Atlas Air Flight 3591

On February 23, 2019, at 1239 central standard time, Atlas Air Inc. (Atlas) flight 3591, a Boeing 767-375BCF, N1217A, was destroyed after it rapidly descended from an altitude of about 6,000 ft mean sea level (msl) and crashed into a shallow, muddy marsh area of Trinity Bay, Texas, about 41 miles east-southeast of George Bush Intercontinental/Houston Airport (IAH), Houston, Texas.

The captain, first officer (FO), and a nonrevenue pilot riding in the jumpseat died. Atlas operated the airplane as a Title 14 Code of Federal Regulations (CFR) Part 121 domestic cargo flight for Amazon.com Services LLC, and an instrument flight rules flight plan was filed. The flight departed from Miami International Airport (MIA), Miami, Florida, about 1033 (1133 eastern standard time) and was destined for IAH. A review of cockpit voice recorder (CVR) and flight data recorder (FDR) data determined that the flight's departure from MIA, en route cruise, and initial descent toward IAH were uneventful. The FO was the pilot flying (PF), the captain was the pilot monitoring (PM), and automated flight functions (autopilot and autothrottle) were engaged.

At 1230:37, when the flight was about 73 miles southeast of IAH and descending normally through about 17,800 ft msl, the captain checked in with the Houston terminal radar approach controller and reported that the flight was descending toward the airport on the assigned arrival route. At 1234:09, the approach controller advised the flight crew of an area of light-to-heavy precipitation about 35 miles ahead of the flight's position and that they could expect vectors to navigate around it. The FDR data showed the flight continued to descend normally on the assigned arrival route.

According to CVR audio, at 1236:07, the FO said, "okay – I just had a…," then, 3 seconds later, he initiated a positive transfer of airplane control to transfer PF duties to the captain, stating, "your controls." The captain responded, "my controls." At 1237:07, the FO made a comment about the electronic flight instrument (EFI) switch. Two seconds later, the FO said, "okay, I got it back," and the captain said, "now it's back." The FO then said, "I press the EFI button, it fixes everything," and the captain acknowledged

While acting as PM, the FO advised

the air traffic controller that the flight would like a vector west of the weather and acknowledged the controller's instructions for the flight to "hustle all the way down" in its descent to 3,000 ft msl.

As the airplane continued its descent, the speedbrakes were extended. The controller advised the flight to turn left to 270°, which the captain acknowledged before transferring PF duties back to the FO at 1237:24. After the FO resumed PF duties, the CVR recorded comments between the FO and the captain that were consistent with setting up the flight management computer (FMC) and configuring the airplane for the approach to IAH, including lowering the slats (consistent with the "flaps 1" setting). The FDR data showed that the airplane continued to descend normally until 1238:31, when the airplane's go-around mode was activated.

At the time, the airplane was about 40 miles from IAH at an altitude of 6,300 ft msl. During the next 6 seconds, the airplane's automated flight functions commanded nose-up pitch and an increase in engine thrust, consistent with go-around mode-driven commands. Neither crewmember made any callout to indicate intentional activation of the go-around mode or took action to disconnect the automation. The captain continued to receive and respond to routine air traffic control (ATC) communications. About 1238:36, the speedbrakes were retracted, then the airplane's elevators moved in response to manual control inputs to command nose-down pitch. The amount of nose-down pitch continued to increase, and the airplane entered a steep descent. Beginning at 1238:44, the FO said, "oh," then said in an elevated voice "whoa… (where's) my speed, my speed…we're stalling;" he then exclaimed "stall" at 1238:51. A review of FDR data determined that the airplane's airspeed and pitch parameters were not consistent with the airplane at (or near) a stalled condition, and none of the stall warning system indications activated. At 1238:56, the captain asked, "what's goin' on?" Three seconds later, the pilot riding in the jumpseat shouted, "pull up." About this time, the elevators moved consistent with manual control inputs to command airplane nose-up pitch. The nose-up pitch control inputs were held for the remaining 7 seconds of the flight but were unsuccessful in arresting the airplane's descent in time to prevent its crash into the marsh (see figure 1).

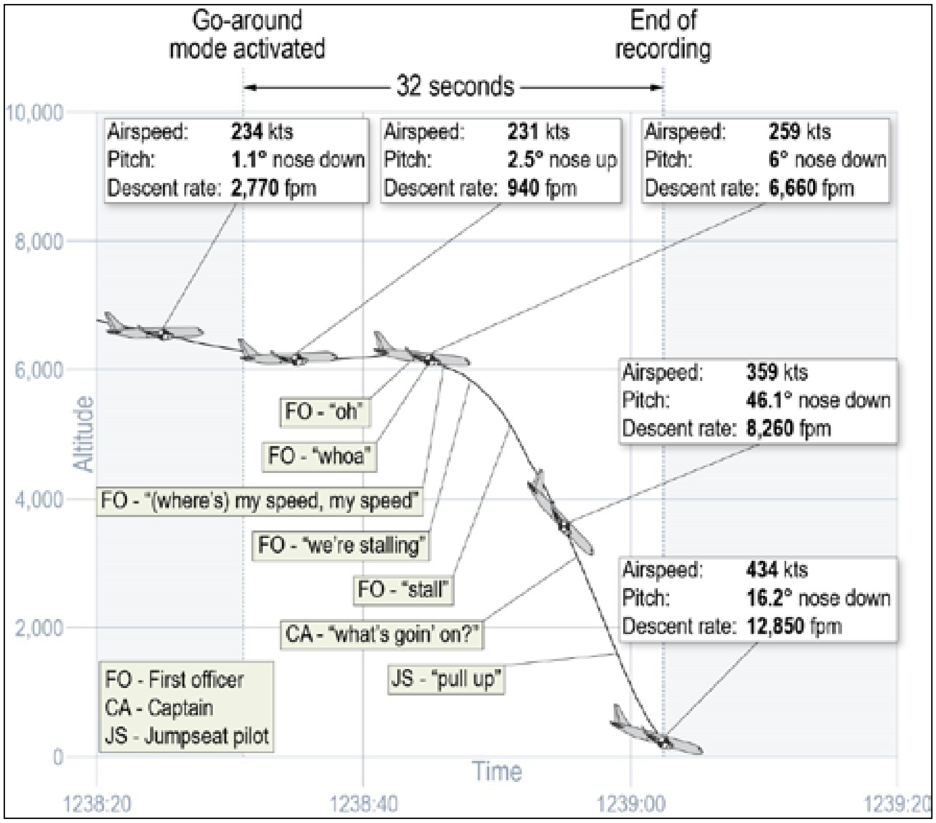
Tests and Research

Airplane Performance Study

The NTSB's airplane performance study used FDR data, automatic dependent surveillance-broadcast data, and CVR information to evaluate various airplane parameters recorded during the flight. (Basic airplane systems information is included in this section for context.) Before the go-around mode was activated, the airplane was descending normally at a reduced thrust setting (thrust levers were about 32° to 33°) with an airplane pitch attitude of about 1° nose down and operated with the autopilot and autothrottle engaged. The airplane's automated flight control system could perform climb, cruise, descent, and approach functions as selected by the flight crew using the mode control panel (MCP), FMC, and thrust mode selector.

The FDR data indicated that the crew had the assigned altitude of 3,000 ft msl selected using the MCP. FDR data showed that airplane vertical load factor variations began about 1238:25, with a peak vertical acceleration of 1.26 gravitational acceleration (g), the flight was in the immediate vicinity of the leading edge of a cold front at the time.

FDR data at 1238:31 showed that the airplane's automated flight system status for the go-around mode changed to "activated," and the CVR recorded a "click" at this time. In the accident, the airplane's configuration with autopilot and autothrottle engaged, the autopilot/flight director system (AFDS) and autothrottle would be expected to respond by controlling airplane pitch, roll, and thrust to maintain ground track, hold the existing airspeed, and establish a climb rate of at least 2,000 ft per minute. During the next 6 seconds, automated flight commands advanced the thrust levers to about 80° to 82°, resulting in increased thrust and longitudinal acceleration, and moved the control column and elevators to command nose-up pitch; during this time, the airplane's pitch increased to about 4° nose up.



About 1238:36, the speedbrake lever was moved from the extended position to the armed position, which retracted the speedbrakes. Recorded airplane parameters at this time, including those for air/ground sensing and flap setting criteria, did not meet the conditions for automatic speedbrake retraction. Between about 1238:38 to 1238:56, the airplane pitched nose down and continued to accelerate, reaching a peak longitudinal acceleration of 0.27 g at 1238:42.

During this time, the position of the left elevator control column (the only side for which the FDR recorded position data) matched the position of the elevators, which was consistent with the elevators responding to manual inputs from a crewmember on an elevator control column.

Such a manual override of the autopilot would require control column inputs in excess of 25 lbs. The airplane's nose-down pitch during this time progressed rapidly to about 49° nose down, and the airplane entered a steep descent. At 1238:40, the CVR recorded a beeping sound consistent with the "owl" beeper; the FO then said, "oh" at 1238:44 and "whoa" at 1238:45.27 Between 1238:46 and 1238:56, the right elevator was in a more airplane nose-down position than the left elevator, which would be consistent with the captain and the FO each applying differing manual inputs on their respective control columns.

At 1238:48 and 1238:51, the FO stated that the airplane was stalling. Review of the airplane's recorded vane angle of attack (AOA), which was below -15°, and airspeed, which was above 250 knots (kts), determined that the airplane's wing stall AOA was not exceeded, and the airplane was not at or near a wing-stalled condition. Also, the FDR's recorded parameter for the stick shaker did not record the stick shaker as being active at any point in the flight. Beginning about 1238:45, the thrust levers were reduced to 33° within 1 second then increased to about 80° to 85° within 2 seconds. These rates of thrust lever movement were faster than the autothrottle system could command.

At 1238:56, the captain asked, "what's goin' on?" At the time, the airplane was descending through an altitude of about 3,000 ft msl, and both elevators began to move concurrently toward an airplane nose-up position. About 2 seconds later, both elevators attained the full airplane nose-up position and remained there until the end of the FDR recording.

During this time (beginning at 1238:56), a series of beeps consistent with the "siren" sounded, and the FDR recorded an overspeed.

Just before the FDR recording ended at 1239:03, the airplane's pitch was about 20° nose down, its airspeed was in excess of 400 kts, and its load factor was more than 4 g.

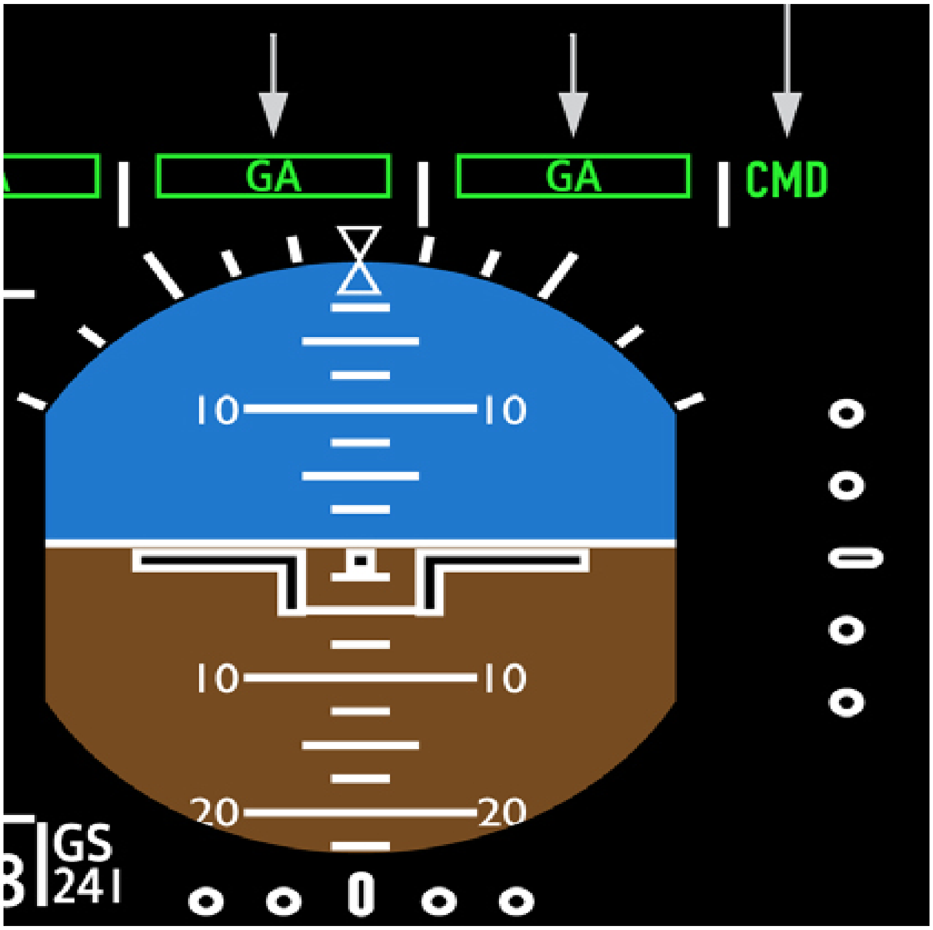
Boeing 767 Simulator Scenario Observations

Investigators performed a series of scenarios in a Boeing 767 full-flight simulator to document various indications, alerts, and airplane responses related to operation of the autopilot, autothrottle, go-around switches, speedbrake handle, and EFI switch. The scenarios were flown by a PF in the right seat to enable investigators to observe how a pilot seated on that side of the airplane interacted with the various airplane controls and displays. In one scenario, the PF was expediting a descent to 3,000 ft msl (with 3,000 ft msl set on the MCP) with the speedbrakes extended and the autopilot and the autothrottle engaged. At 6,400 ft msl, the PF pushed one of the go-around

switches. The investigators observed that the airplane responded by climbing and the speedbrakes did not automatically retract. Concurrent with go-around mode activation, the flight mode annunciator at the top of each ADI display annunciated "GA/GA/GA/CMD" in green (with a temporary box around each "GA") to indicate, respectively, that the go-around mode was active for autothrottle, pitch, and roll and that the autopilot function of the AFDS was engaged.

According to Atlas' flight crew operating manual (FCOM), when using the speedbrakes during flight, "the PF should keep a hand on the speedbrake lever…This helps prevent leaving the speedbrake extended when no longer required." One Atlas pilot interviewed said that, in his experience, the "overwhelming majority [of pilots] if not almost everybody" followed this procedure.

Investigators performing the simulator scenarios had the pilot hold the speedbrake lever using a variety of different hand grip and arm positions. The investigators observed that, when the right-seat PF kept his left hand on the speedbrake lever during the descent (consistent with Atlas' procedures), the PF's left hand and wrist could be under the thrust levers and close to the left goaround switch. (The distance between the hand/wrist and the go-around switch varied with different hand grip and arm positions.) The scenarios showed that, if a PF were wearing a watch on the left wrist (as photographs showed the accident FO had done at times), this could result in decreased clearance beneath the go-around switch (see figure 12). Investigators also observed that cycling the EFI switch (to reset the respective SG) took less than 4 seconds to accomplish, did not change the ADI's presentation of the airspeed data, and did not affect the information displayed by the two conventional Mach/airspeed indicators.



Events Involving Inadvertent Go-Around Mode Activation

In response to NTSB requests for data about any reported events involving inadvertent activation of the go-around mode on Boeing 767-series airplanes, The Boeing Company, Atlas, one other domestic airline (among several contacted), and the National Aeronautics and Space Administration's (NASA) Aviation Safety Reporting System (ASRS) identified no such reports in their respective databases. The ASRS database contained 11 reported events of inadvertent goaround activation that occurred between 1990 and 2017 involving other airplane models, including Boeing 737-, 747-, and 777-series; Airbus A320; Bombardier CL-600; and Embraer EMB170 airplanes.35

A review of these ASRS reports revealed that each flight crew was able to correct the situation, but some experienced undesirable results, such as altitude deviations, a missed crossing restriction, and a flap overspeed. One event, which involved a flight crew on a Boeing 747, progressed to stick shaker activation before they regained situational awareness and corrected the condition. The NTSB is aware of two 1994 accidents and a 1989 incident that involved transportcategory airplane models other than the Boeing 767 and included inadvertent activation of the goaround mode in the sequence of events.

Terrain Awareness and Warning System Simulation

The airplane was equipped with a Honeywell enhanced ground proximity warning system, which is a terrain awareness and warning system (TAWS) designed to reduce the risk of controlled flight into terrain by providing flight crews with alerts and warnings about potential terrain conflicts. The unit was not located in the wreckage, and FDR data showed that all parameters related to TAWS alerts remained "off" for the entire accident sequence. A simulation of TAWS functions performed by the manufacturer using data from the accident flight found that the change in radio altitude values near the end of the FDR recording was considered excessive by the system, which flagged it for internal reasonableness. The system's logic flag caused the simulation to disregard the radio altitude data for 3 seconds. The simulation found that, due to this logic flag and another associated with the rapidity of the accident flight's descent, the FDR recording ended before a TAWS alert would have been issued.

Flight Crew Performance

Before the inadvertent activation of the go-around mode, the airplane was descending to a target altitude of 3,000 ft msl, and the flight crew would have been expecting the airplane's automation to increase thrust and increase pitch slightly from about 1° nose-down to level off once the flight reached that altitude. However, once the go-around mode was inadvertently activated about 6,300 ft msl, the airplane's automation advanced the thrust levers and increased the airplane's pitch to about 4° nose up to initiate a climb. In addition, the flight mode annunciator changed to indicate go-around mode activation by illuminating "GA/GA/GA/CMD."

The unexpected mode change associated with the inadvertent go-around mode activation (and the higher altitude at which it occurred) would have been recognizable to the FO and the captain through an effective instrument scan. Both the flight mode annunciator and the engine indicating and crew-alerting system (EICAS) would have displayed "GA" indications, and the altimeter would have indicated about 6,300 ft msl. According to Atlas' procedures, the expected crew response to unwanted operation of automated flight systems was to disconnect the automation. However, neither the FO nor the captain ever acknowledged that the airplane had transitioned to go-around mode or disengaged the autopilot or autothrottle. Thus, the NTSB concludes that, despite the presence of the go-around mode indications on the flight mode annunciator and other cues that indicated that the airplane had transitioned to an automated flight path that differed from what the crew had been expecting, neither the FO nor the captain were aware that the airplane's automated flight mode had changed. Research has shown that pilots can miss changes in displayed modes, particularly those that are unexpected (Mumaw et al 2000), and other factors (discussed in the next sections) may have reduced the effectiveness of each crewmember's scan

First Officer's Incorrect Response Following Unexpected Mode Change Although the FO did not verbalize awareness that something unexpected had happened until about 13 seconds after go-around mode activation (when he said "oh" and then "whoa" in an elevated voice), manual control inputs that began sooner suggest that the FO (as PF) had sensed changes in the airplane's state and had begun to react without fully assessing the situation. The manual retraction of the speedbrakes 5 seconds after go-around mode activation was likely performed by the FO (as PF) instinctively once he felt the increased load factor from the airplane leveling off and heard and felt the engine thrust increasing. He had likely been anticipating the need to perform this task when the airplane leveled off. However, beginning about 1 second later, as the airplane's acceleration and upward pitch began to increase (which would have resulted in the aft movement of the GIF vector sensed by the pilots), manual forward control column inputs were applied, overriding the small, autopilot-driven pitch-up command and resulting in decreasing pitch. Thus, the NTSB concludes that, given that the FO was the PF and had not verbalized any problem to the captain or initiated a positive transfer of airplane control, the manual forward elevator control column inputs that were applied seconds after the inadvertent activation of the go-around mode were likely made by the FO. Further, the captain was communicating with an air traffic controller at the time, consistent with his PM duties

Somatogravic Illusion

The human body uses three integrated systems to determine orientation and movement in space: vestibular (otolith organs in the inner ear that sense position), somatosensory (nerves in the skin, muscles, and joints that sense position based on gravity, feeling, and sound), and visual (eyes, which sense position based on sight) (FAA 2016, 17-6). The vestibular and somatosensory systems alone cannot distinguish between acceleration forces due to gravity and those resulting from maneuvering the airplane.

Thus, when visual cues are limited and an airplane rapidly accelerates or decelerates, a pilot may be susceptible to a somatogravic illusion (FAA 2016, 17-6). Somatogravic illusion is a form of spatial disorientation that results from a false sensation of pitch due to the inability of the otolith organs of the human inner ear to separate the gravitational and sustained linear acceleration components of the GIF vector (Young 2003 and Cheung 2004). Rapid acceleration in an airplane stimulates the otolith organs in the same way as tilting the head backward and may lead a pilot to mistakenly believe that the airplane has transitioned to a nose-up attitude (FAA 2016, 17-7).49 The accident airplane was likely flying in IMC when the go-around mode was activated. The timing of the FO's subsequent nose-down control inputs correlated with increases in the airplane's longitudinal acceleration associated with the go-around mode-commanded an increase in engine thrust and retraction of the speedbrakes. This relationship suggests that the FO experienced a pitch-up somatogravic illusion at that time. Somatogravic illusion has long been recognized as a significant hazard that is likely to occur under conditions of sustained linear acceleration when outside visual references are obscured (Buley and Spelina 1970, 553-6). Further, such conditions can degrade a pilot's ability to effectively scan and interpret the information presented on primary flight displays. For a pilot flying in IMC with no external visual horizon, maintaining spatial orientation when presented with conflicting vestibular cues depends upon trusting the airplane's instruments and disregarding the sensory perceptions (FAA 2003, 8). However, for some pilots (particularly those who are not proficient with maintaining airplane control while referencing only instruments), the introduction of misleading vestibular cues can be compelling enough that the pilot may find it difficult to accurately assess or believe reliable sources of information about airplane attitude, such as the airplane's instruments. Thus, the NTSB concludes that the FO likely experienced a pitch-up somatogravic illusion as the airplane accelerated due to the inadvertent activation of the go-around mode, which prompted him to push forward on the elevator control column. After the FO began pushing forward on the control column and the airplane's pitch dropped below the horizon, its vertical acceleration rapidly decreased. Due to this change and the airplane's continued longitudinal acceleration, the resultant GIF vector sensed by the pilots swung dramatically aft. This likely exacerbated the FO's pitch-up sensation and possibly produced a sensation of tumbling backward, known as the inversion illusion (Cheung 2004). The FO's comments "oh" and "whoa," which expressed surprise, likely reflected his experience of one or both phenomena. 2.3.1.2 Other Factors Adversely Affecting Performance Surprising events in the cockpit increase task demands on a pilot to resolve them (Lazarus and Folkman 1984). These types of events can also cause acute stress, which involves perceiving an immediate danger, and can trigger a "fight or flight" response (FAA 2016, 17-12). The effectsof both surprise and stress can increase a pilot's perceived need to act while degrading the pilot's ability to accurately assess what needs to be done; this can result in impulsive and incorrect actions due to a physiological reaction known as a "startle response" (Landman et al 2017, 1161-72). About the time the FO expressed surprise, he rapidly brought the control column to an almost neutral position, then pushed it forward again. This action could have constituted intentional testing behavior to see how relaxing forward pressure on the column affected sensations of motion, or it could have occurred reflexively as a result of a startle response. About this time, the combined effects of the changes in the airplane's motion resulted in changes to the GIF vector similar to what would occur if the airplane were descending vertically in a near-level pitch attitude, which likely produced a sensation of falling. About this time, the FO exclaimed, "where's my speed" and "we're stalling," and continued to push the control column forward, exacerbating the airplane's dive. Although the FO declared that the airplane was stalling, the NTSB's airplane performance study found that the airplane's airspeed and wing AOA were not consistent with the airplane having been at or near a nose-high stalled condition. Further, the FO's response to excessively lower the nose of the airplane was contrary to standard procedures and training for responding to a stall, which prescribed first assessing the readily identifiable cues indicative of the airplane approaching an impending stall and disconnecting the automation. No such cues—such as stick shaker activation, stall warning annunciations, nose-high pitch indications (including those provided by the ADI's airplane attitude presentation and pitch limit indicator), and low airspeed indications-were present. The NTSB's investigation found no evidence that any of the sources of airspeed and airplane pitch information available to the FO were malfunctioning; thus, the FO's comments about airspeed and stall indicate that he was not effectively scanning his instruments and interpreting the information they provided. The FO's attention appears to have been fully absorbed by the incorrect sensations of pitching up and falling, which, for him, were the most compelling cues in his environment, leading him to incorrectly conclude that the airplane was stalling. This would have reinforced his perceived need to continue nose-down control inputs. The effects of sensory illusions, stress, and the startle response can adversely affect the performance of any pilot, and pilot training program and proficiency check requirements for Part 121 air carriers include emergency procedures scenarios intended to help a pilot develop and maintain the skills to appropriately assess and respond to a variety of stressful, startling scenarios. However, the accident FO had a history of training performance deficiencies in which he performed poorly in response to unexpected stressful events. Various instructors and check airmen from throughout the FO's career described training scenarios in which the FO demonstrated low situational awareness, became overwhelmed, overcontrolled the airplane, made numerous mistakes, and responded impulsively with inappropriate actions.

Based on the FO's history of training performance deficiencies, the FO was susceptible to responding impulsively and inappropriately when faced with a stressful, unexpected event. Therefore, the NTSB concludes that, although compelling sensory illusions, stress, and startle response can adversely affect the performance of any pilot, the FO had fundamental weaknesses in his flying aptitude and stress response that further degraded his ability to accurately assess the airplane's state and respond with appropriate procedures after the inadvertent activation of the goaround mode.

Captain's Delayed Awareness and Ineffective Response

Like the FO, the captain had been expecting the airplane to automatically increase thrust and slightly increase pitch to level off at the MCP-selected altitude of 3,000 ft msl. The captain, as PM, was required to actively monitor the flight, including the airplane flightpath, automation status, and the FO's actions as PF. Effective monitoring and crosschecking are essential because detecting an error or unsafe situation can be the last line of defense to prevent an accident (FAA

2004, 14). Based on the available CVR information, from before activation of the go-around mode until about 10 seconds after, the captain was setting up the approach to IAH on the FMC and communicating with ATC. While setting up the approach, the captain was likely head-down and concentrating on the FMC rather than monitoring the flight instruments or the FO's actions. This would reduce the captain's awareness of the airplane's automation status and energy state and could explain why the captain did not notice the "GA" indications on the flight mode annunciator or the EICAS or that the anticipated increase in airplane thrust began when the airplane was at a much higher-than-expected altitude. However, the captain's response to less subtle aspects of the developing situation, such as the FO's nose-down control column inputs associated with his spatial disorientation, were also delayed. Research has shown that a PM may be slow to take control when the PF is subtly incapacitated (for example, due to spatial disorientation) because the PM's recognition of something being wrong can be delayed if his or her attention is focused on normal operational tasks or if the deviation in performance is a surprise (Harper, Kidera, and Cullen 1971). As previously mentioned, at 1238:44, the FO said, "oh," indicating surprise, which was about 2 seconds after the captain's last routine radio communication to the controller and concurrent with the controller's response. It also occurred about 4 seconds after the cockpit's owl beeper sounded, which, based on the FDR data, likely indicated an autopilot caution alert (due to the opposing manual inputs on the control columns). At 1238:46 (about 15 seconds after the inadvertent activation of the go-around mode), the captain took hold of the left control column and started pulling back, countering the FO's continued nose-down control inputs. The NTSB concludes that, while the captain was setting up the approach and communicating with ATC, his attention was diverted from monitoring the airplane's state and verifying that the flight was proceeding as planned, which delayed his recognition of and response to the FO's unexpected actions that placed the airplane in a dive. About the time that the captain took hold of the left control column and started pulling back, the thrust levers were abruptly reduced then advanced; however, it is unknown which crewmember took this action. The captain's action on the control column was not followed by the command "I have control" to indicate a positive transfer of control of the airplane, as required by Atlas procedures. As a result, the captain and the FO each continued to apply opposing forces on the elevator control columns, with the captain adding enough force to overcome the elevator system's control column override mechanism and split the positions of the elevators on each side. The captain's and the FO's opposing elevator control forces continued for about 10 seconds, during which the airplane's dive continued to steepen. Thus, the NTSB concludes that the captain's failure to command a positive transfer of control of the airplane as soon as he attempted to intervene on the controls enabled the FO to continue to force the airplane into a steepening dive. Although the captain may have been trying to diagnose the situation and determine what corrective actions were needed, he likely experienced startle and surprise once he recognized that the airplane was in a dive, resulting in increased stress and reduced performance. Also, the situation was likely difficult for the captain to evaluate, considering that the FO's control inputs, the automated inputs, and external forces were each affecting control feel and airplane behavior. Although the captain asked the FO what was happening, the FO made only panicked statements and was unable to provide the captain with any useful information. The captain was being subjected to the same stressful and disorienting accelerations as the FO, which could have degraded his ability to correctly interpret the instruments and identify the most appropriate course of action. When such situations occur unexpectedly, they can be ambiguous and confusing. The captain's failure to disconnect the autopilot or autothrottle, in keeping with Atlas' procedures, during any point in the accident sequence suggests that he had not fully processed the airplane's energy state, automation status, or the reason for the FO's actions. Analysis of the available weather information determined that, once the airplane had descended through an altitude of about 3,000 ft msl (which corresponded with the expected cloud base heights for the area), it would have been exiting IMC; thus, the crew would have been able to clearly see the airplane's attitude and descending trajectory. About this time, both elevators began to move concurrently to an airplane nose-up position, attaining the full airplane nose-up position and remaining there until the end of the FDR recording. Thus, it likely that both the FO and the captain were pulling back on the control columns to arrest the airplane's descent, but, by this time, the situation was unrecoverable. Therefore, the NTSB concludes that the captain's degraded performance, which included his failure to assume positive control of the airplane and effectively arrest the airplane's descent, resulted from the ambiguity, high stress, and short time frame of the situation. FIP