National Aeronautics and Space Administration

The Poldercrash:

Turkish Airlines Flight 1951

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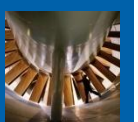

BACKGROUND

February 25, 2009; a Boeing 737-800 lay in pieces on a farm field approx. 1.5 kilometers short of runway 18R at Amsterdam-Schiphol International Airport (AMS). The flight, Turkish Airlines 1951 (TK1951), was en route from Istanbul- Atatürk International Airport (IST), with128 passengers and 7 crewmembers. Although 5 passengers and 4 crewmembers died (including all 3 pilots), 126 survived the crash. Six weathered the crash unscathed, while the remaining 120 sustained minor to severe injuries. Analysis of flight data would discover a critical flight instrument malfunction—discoverable by the pilots, but subtle in its impact on the automated flight controls in use. As Flight TK1951 approached runway 18R (locally known as the Polderbaan), these effects would have disastrous consequences.

The Boeing 737-Series

- Boeing's 737-series aircraft, first manufactured in 1967, serves worldwide in unmatched numbers. By 2012, over 7,000 of the short- to medium-range aircraft have been delivered to various operators.
- On average, 1,250 Boeing 737s fill the skies at a given moment. Produced in many variants for differing commercial demands, the aircraft has been met with great popularity and success.

Boeing 737-800 Automated Flight

- The 737-800 may be flown and landed "hands-off" using the autopilot for the flight controls and an autothrottle system for engine thrust.
- The autothrottle, which receives radio altitude data, automatically controls the airspeed of the aircraft by regulating the thrust on both engines during an automated approach.
- A low range radio altimeter (LRRA) system of two independent radio altimeters provides redundancy in the event that one radio altimeter fails, or the inputs from one are recognized as erroneous by the autothrottle. The left radio altimeter was the primary in the mishap aircraft, additionally transmitting altitude data to the cockpit left side (pilot's) instrument display. The right radio altimeter transmitted altitude data to the cockpit right side (copilot's) instruments. In the event the left radio altimeter signal becomes erroneous, the autothrottle will use data from the right radio altimeter system.

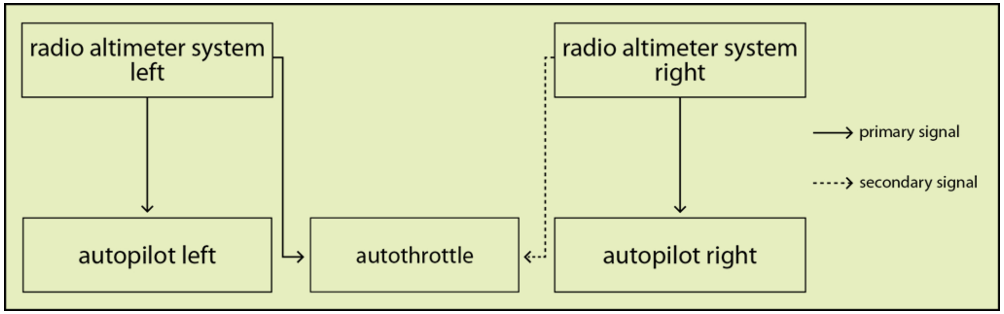

Figure 1: ***Overview of the 737-800 radio altimeters connected to autopilot controls and autothrottle***

The Flight

- Flight TK1951 was a "Line Flight Under Supervision" exercise.
- First officer flew the final approach to AMS from the right seat under supervision of instructor captain (one of Turkish Airlines' most seasoned pilots). Safety Pilot acted as observer during the flight.
- Flight proceeded without incident.

WHAT HAPPENED

Convergence of Conditions

- TK1951 was directed to descend to 2,000 feet and turn toward the final approach course for the Polderbaan.
- The descending turn placed aircraft above the normal approach path and almost one mile closer to the runway than procedurally established by local Air Traffic Control (ATC) and needed to intercept from above. Although not unsafe, this placed pressure on the cockpit crew to complete pre-landing tasks and required rapid descent with a very low thrust setting.
- Cloud cover obscured outside visual cues of descent rate and altitude.
- Crew configured for an ILS approach with autopilot and autothrottle engaged, flaps at 15 degrees, and landing gear down.
- At 2,000 feet the landing gear warning sounded.
- The left hand radio altimeter displayed an input of -8 feet. This data—not identified as erroneous by the LRRA—was routed to the autothrottle.
- The acting pilot, First Officer, flying from his right seat, observed correct altitude input from his fully accurate right side radio altimeter. Neither the Boeing nor Turkish Airline manuals contained off-nominal procedures for a radio altimeter mismatch encountered inflight.
- Faulty left-side radio altimeter input commanded the autothrottle into "retard flare" mode, selection normally applied during final landing phase below 27 feet.
- This reduced thrust to an idle at an altitude and airspeed insufficient to reach the runway.
- The only indication of this mode is a small green "RETARD" annunciator on the instrument display. Neither cockpit voice recorder nor flight data recorder data show that the pilots were aware of the appearance of the "RETARD" flight mode annunciation and the speed reduction.
- The crew was intent on completing the landing checklist—postponed by late glide path entry.
- The right hand auto pilot, using correct altitude input from the right LRRA, struggled to keep TK1951 on the correct glide path as long as it could by raising the aircraft's nose. The aircraft lost airspeed and approached a stall condition.

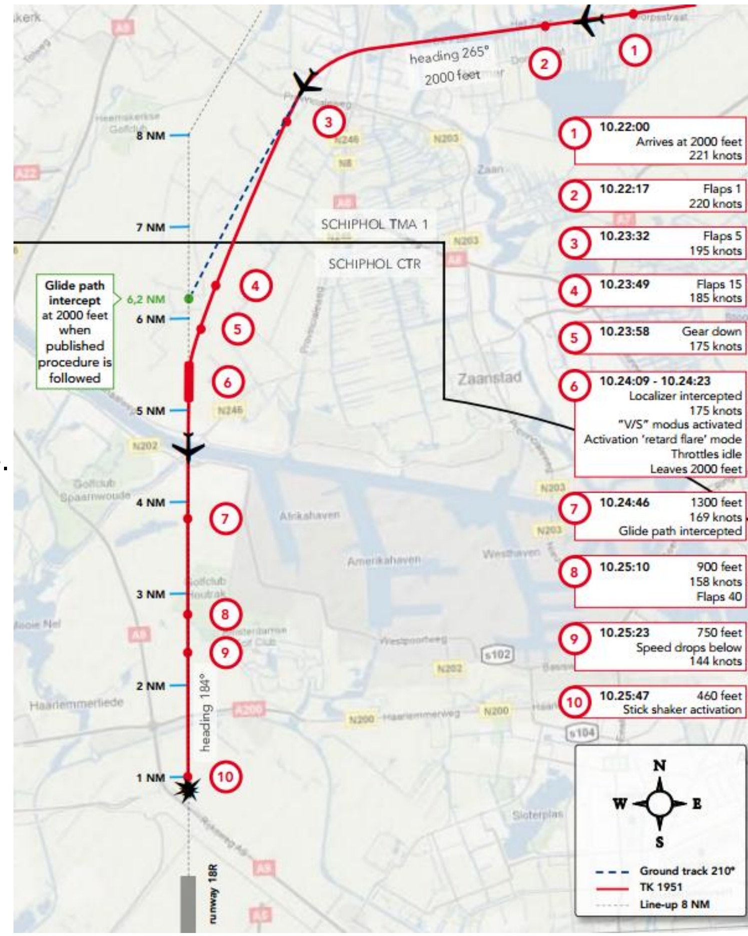

Figure 2: Glide path of TK1951 compared to normal glide path

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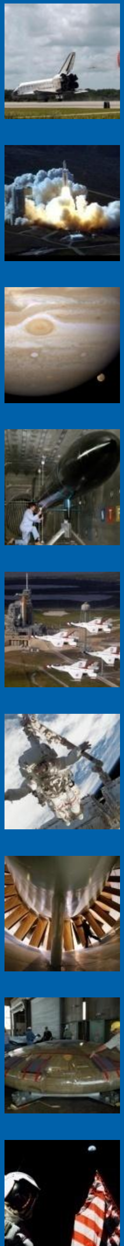
WHAT HAPPENED (cont.)

Stall Event

- First officer's stick-shaker device warned of stall at 460 feet. Reacted by pushing the nose of the aircraft down and thrust levers forward—overpowering the autothrottle to regain airspeed and control.
- Then, captain called for and took control of the aircraft. In response, first officer relaxed his push on the thrust levers.
- The autothrottle immediately pulled thrust back to idle in its RETARD mode.
- The captain disconnected the autothrottle and moved the thrust levers forward, but it was too late; the aircraft stalled at 350 feet at a speed of 105 knots.

Figure 3: The crash site and wreckage of TK1951.

- Flight TK1951 impacted farmland and was destroyed; breaking into three main sections.
- Survivors escaped through emergency exits, a tear in the aircraft's fuselage, and an opening at the rear of the main section of the fuselage.
- Flight recorder data revealed that no other systems failed during flight.



PROXIMATE CAUSE

The Dutch Safety Board (DSB) issued a report attributing the cause of the crash to a convergence of circumstances. The faulty radio altimeter had a serious impact on automated flight systems. Cockpit warnings and indicators were not effective in alerting the preoccupied crew of the decreased thrust condition. It is unknown if the crew connected the landing gear warning to a faulty altimeter signal, but even if they had, it is possible that they lacked systems knowledge of the LRRA design and its primary autothrottle altitude input from the left radio altimeter. Furthermore, the DSB found Boeing 737 radio altimeter anomalies had occurred more often than formally reported post-flight to maintenance personnel at Turkish Airlines and other operators. Low perceived prevalence and consequence of this issue limited the crew's risk acuity.

UNDERLYING ISSUES

Under Reporting, Inability to Diagnose

- TK1951's flight recorder revealed similar radio altimeter incidents on the two days before the crash, February 23 and 24, 2009. Both occurred during the landing phase. Each crew landed safely after taking manual control of the aircraft.
- Further examination of the flight recorder showed that erroneous radio altimeter signals occurred 148 times over a 10 month period with only a few reported by pilots as minor technical issues. Some radio altimeter errors occurred while the aircraft flew above 2,500 feet, undetectable on cockpit displays but visible by recorder data search.
- The DSB determined that there was a possibility that Turkish Airline pilots had not been reporting radio altimeter errors if they perceived low safety impact on aircraft operations.
- Communications to resolve the altimeter issue occurred between Boeing and Turkish Airlines. From 2001 to 2003 regular complaints from Turkish Airlines were made to Boeing concerning fluctuating and negative radio altimeter heights. The cause of the problems, however, could not be discovered.
- Turkish Airlines and Boeing shifted to a focus on the antenna supplier and manufacturer where a possible unintentional 'direct coupling' of radio altimeter transmitter to receiver was identified but evidence was lacking.
- Turkish Airlines sought Boeing's permission to protect the antennas from moisture via gaskets. Boeing wrote the there was 'no objection' to this practice. Between April 2004, and December 2008, all Turkish Airlines 737- 800 aircraft were fitted with gaskets.

Redundancy Compromised

- The mishap aircraft was equipped with a Smiths autothrottle linked to two flight control computers. Optional software updates for the Smiths autothrottle were periodically developed and available up to 2003: no requirement existed from the Federal Aviation Administration (FAA), other aviation authorities, or Turkish Airlines to update autothrottle software.
- From 2003 forward, Boeing incorporated Rockwell Collins Enhanced Digital Flight Control System (EDFCS) with integrated autothrottle in new 737s. Software updates occurred four times up until 2009, with one being mandated by the FAA. The mandatory update included a comparator function which prevented unwanted retard flare mode unless the difference between the 2 radio altimeters was no more than 20 feet.
- The older fleet aircraft employing the Smiths autothrottle—one of which was the involved aircraft— could not use this comparator update.
- Boeing distributed a service letter advising operators, including Turkish Airlines, on how to acquire the EDFCS with integrated autothrottle and comparator, however no requirement from the Federal Aviation Administration (FAA) or other aviation authorities for this action existed.
- In addition to failure in hardware redundancy, it is important to note that the system of using a safety pilot to assist in monitoring the aircraft during training scenarios did not alleviate pressures or workloads of the pilot and copilot of TK1951.

AFTERMATH

- DSB report warned in 2010 of the undesirable situation that older certified Boeing 737 models responded to erroneous radio altimeter signals in the same fashion.
- As a result of the February 2009 incident, Boeing announced it would look into including a comparator for the older autothrottle system still used by pre-2003 737s. Information on the status of this action was unavailable to the public at time of publishing this document.
- Boeing released a Multi-Operator Message (MOM) on March 4, 2009, in response, recommending operators to inform flight crews of the investigation details and the DSB interim report and to remind crews to carefully monitor primary flight instruments.
- Furthermore, the warning advised against engaging autopilot or autothrottle systems during approach and landing in the event of a radio altimeter malfunction.

Figure 4: Remains of Turkish Airlines Flight TK1951; the runway lights of the Polderbaan can be seen in the distance.

- The DSB also warns that information featured in the Turkish Airlines Quick Reference Handbook regarding the use of the autopilot, the autothrottle, and the need for trimming in the approach to stall recovery procedure is unclear and insufficient.

FOR FUTURE NASA MISSIONS

- Despite careful design and exhaustive testing that was required to qualify and certify a complex autothrottle system for passenger-carrying flight operations, a scenario filled with rapidly changing conditions allowed a single erroneous data feed to rapidly place an aircraft in a low-speed, low-altitude state from which a distracted crew could not recover in time.

- Charles Perrow, in his book ***Normal Accidents***, describes complex interactions (many hardware/ software/ human interfaces enable unintended sequences not visible or immediately comprehensible), and tight coupling (no slack or buffer to prevent one item from immediately affecting another in a system).

- Either condition by itself can create hazardous situations; combine both conditions in a single system, and Perrow describes a catastrophic outcome as inevitable, or 'normal.' Beyond narrowly defining technical issues (and missing larger safety impacts) we must deal with social complexity, where the time needed to elevate technical concerns to safety concerns to regulatory requirements can lag behind technical progress.

- This can occur for an entire system, but can be harder to identify when just part of a system evolves at a different rate than other interfaced parts. A careful systems approach that integrates technical, social, and organizational risks was recently explored by the Constellation Program.

- Heeding recent lessons captured by both Constellation and Shuttle program efforts will benefit NASA and future commercial efforts to avoid the potential deadly combination of complex interactions and tight coupling.

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