simulator environment – the sights, sounds, control motions, and feelings of motion – should duplicate the actual accident scenario as much as possible. Of particular interest to the Human Performance Group are the sensations experienced by the flight crew as a result of the motion of the airplane and the associated load factors in the cockpit.
>
> Traditional motion-based flight crew training simulators are mounted on hexapod motion systems, which can produce mild accelerations and load factors that enhance the experience of certain flight regimes such as takeoffs, landings, flight in turbulence, turn entries and entries into climbs and descents. However, because of their limited range of travel, these motion systems can not generate large or sustained load factors. In addition, the legs of the motion base are used to generate all the motions of the cab, so if they are being used to generate motion in one axis (pitch, for example), the range of motion in other axes (such as roll or lateral motion) will be reduced.
>
> The NASA Vertical Motion Simulator (VMS) is a motion based simulator designed specifically to develop larger and more sustained load factors independently in all axes (forward/aft, up/down, left/right, and yaw, pitch, and roll). While the VMS also has its limits, it is much more capable than a hexapod based simulator, and is a better tool for recreating the load factor environment of flight 587.
>
> The human performance testing performed in the VMS is described in the [*Human Performance Group Chairman's Study Report: Vertical Motion Simulator Activities Phase I: Backdrive of Accident Flight* (linked above)]. The Aircraft Performance Group Chairman assisted the Human Performance Group in the VMS effort by providing the data with which to drive the VMS motion, visual displays, instruments, and cockpit controls.
>
> Data from the takeoff roll to the end of the FDR data were used to drive the VMS ….

A photograph of a model of the VMS is presented in Figure 9. Additional details about the VMS and its limitations, and the objectives and observations of the AA587 Human Performance Group concerning the backdrive, are contained in the *Vertical Motion Simulator Phase I* study report. Of note, the VMS cab did not represent an A300 cockpit exactly; instead, as described in the study report,

> The simulator cab used was the T-cab, which had a two-place side-by-side pilot station configuration typical of transport category airplanes, as shown in Figure [10]. The cockpit displays were configured with three side-by-side monitors at each pilot station. At each station, the outboard monitor presented graphical strip charts of input and actual accelerations for longitudinal, lateral, and vertical (normal) axes and flight control positions; the inboard monitor displayed a centered compass rose navigation display of heading and track information, and a wind vector indicator with digital readouts of wind speed and direction in the lower left corner; and the center monitor was a primary flight display (PFD …) presenting altitude, attitude, and airspeed information. A digital readout of event time was displayed in the upper left corner of the PFD. The PFD also contained an operable sideslip indicator (trapezoid below the sky pointer) that presented lateral acceleration data based on Airbus Industrie specifications for the A300-600 sideslip indicator.
>
> The cab was equipped with a transport category style control wheel and column, adjustable rudder pedals, and adjustable pilot seats. The cab was configured with four throttle levers. For this activity, throttle levers 1 and 2 indicated the throttle lever position from the throttle 1 parameter on the FDR and throttle levers 3 and 4 indicated throttle lever position from the throttle 2 parameter on the FDR. Control wheel, column, rudder pedal, and throttle positions were backdriven based on interpolated FDR data during backdrive runs. Although the cab was equipped with gear, spoiler, and flaps levers, the positions of these controls were not backdriven and did not affect the activity.

The procedures followed by the Human Performance Group during the backdrive activity were as follows:

> On Tuesday, August 13, 2002 the Human Performance group experienced the VMS backdrive with the accompanying audio segments of the CVR. Full motion, out-the-window visual scene graphics, the primary flight display (PFD) graphics, the compass rose navigation display, and the electronic strip chart displays were presented in the VMS cab. Two video recordings were made of each backdrive run, one showing an overhead view of the cab and the seated occupants, the other showing the graphical display of accelerations and flight control positions, the PFD and the "chase plane" view. Additionally verbal comments made by the group members at the conclusion of each run were recorded.
>
> On the second day, the Human Performance group repeated the VMS backdrive. The group members also experienced three additional conditions on the second day. These conditions included:
>
> 1. Full VMS motion backdrive with the pedals simulated as a variable ratio limiter system,[12]
> 2. VMS backdrive with visuals and flight control movement but without the cab motions; and
> 3. VMS backdrive with visuals and cab motion but without control surface motion.
>
> Upon conclusion of these backdrive runs, the Human Performance group met to review and summarize the VMS activities.

A comparison of the load factors that were achieved in the VMS T-Cab during the backdrive with the load factors recorded on the AA587 FDR is presented in Figure 11. The study report notes that Human Performance Group members "did not observe a visual or acceleration cue that would lead a pilot to apply the observed initial magnitude of wheel and pedal in response to the [wake encounter]." They also

> concluded that the VMS, while constrained by the limitations previously noted, provided insight and was a beneficial tool for experiencing time synchronized motions, flight control motions, and displays as opposed to just looking at tabular or charted data.

Moncks Corner midair collision

The *Aircraft Performance Radar & Cockpit Visibility Study* for the Moncks Corner midair collision between a Cessna 150 and an F-16 (linked above) presents the results of using Charleston Air Force Base / International Airport Surveillance Radar data and recorded data from the F-16 to calculate the position and orientation of each airplane in the minutes preceding the collision. The *Study* then uses that information to estimate the approximate location of each airplane in the other airplane's field of view (the "visibility study"), and to estimate the Cockpit Display of Traffic Information (CDTI) data that could have been presented to the pilots had the airplanes been equipped to provide that information. (Of note given the context of this paper, the CDTI recreation is an example of a Tier 2 "desktop" simulation of a particular aircraft system.)

The *Study* describes the process for determining the visibility of each airplane from the cockpit of the other as follows:

> Once the position and orientation of each airplane has been determined, their positions in the body axis system of the other airplane can be calculated. These relative positions then determine where the "target" aircraft will appear in the field of view of the pilot of the "viewer" aircraft.
>
> For this *Study*, the relative positions of the two aircraft (and the visibility of each from the other) were calculated beginning when the C150 was detected by the KCHS ASR, and then at 1-second intervals up to the collision.
>
> The "visibility angles" from the "viewer" airplane to the "target" airplane correspond to the angular coordinates of the line of sight between the airplanes, measured in a coordinate system fixed to the viewer airplane (the viewer's "body axis" system), and consist of the azimuth angle and elevation angle (see Figure [12]). The azimuth angle is the angle between the x-axis and the projection of the line of sight onto the x-y plane. The elevation angle is the angle between the line of sight itself, and its projection onto the x-y plane. At 0° elevation, 0° azimuth is straight ahead, and positive azimuth angles are to the right. 90° azimuth would be out the right window parallel to the y axis of the airplane. At 0° azimuth, 0° elevation is straight ahead, and positive elevation angles are up. 90° elevation would be straight up parallel to the z axis. The azimuth and elevation angles depend on both the position (east, north, and altitude coordinates) of the viewer and target airplanes, and the orientation (yaw, pitch, and bank angles) of the viewer. The azimuth and elevation angles of points on the target away from its CG also depend on the orientation of the target.
>
> …
>
> The target airplane will be visible from the viewer airplane unless a non-transparent part of the viewer's structure lies in the line of sight between the two airplanes. To determine if this is the case, the azimuth and elevation coordinates of the boundaries of the viewer's transparent structures (windows) must be known, as well as the coordinates of the viewer's structure visible from the cockpit (such as the wings and wing struts). If the line of sight passes through a non-transparent structure (such as the instrument panel, a window post, or a wing), then the target airplane will be obscured from the viewer.
>
> For this *Study*, the azimuth and elevation angles of the window boundaries and wings of the F-16 and C150 were determined from the interior and exterior dimensions of exemplar airplanes, as measured using a FARO laser scanner. The laser scanner produces a "point cloud" generated by the reflection of laser light off of objects in the laser's path, as the scanner sweeps through 360° of azimuth and approximately 150° of elevation. The 3-dimensional coordinates of each point in the cloud are known, and the coordinates of points from multiple scans (resulting from placing the scanner in different positions) are "merged" by the scanner software into a common coordinate system. By placing the scanner in a sufficient number of locations so that the scanner can "see" every part of the airplane, the complete exterior and interior geometry of the airplane can be defined.
>
> In this *Study*, the scanner was placed in several locations to scan the exterior of the airplanes, and in the pilot seats to scan the interior of the airplanes. The scanner software was then used to identify the points defining the outline of the cockpit windows (from the interior scans) and exterior structures visible from the cockpit (from the exterior scans). The coordinates were transformed into the airplane's body axis system and, ultimately, into azimuth and elevations angles from the pilot's eye position. The transformation method is described in Appendix A [of the *Study*].

Perhaps the most intuitive way to present the results of a visibility study is to recreate each pilot's field of view graphically on a computer screen, depicting the cockpit structure, the scene visible through the windows, and the location of the conflicting airplane in the field of view. Since the outside scene and location of the conflicting airplane change with time, a series of images is required; assembling these images together results in a video or animation of the collision from the point of view of each pilot. Animations of external views of the airplanes converging (for

example, a “chase plane” view) is another helpful way of visualizing the collision (of course, these external views are not suitable for determining the visibility of each airplane from the cockpit of the other).

As noted above, animations can be constructed using general-purpose 3D modelling and video editing software. However, doing so can be very time consuming. In contrast, animations for investigative purposes (and that can serve as the basis for more formal / polished animations finalized using video editing software) can be created in minutes using flight simulator “games” such as *X-Plane* and *Microsoft Flight Simulator*.

Animations of the Moncks Corner midair collision were created using *Microsoft Simulator X* (*FSX*).[13] The *Study* describes the process as follows:

> The cockpit structure of each airplane at the nominal pilot’s eye point (based on the laser scans) was constructed in *FSX* as semi-transparent instrument panels that “mask” the view from each cockpit (see Appendix B [of the *Study*]); the cockpit geometry built into the airplane models used in the simulation was not used. Airplane models were only used to represent the exterior “target” airplane geometry in the recreated views. The airplane models were chosen based on their color resemblance to the accident airplanes, and are freely provided by *FSX* enthusiasts. The position (latitude, longitude, and altitude) and attitude (heading, pitch, and roll) of each airplane was recreated in *FSX* using the *FS Recorder* program developed by Matthias Neusinger,[14] based on the final estimated position and attitude data for each airplane ….
>
> *FSX* contains inherent options to customize the time, date, and weather depiction in the simulation. The time and date were set to those of the accident (11:00 EDT on July 7, 2015), which results in the correct placement of the sun in the sky. The sky conditions were selected to match those of the 10:55 EDT METAR from KMKS: 2600 ft. scattered and 10 miles visibility …. Of course, the clouds depicted in the simulation are only a generic representation of the reported sky condition, and do not recreate the clouds in the skies over KMKS on the day of the accident precisely. However, this presentation of the sky is likely more “realistic” and representative of the accident conditions than a clear, cloudless sky with unlimited visibility.
>
> The view depicted by *FSX* depends on the “camera” settings. In this *Study*, the *FSX* camera is equivalent to the pilot’s eyes: the view from the cockpit depends on the camera’s position, orientation (where it’s pointed), and its “field of view” (i.e., the range of azimuth and elevation angles that can be “seen” by the camera). The widest field of view available in *FSX* is 90° horizontally and about 62° vertically. Consequently, if the camera is pointed straight ahead (0° azimuth), then only azimuth angles between -45° and +45° will be visible in that view. If objects of interest (e.g., the target airplane) are beyond this range, then to “see” them the camera will have to be rotated away from 0° azimuth toward the object. However, in this case, a portion of the view straight-ahead will be lost, which may be unsatisfactory for the purpose of giving the viewer a good sense of the airplane’s direction of travel and general situation relative to the outside world.
>
> To see objects beyond ±45° of azimuth while at the same time preserving a field of view of at least ±45° of azimuth about the direction of travel, the view from two co-located cameras can be joined side-by-side: the first camera pointed away from 0° azimuth to capture the object, and the second camera pointed in such a way that the boundaries of the fields of view of the cameras coincide at a particular azimuth angle. For example, if one camera is rotated to -75° azimuth, the left boundary of its field of view will be at -75° - 45° = -120°, and the right boundary will be at -75° + 45° = -30°. If the second camera is rotated to +15° azimuth, its left boundary will be at +15° - 45° = -30° (coinciding with the right boundary of the first camera), and its right boundary will be at +15° + 45°

> = 60°. Setting the views from the cameras side-by-side, a continuous field of view from -120° to +60° is obtained.
>
> However, discontinuities (kinks) in straight lines may appear at the boundary of these views when they are viewed side-by-side on a flat surface (such as a computer screen), because the viewer will be viewing both from the same angle, whereas the view on the left is intended to be viewed at an angle rotated 90° from that on the right. The discontinuities can be removed if each view is presented on a separate surface (monitor), and then the surfaces are joined at a 90° angle. However, this solution may be impractical (and is impossible for presenting screenshots of these views in a single document), and so the line discontinuities at the boundaries of the views may simply need to be tolerated, as they are in the present *Study*.
>
> … the C150 remained within ±15° of azimuth and between -20° and 0° of elevation of the F-16 pilot's field of view for its entire flight. Consequently, a single camera pointed straight ahead and with a horizontal field of view of ±45° is sufficient to depict the C150 and the direction of travel of the F-16. However, the F-16 approached the C150 from an azimuth angle of about -75°; consequently, for the C150 two cameras are needed to depict both the approach of the F-16, and the view in the C150's direction of travel. Based on these observations, the F-16 cockpit view was recreated using a single camera pointed at 0° azimuth, and the C150 cockpit view was recreated using two cameras, pointed at -75° and +15°, respectively. …

FSX recreations of the cockpit views from the F-16 and the C150 0.6 seconds before the collision are shown in Figures 13 and 14. The "radar scope" objects in the Figures are the results of the CDTI simulation for each airplane, superimposed on the *FSX* images (see the *Study* for a description of the CDTI simulations). Animations of the accident are linked above.

Access to devices and models

Accessing Tier 1 Full-Flight Simulators

The NTSB has developed its own *MATLAB*-based simulation engine, that incorporates a "math pilot" (described above) and the all *computational* elements of an FFS depicted in Figure 1, except for the aerodynamic and system models for particular aircraft. The NTSB does not possess any of the *hardware* elements of an FFS, such as a cab or motion system; consequently, for Tier 1 simulations, the NTSB relies on parties to the investigation or commercial training vendors to provide these devices. (Like many individuals, the NTSB does own copies of *FSX* and the associated hardware (desktop computers, monitors, joysticks, and other simple hardware interfaces) required to run and interact with the program.[15])

When selecting an FFS provider, it is important to consider how the activities in the FFS will be documented for inclusion into the larger accident investigation report. Generally, FFS devices operated by aircraft manufacturers or an airline's training department will have built-in data recording capabilities that can create a record of relevant parameters during the simulation tests, much like an aircraft's FDR. FFS devices operated by commercial training organizations might not have data recording capabilities, or the organization might not be willing to release such recordings, citing proprietary data concerns. In these cases, video recordings can serve to document the simulation tests (video is helpful in general, to capture the participants' comments

and observations during the tests). Permission to take and retain video should be requested and obtained prior to the selection of an FFS provider.

Accessing simulation models for Tier 2 desktop simulations

For Tier 2 desktop simulations, the NTSB relies on parties to the investigation (usually aircraft manufacturers) or other sources (such as simulator manufacturers and model developers) to obtain the mathematical models describing particular aircraft. These models are intellectual property developed at considerable cost by their owners, and often contain sensitive trade secrets. Consequently, these models must be rigorously protected from disclosure to the public. The United States Freedom Of Information Act (FOIA) shields proprietary information provided to the NTSB by parties to the investigation from public disclosure;[16] nonetheless, parties can be very hesitant, or flatly refuse, to provide this information. In addition, the set of models that completely define the aerodynamics and systems underlying an FFS of a modern transport-category airplane can be too voluminous and complex to be implemented and validated in the NTSB's simulation engine within the timeframe required to support an investigation.

To resolve these difficulties associated with obtaining proprietary and / or complex aircraft models, negotiation with the model owners is required. A successful negotiation will allow accident investigators to fulfill their mandate of performing thorough and independent investigations, while protecting the intellectual property involved. A variety of solutions are possible. The NTSB has exercised proprietary models in desktop simulations in the following ways:

- By obtaining a complete or partial[17] simulation data package from the aircraft manufacturer or a simulator manufacturer or model developer
- By travelling to the aircraft manufacturer's facility and using a desktop simulation there
- By overseeing simulation work performed by the aircraft manufacturer itself

The most practical solution usually depends on the circumstances of each investigation. In general, however, it is the author's opinion that the thoroughness, timeliness, and independence of an agency's investigation are best served by obtaining and implementing the required aircraft models (or relevant portions of those models) in the agency's own desktop simulation program. The best way to understand the aircraft performance aspects of an accident is to wrestle with the physical details required to simulate the event so as to match known quantities, such as evidence at the scene and data recorded on an FDR. Overseeing the efforts of others might suffice for the purposes of an investigation, but inevitably sacrifices some of this familiarity and understanding.

Furthermore, the "independence" of an investigation involves more than simply "getting one's hands dirty" with computational details. An investigator with his own simulation can choose how much time and effort to dedicate to a problem, and the priority that work has over other tasks. When investigators travel to an aircraft manufacturer's site to exercise a simulation, they have only the time available during that trip, and once they return, it can be hard to perform follow-up work based on insights gained during the initial effort. When investigators oversee simulation work done by parties to the investigation, they are hostage to the timeframe and priorities of those parties, which rarely coincide with those of the investigator – as cooperative as the parties might be. The scope of the simulation effort might contract as a result, but be tolerated because the timeframe of the larger investigation demands a deadline. Parties can unintentionally "run out the

clock" on simulation work done on behalf of an investigative agency simply because from their point of view, their employees have other, higher priority tasks to perform.

Based on these considerations, the first choice for exercising Tier 2 desktop simulations should be the acquisition and implementation of the required proprietary models in an agency's own simulation program, when possible. The initial time investment required to implement and validate the simulation will pay dividends in terms of the insight gained into the physics of the problem and the thoroughness, timeliness, and independence of the results.

Performing desktop simulations when no aircraft models are available

In some cases, a full six-degree-of-freedom simulator model of the required aircraft will simply not exist. Nonetheless, as stated above, some aircraft performance problems can be addressed with very simple, low-fidelity models – for example, when the simulator is used to create a physically realistic, smooth flight path through noisy radar data, and only the motion of the aircraft's center of gravity is of interest. The aerodynamic coefficients and stability derivatives comprising the "models" underlying these simulations can be based on exemplar "textbook" values, along with the actual airplane wing area and gross weight.

If relatively accurate lift and drag data can be obtained, these can be incorporated into the simple models, and used to produce an estimate of the thrust required to fly a given trajectory. In addition, the airplane's maximum lift coefficient can be determined from stall speed information published in the Airplane Flight Manual (AFM), and compared to the lift coefficients computed by the simulation to inform a conclusion as to whether the airplane approached or entered a stalled condition.

Basic lift and drag data might be available from an aircraft manufacturer's design records or wind tunnel tests, or estimated based on the wing geometry and theoretical methods combined with climb and glide performance published in the AFM. In one NTSB case, the lift and drag coefficients of the Cirrus SR-22 at different flap settings were computed from data acquired during NTSB-requested flight tests of an actual airplane, with NTSB investigators participating, using the airplane's Avidyne avionics as the flight-test instrumentation system.[18]

Summary and conclusions

This paper defines three "Tiers" of aircraft simulation, depending on which elements of an FFS are exercised. Tier 1 simulations include all the elements of an FFS; Tier 2 or "desktop" simulations include only the computational elements of an FFS, and exclude the pilot-interface elements; and Tier 3 simulations are not really simulations at all, but only "media players" of pre-existing flight data. Tier 3 simulations include simple animations, which can be created very quickly using simulation "games" such as *X-Plane* and *Microsoft Flight Simulator*, and "backdrive" simulations, which require the pilot-interface elements of an FFS but not any of the aircraft models.

Tier 1 simulations are used when the interactions of the pilot with the aircraft and the operational and human performance aspects accident scenario are of primary interest. Tier 2 simulations focus on the performance of the aircraft itself, with control inputs defined in pre-existing data or computed so as to achieve a desired aircraft trajectory. "Backdrive" simulations are used to

recreate an accident scenario from the pilots' point of view, and animations are used to communicate the complex circumstances of an accident to investigators and the public in an intuitive, easy-to-understand way. Some investigations, such as the AA587 case discussed here, can benefit from all three Tiers of simulation.

Full-flight simulators for Tier 1 and "backdrive" simulations must be accessed through parties to the investigation (aircraft manufacturers or operators), or commercial training providers. Models underlying Tier 2 simulations can be obtained from aircraft manufacturers, simulator manufacturers, or model developers. These models are valuable intellectual property and must be protected accordingly; in most cases, negotiation with the model owners will be required in order to access the models.

While there are several ways an agency can exercise proprietary simulation models, including traveling to an aircraft manufacturer's facilities or overseeing simulations performed by parties to the investigation, the thoroughness, timeliness, and independence of an agency's Tier 2 simulations are best served by enabling investigators to obtain and implement the required aircraft models (or relevant portions of those models) in their own desktop simulation programs.

When full six-degree-of-freedom simulation models for an aircraft do not exist, some aircraft performance problems can still be addressed using very simple, low-fidelity models developed from textbook methods and supplemented with information gleaned from the aircraft AFM and from design and / or wind tunnel data provided by the aircraft manufacturer.

Endnotes

[1] The simulator "tiers" described here are not to be confused with the simulator qualification "levels" defined in simulator certification standards such as 14 Code of Federal Regulations (14 CFR) Part 60 (§60). The "tiers" described in this paper define subsets of the full-flight simulator components illustrated in Figure 1 that are used for different analysis tasks; the qualification "levels" described in §60 describe simulator and flight training device fidelity and capability requirements for different aspects of pilot training.

[2] Although the simulation tiers defined in this paper do not correspond to the simulator qualification levels defined in §60, the FFS tier described here does reflect the definition of a "full flight simulator" in §60: "a replica of a specific type, make, model, or series aircraft. It includes the equipment and computer programs necessary to represent aircraft operations in ground and flight conditions, a visual system providing an out-of-the-flight deck view, a system that provides cues at least equivalent to those of a three-degree-of-freedom motion system, and has the full range of capabilities of the systems installed in the device as described in part 60 of this chapter and the [Qualification Performance Standards] for a specific FFS qualification level."

[3] See, for example, simulations of the Boeing 767 elevator actuator performance conducted during the EgyptAir Flight 990 investigation (NTSB # DCA00MA006), here: https://data.ntsb.gov/Docket/Document/docBLOB?ID=40125382&FileExtension=.PDF&FileName=Aircraft%20Performance%2013%20-%20Addendum%201%20-Master.PDF. The Cockpit Display of Traffic Information (CDTI) simulation described in the Moncks Corner midair collision Aircraft Performance / Cockpit Visibility Study (linked below) is another example of an independent Tier 2 simulation of a particular aircraft system.

[4] Animations can also be supplemented with audio information, such as a narration describing the scene or the context of the animation, or even (for investigative purposes only) synchronized CVR audio.

[5] The animation of accidents using *FSX* is described in the Moncks Corner midair collision Aircraft Performance / Cockpit Visibility Study (linked below).

[6] For a final animation product that is presented to the public, video editing software is still required to place the animations created with simulation programs into a larger video that incorporates additional elements, such as maps of the accident area, text disclaimers, and a voiced narration. In addition, 3D modelling and video editing software is used to create animations of the operation of aircraft systems (such as control systems), and to combine different animation, graphic, and audio elements into one composite video presentation.

[7] See *Ditching Requirements, Airbus Substantiation for the A320 and a comparative assessment of US Airways Flight 1549*, here: file:///C:/Users/ocaj/OneDrive%20-%20NTSB/Downloads/Structres%207H%20-%20A320_%20Ditchimg%20Requirements,%20Airbus%20Substantiation%20and%20a%20Comparative%20Assessment%20of%20US%20AIR%201549-Master.PDF.

[8] The "fidelity" of a model refers to how well it represents the real aircraft. The fidelity requirements of an FFS and other training devices are specified in §60 and its Appendices, and a simulator's compliance with these requirements is documented in "proof of match" comparisons of simulator output with flight-test data.

[9] The simulation engine and math pilot used in the Amarillo PC-12 investigation were developed in the *MATLAB* environment by the author and a colleague at the NTSB.

[10] The PC-12 is certified to 14 CFR Part 23 Normal Category standards, through Amendment 23-42.

[11] Of course, different animation elements can be added to a video using editing software separate from the simulation, creating a composite animation that includes not only an image of the aircraft, but images depicting cockpit instruments, a clock, control positions, and other information.

[12] The variable ratio limiter system allows full rudder pedal travel at all airspeeds but still limits the rudder surface travel. For this condition, the timing of rudder movements was presented as it was recorded by the FDR, but the amplitude of motions was changed so that the pedals were displaced as a ratio of full rudder pedal travel rather than as a ratio of the limited pedal travel.

[13] In 2020, Microsoft and Asobo Studios released a new version of *Microsoft Flight Simulator* that uses imagery and data downloaded in real-time to create stunningly realistic scenery and environments. As of this writing (June 2021), third parties are developing add-ons for this new version that can be used to create animations such as those described here, in which the aircraft states are driven by an external data file.

[14] This program used to be available at http://www.fs-recorder.net/, but the website is no longer operational.

[15] In case #WPR16FA040, *FSX* was used to estimate the pitch and roll angles achieved by the accident helicopter by manually flying a helicopter model through "hoop targets" placed in the simulated environment at the locations defined by recorded GPS positions. In this instance, *FSX* was operated in its normal "game" mode, with the user controlling the simulation with a joystick and the keyboard. For details, see https://data.ntsb.gov/Docket/Document/docBLOB?ID=40469056&FileExtension=.PDF&FileName=Aircraft%20Performance%20Memorandum%20(Final)-Master.PDF.

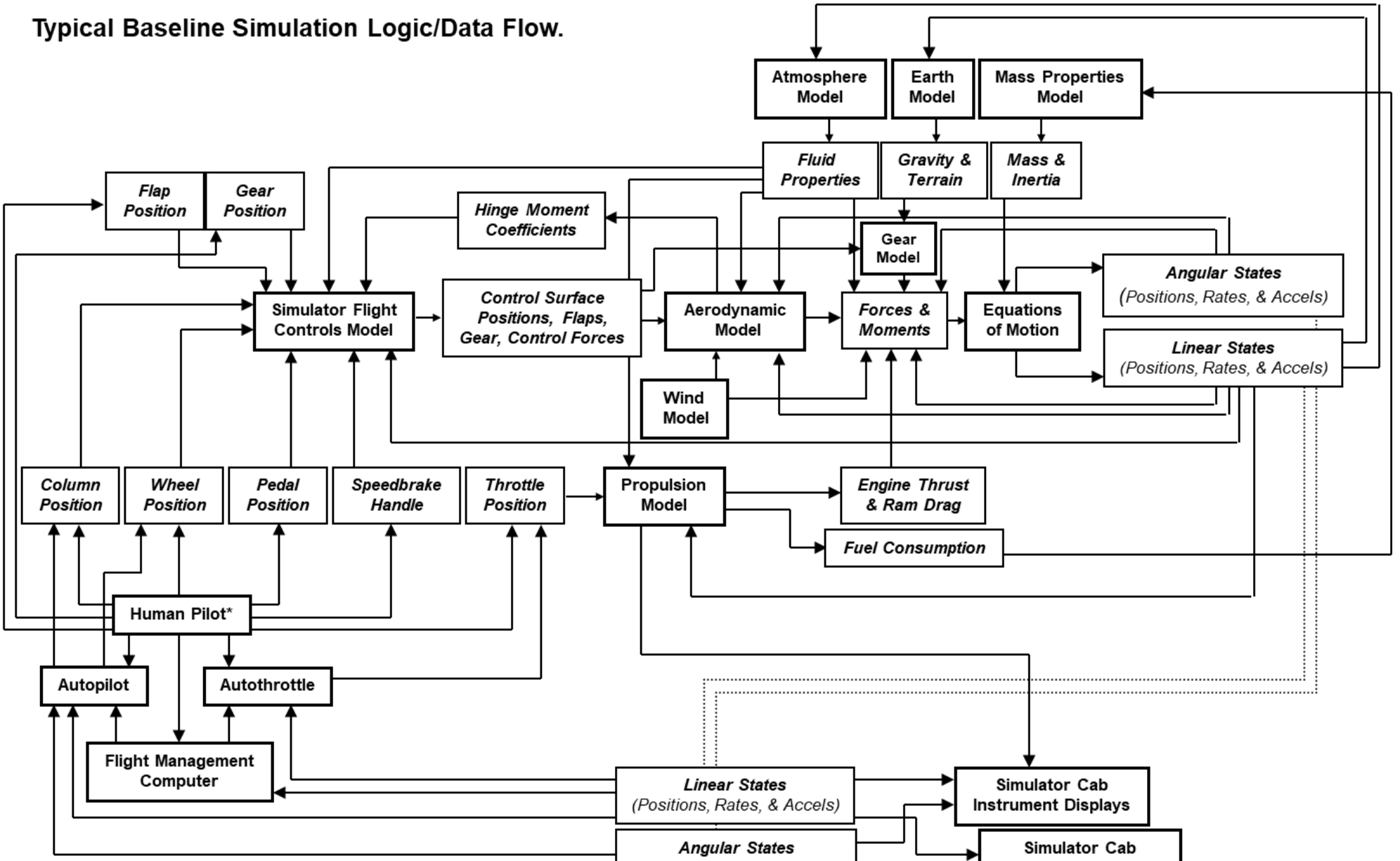
[16] The one case known to the author in which FOIA exemptions failed to protect proprietary simulator model data from public release concerns the Boeing 747-100 models underlying the NTSB's Tier 2 simulations of the 1996 TWA flight 800 accident (NTSB # DCA96MA070). See the following court case record: Lahr v. National Transportation Safety Board, 453 F. Supp. 2d 1153 | Casetext Search + Citator.

[17] In a partial data package, only the relevant subset of models required to address the flight condition at hand are provided. For example, for a landing overrun, only the aerodynamic coefficients of the airplane in the ground attitude at the flap setting in question might be provided. Similarly, only the forward and reverse thrust data corresponding to the elevation, temperature, and speed range of the overrun might be provided.

[18] See the *Aircraft Performance Study* for NTSB case # CHI06FA245, linked here: https://data.ntsb.gov/Docket/Document/docBLOB?ID=40307451&FileExtension=.PDF&FileName=Aircraft%20Performance%2013%20-%20REVISED%20Factual%20Report%20of%20Group%20Chairman-Master.PDF.

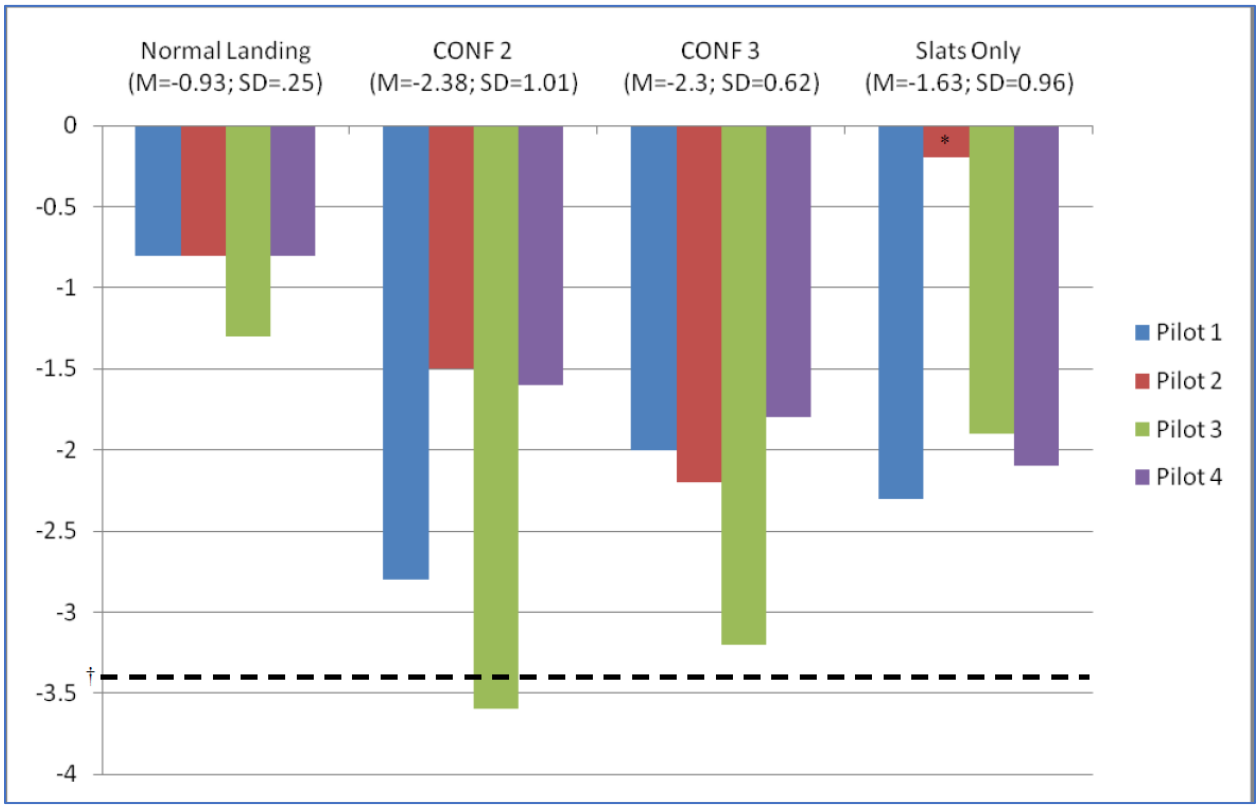
Figures

Typical Baseline Simulation Logic/Data Flow.



*In the case of "backdrive" simulations, the actions of the human pilot are replaced by instructions in user defined "scenario file" computer programs.

Figure 1.



Notes: M=mean; SD=standard deviation. Flight path angle calculated by "$\tan^{-1}$(vertical speed / ground speed)"; * Different landing technique flown to attempt to achieve lowest vertical descent rate possible at touchdown; † Flight path angle (-3.4 degrees) of flight 1549

Figure 2. US1549 ditching simulation results: Flight path angles (in degrees) for a normal landing and different airplane configurations for ditching.

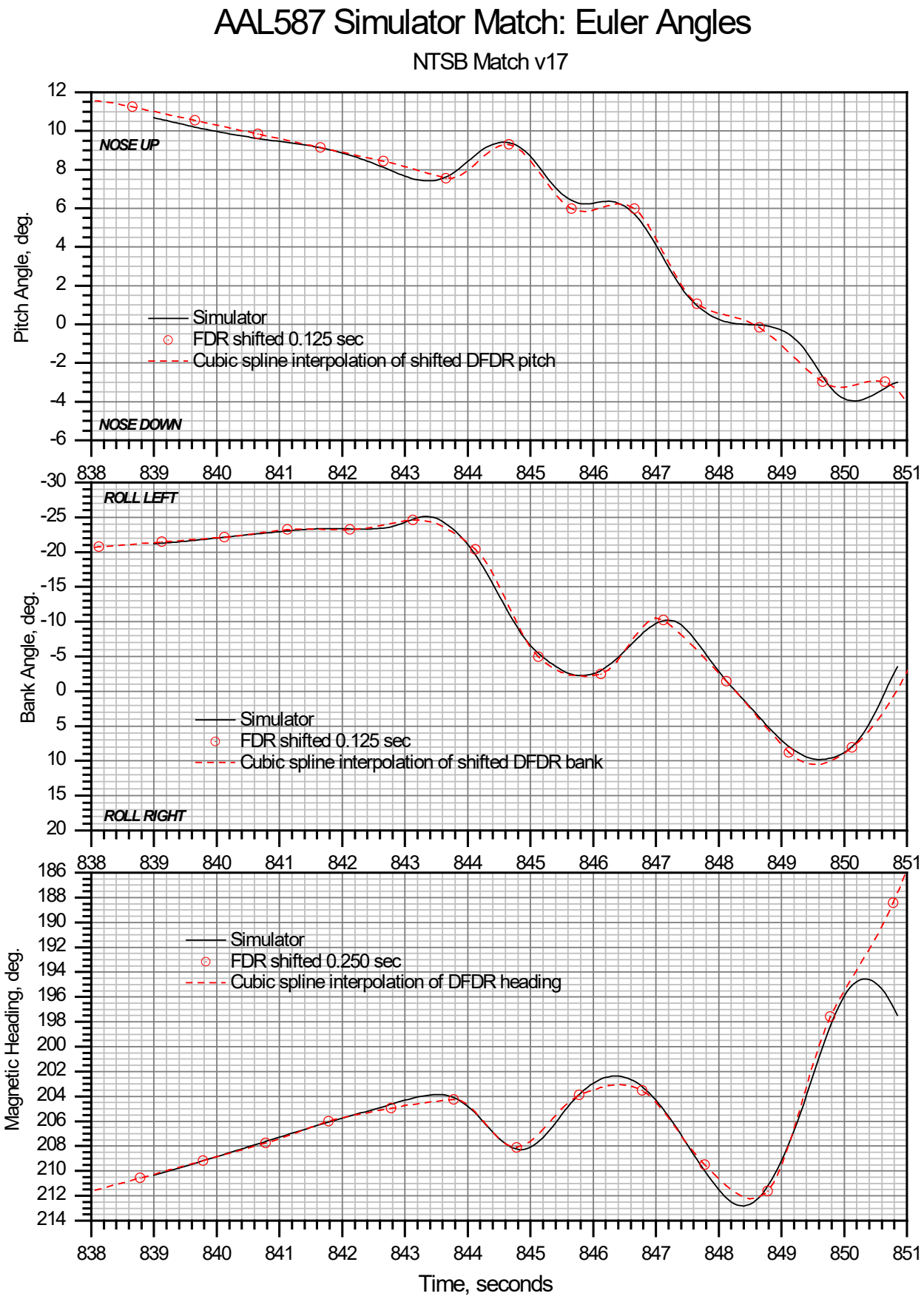


Figure 3: AA587 NTSB simulation Euler angles resulting from including both flight control inputs and wake effects.

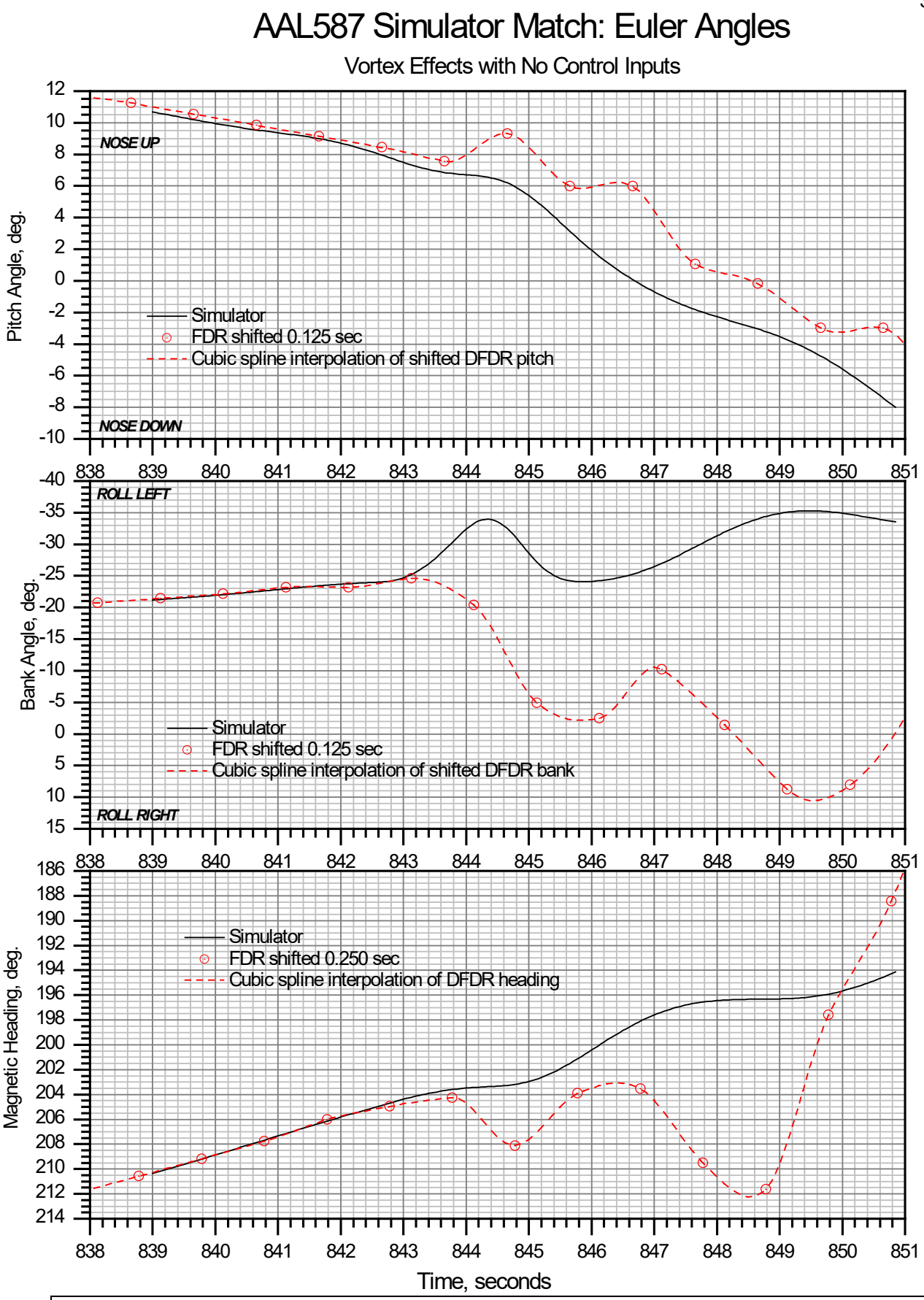


Figure 4: AA587 NTSB simulation Euler angles resulting from including wake effects only (flight controls held at trim positions).

CEN17FA168: Pilatus PC-12, N933DC, Amarillo, TX, 04/28/2017

Plan view of radar data and simulation trajectory

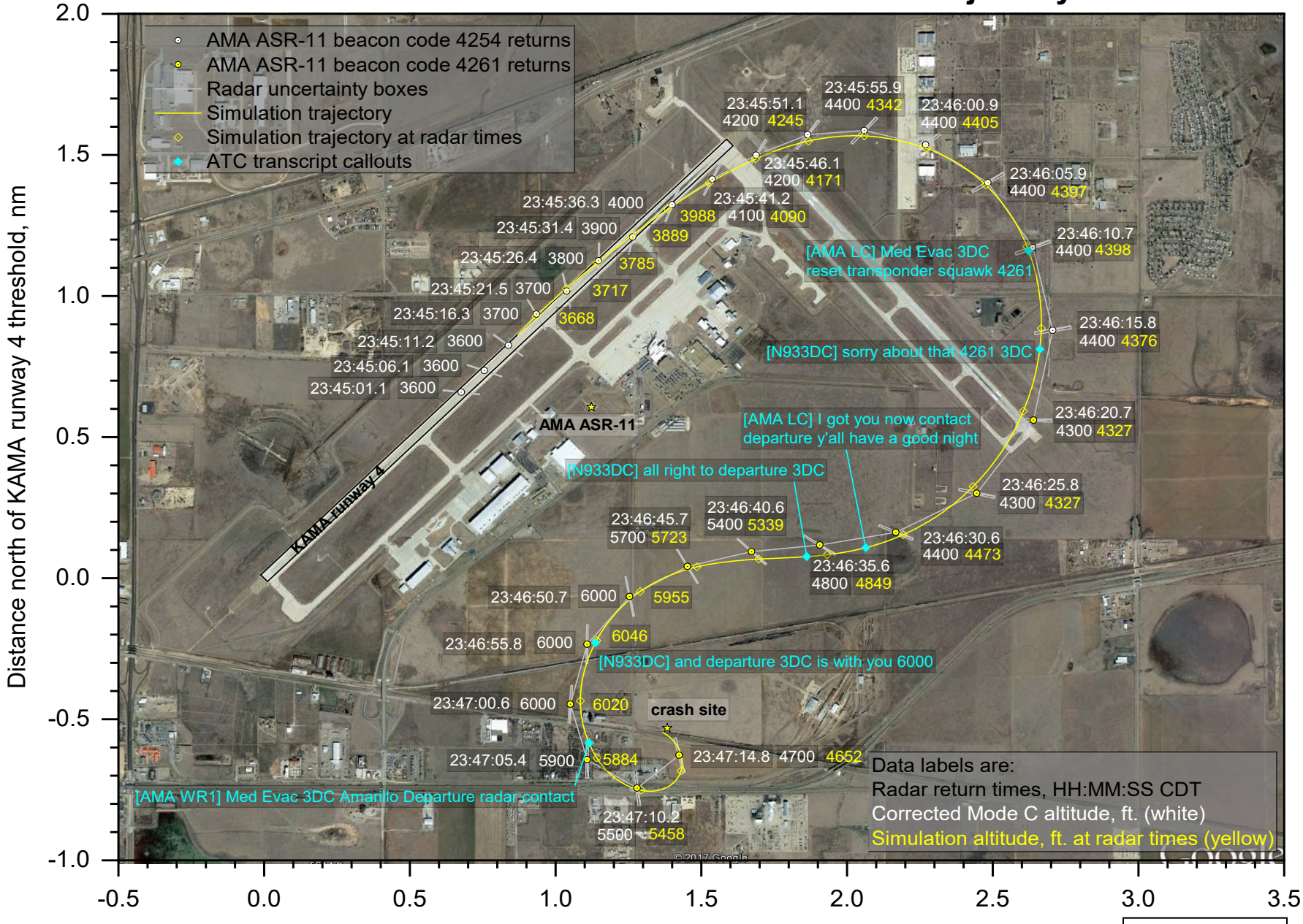
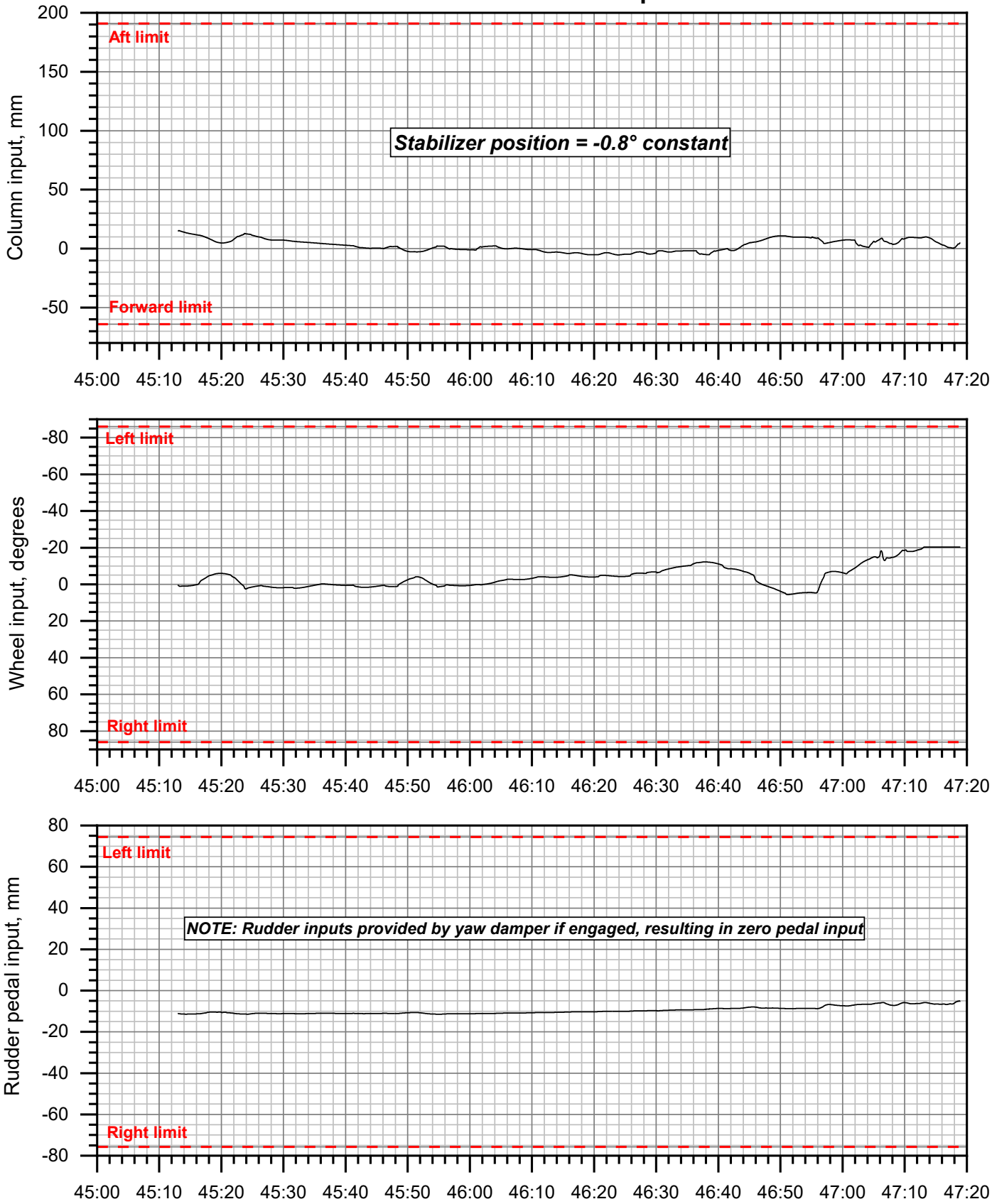


Figure 5.

CEN17FA168: Pilatus PC-12, N933DC, Amarillo, TX, 04/28/2017

Simulation control inputs



AMA ASR-11 time, MM:SS after 23:00:00 CDT

Figure 6.

CEN17FA168: Pilatus PC-12, N933DC, Amarillo, TX, 04/28/2017

Simulation control surfaces

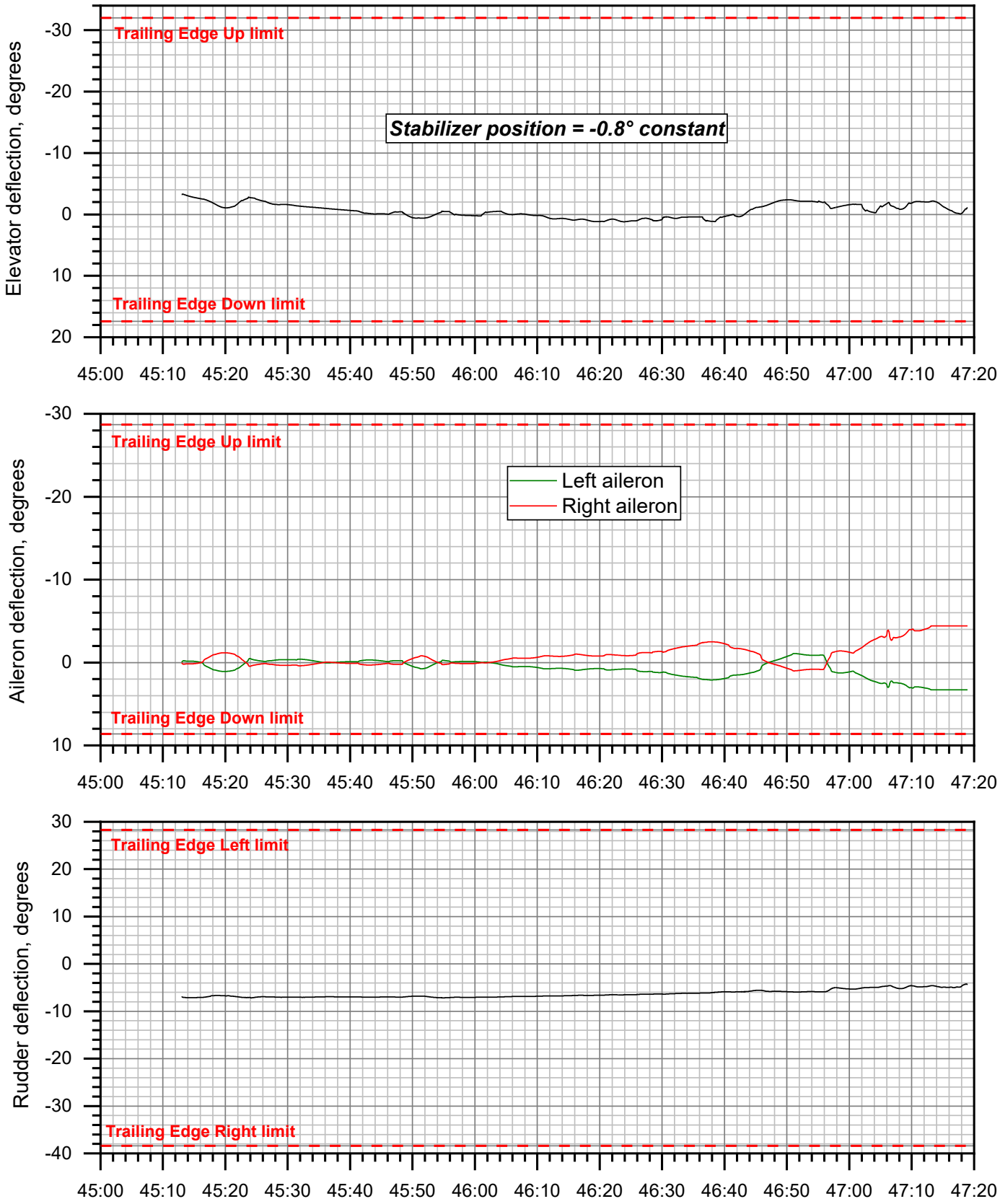
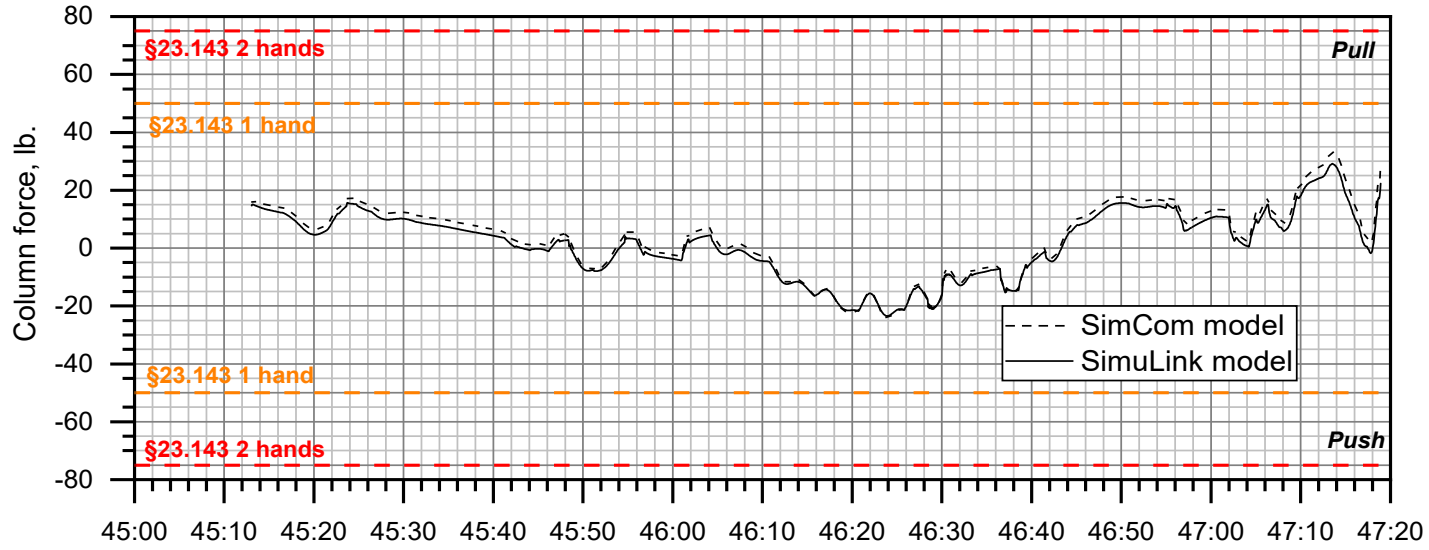
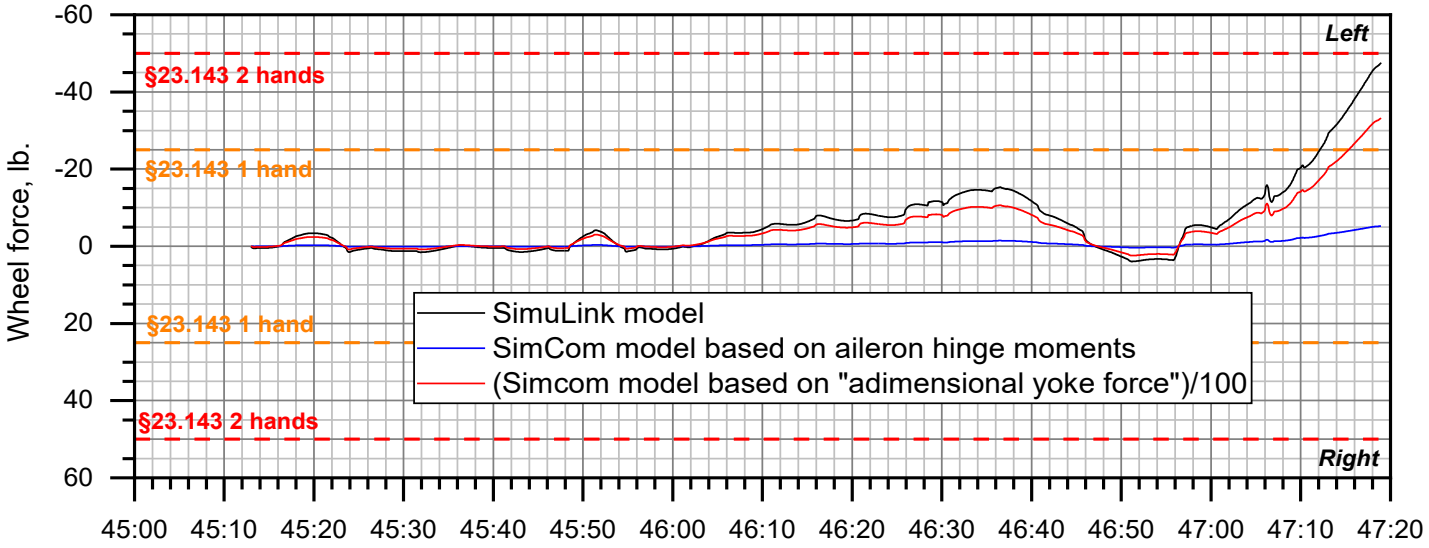


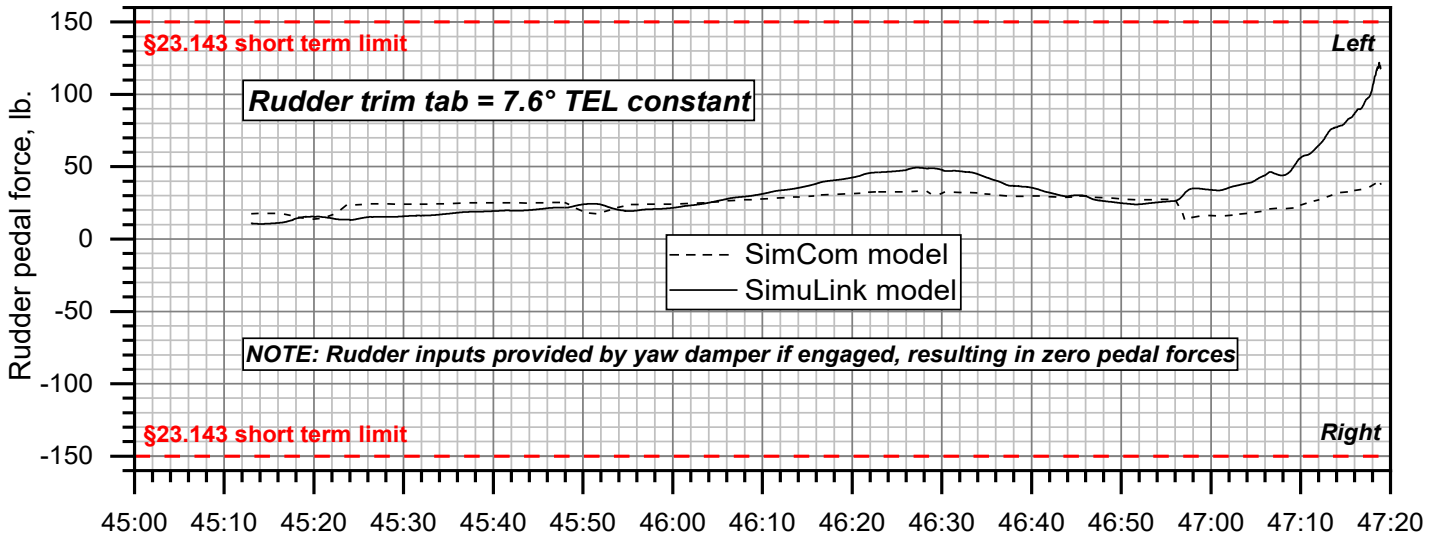
Figure 7.

CEN17FA168: Pilatus PC-12, N933DC, Amarillo, TX, 04/28/2017

Simulation control forces







AMA ASR-11 time, MM:SS after 23:00:00 CDT

Figure 8.

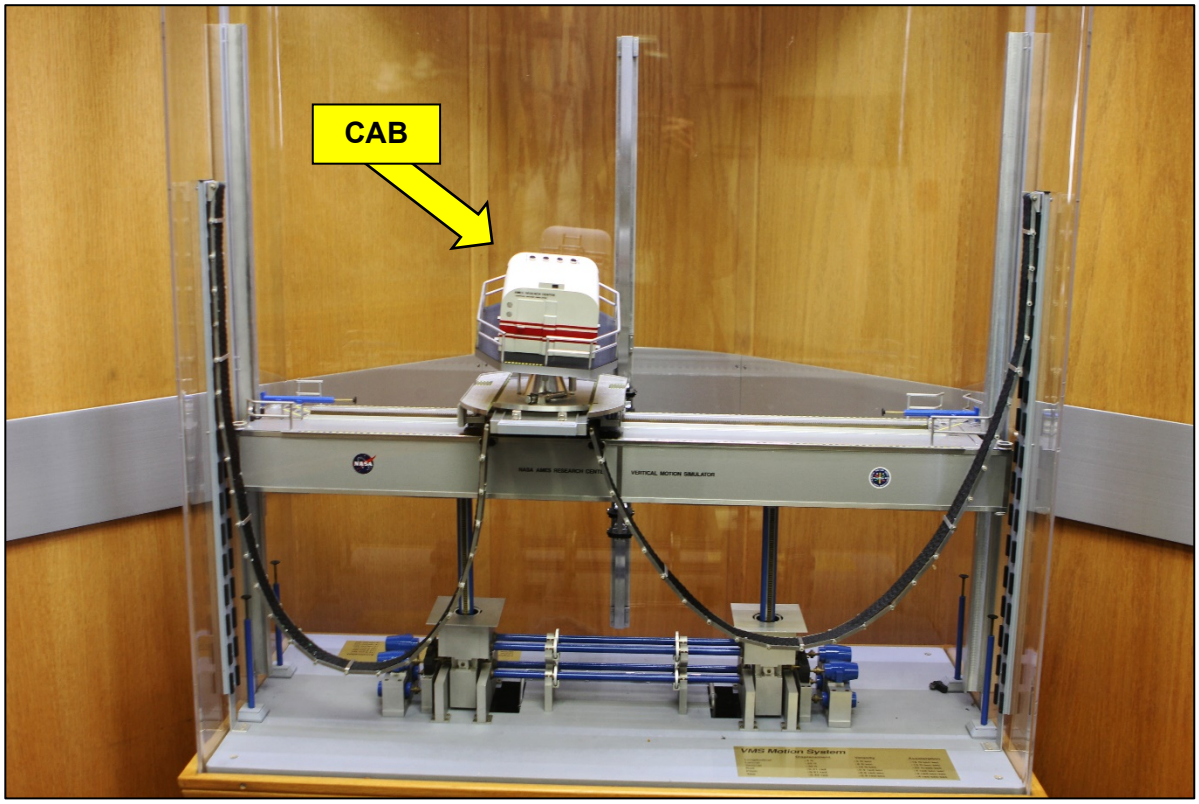


Figure 9. Photograph of a model of the VMS cab and its mounting system.

Figure 10. Photograph of the T-Cab configuration for the backdrive activities.

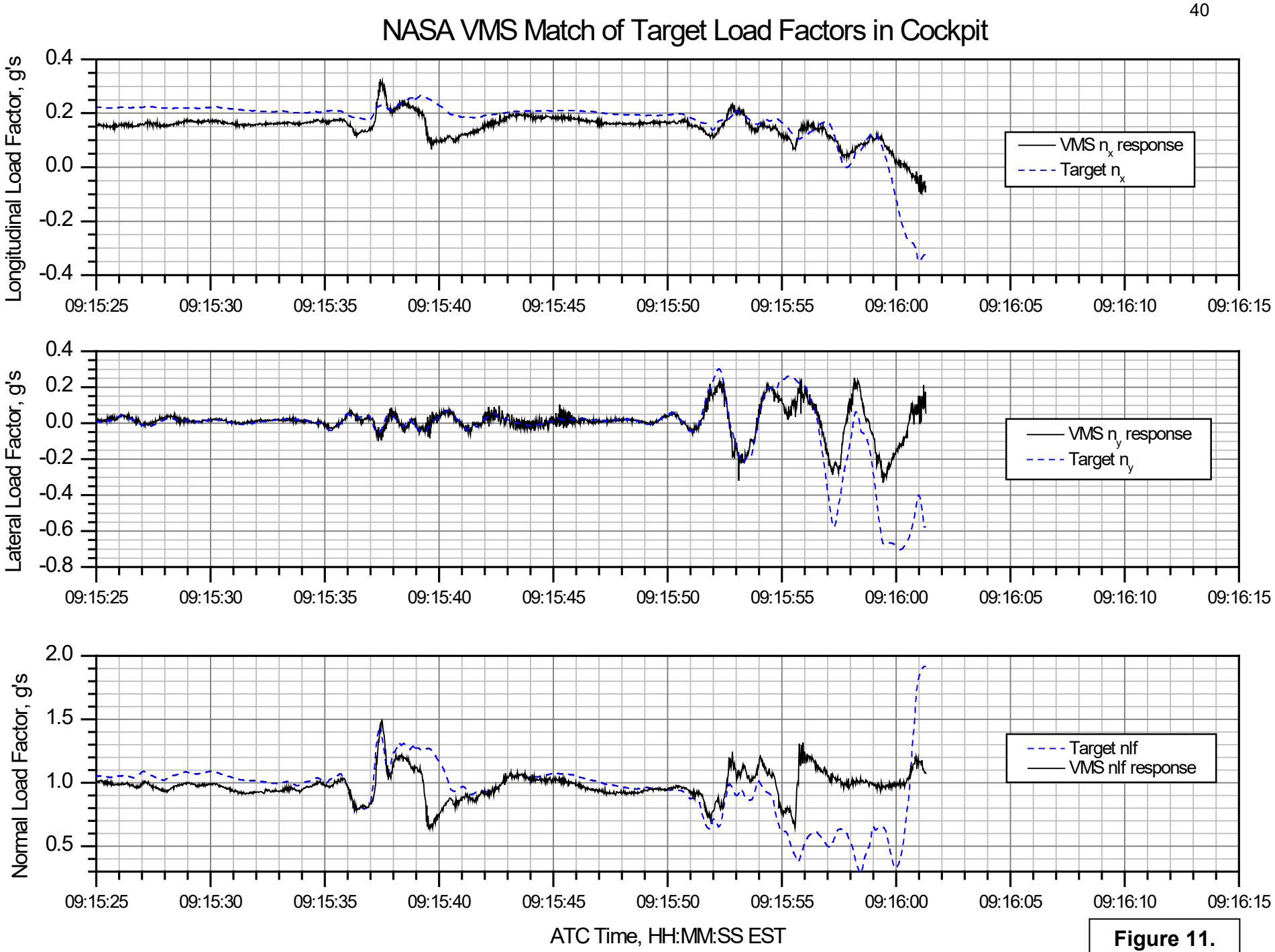

NASA VMS Match of Target Load Factors in Cockpit
Longitudinal Load Factor, g's
0.4
0.2
0.0
-0.2
-0.4
VMS n_x response
Target n_x
Lateral Load Factor, g's
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
VMS n_y response
Target n_y
Normal Load Factor, g's
2.0
1.5
1.0
0.5
Target nlf
VMS nlf response
09:15:25
09:15:30
09:15:35
09:15:40
09:15:45
09:15:50
09:15:55
09:16:00
09:16:05
09:16:10
09:16:15
ATC Time, HH:MM:SS EST

Figure 11.

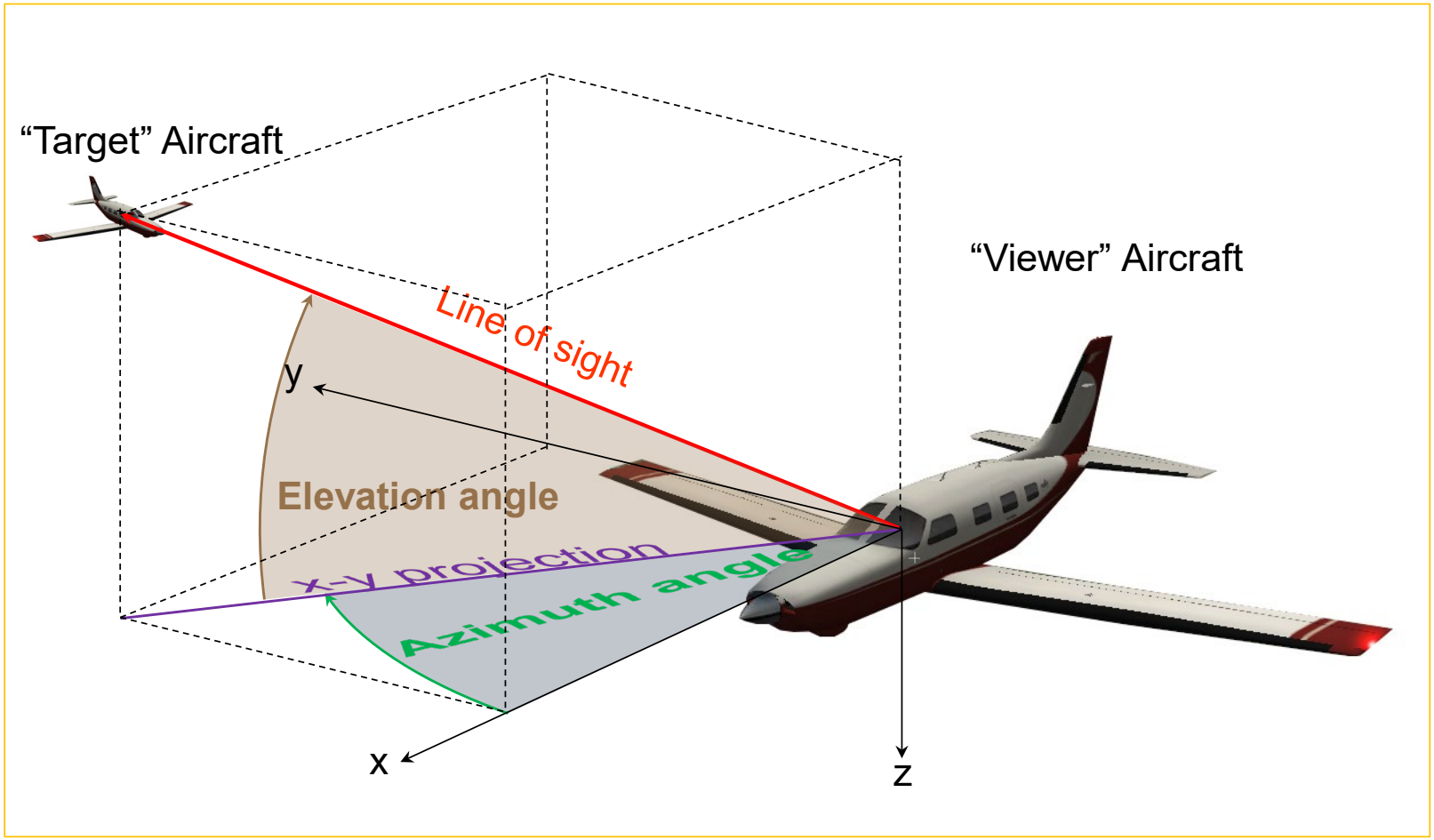
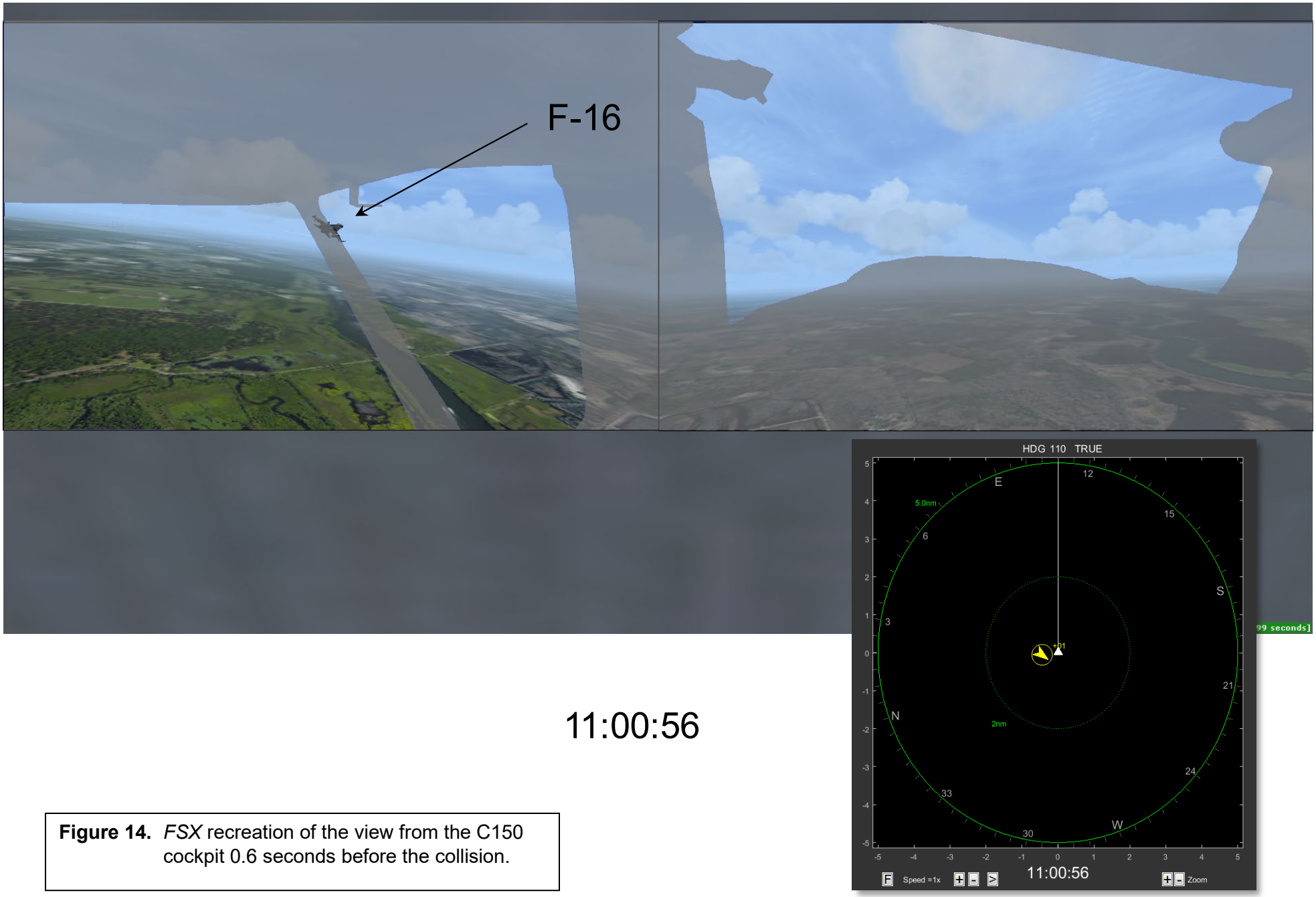


Figure 12. Azimuth and elevation angles from “viewer” airplane to “target” airplane.

11:00:56

Figure 13. *FSX* recreation of the view from the F-16 cockpit 0.6 seconds before the collision.



11:00:56

Figure 14. *FSX* recreation of the view from the C150 cockpit 0.6 seconds before the collision.