



SYSTEM FAILURE CASE STUDIES

APRIL 2012 VOLUME 6 ISSUE 4

The Poldercrash

February 25, 2009: A Boeing 737-800 lay in pieces on a freshly tilled farm field approximately 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) carrying 128 passengers and 7 crewmembers. Although 5 passengers and 4 crewmembers perished (including all 3 pilots), 126 occupants survived the crash. Six weathered the crash unscathed, while the remaining 120 sustained minor to severe injuries. Analysis of flight data would confirm a critical flight instrument malfunction—subtle in its impact on the automated flight controls in use and possibly overlooked by the flight crew. As Flight TK1951 approached runway 18R (locally known as the Polderbaan), this malfunction would prove to be disastrous.



Figure 2: Tail section, broken off of flight TK1951; crashsite located approx. 1.5 kilometers outside of Schiphol Airport.

BACKGROUND

The Boeing 737-Series Aircraft

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 airlines. On average, 1,250 Boeing 737s fill the skies at any 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

To alleviate pilot workload and allow precision landings in low visibility, the 737-800 may be flown and landed “hands-off” using the autopilot for the flight controls and an autothrottle system for engine thrust. Of particular interest to this mishap, the autothrottle, which receives radio altitude data (Figure 1), automatically controls the

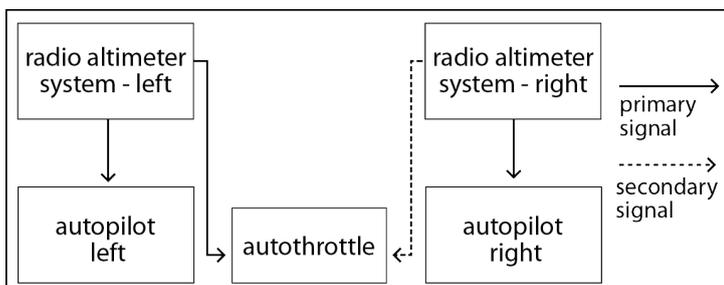


Figure 1: Overview of the 737-800 radio altimeters in relation to autopilot controls and autothrottle.

speed of the aircraft by regulating the thrust on both engines during an automated approach. A low range radio altimeter (LRRRA) 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 provides the primary signal to the autothrottle, additionally transmitting altitude data to the cockpit left side (pilot's) instrument display. The right radio altimeter transmits altitude data to the cockpit right side (copilot's) instruments. If the left radio altimeter signal becomes erroneous, the autothrottle will use right radio altimeter data.

Boeing 737-800 crash lands short of Polderbaan runways; 9 people dead

Proximate Causes

- Faulty radar altimeter provided aircraft systems with erroneous altitude data
- No knowledge of system impact
- Cockpit crew did not notice decrease in airspeed until the approach to stall warning

Underlying Issues

- Poor reporting of altimeter issues affected diagnosis of issue
- Various hardware and software versions led to poor system knowledge
- Crew members not sufficiently trained for approach to stall-recovery situation

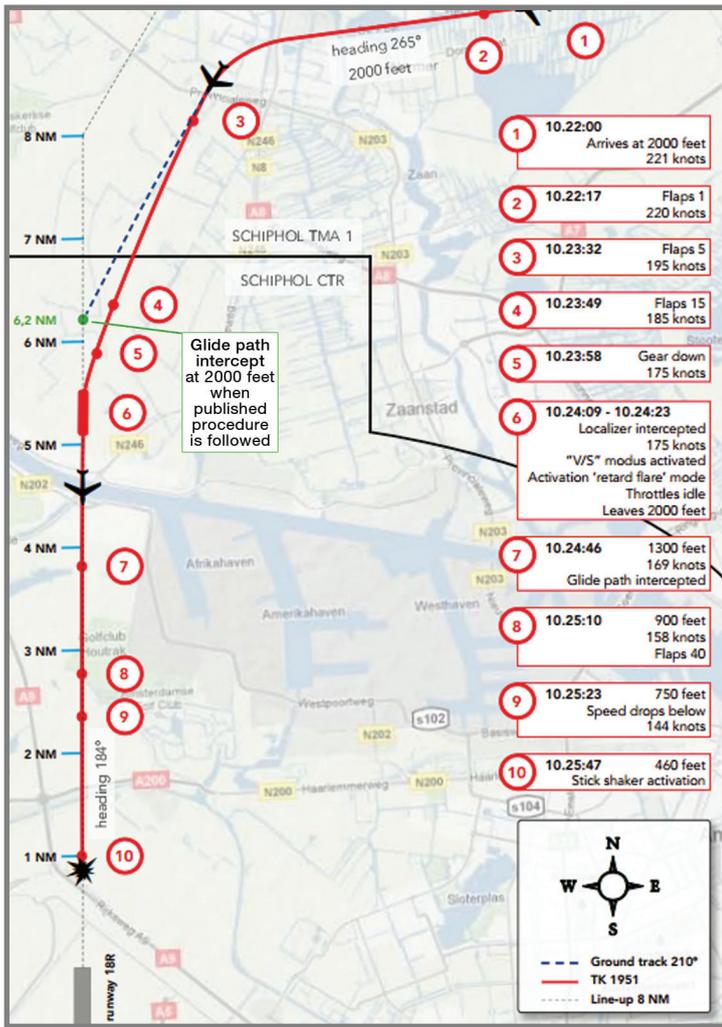


Figure 3: Flight TK1951's approach and timeline of events compared with the typical approach for runway 18R.

WHAT HAPPENED

Convergence of Conditions

Flight TK1951, tail number TC-JGE, was a "Line Flight Under Supervision" exercise. The first officer flew the final approach to AMS from the right seat under supervision of the instructor captain, one of Turkish Airlines' most seasoned pilots. A third pilot acted as a safety pilot and observer during the flight, which had proceeded without incident.

The crew of TK1951 was directed to descend to 2,000 feet and turn toward the final approach course for runway 18R, the Polderbaan (Figure 3). The descending turn placed the aircraft above the normal approach path and almost one mile closer to the runway than procedurally established by local Air Traffic Control (ATC). Whether flown manually or automatically (as in this case), Instrument Landing System (ILS) procedures and equipment are optimized to allow the aircraft to fly to and intercept its final glide path from below. However, TK1951 had to intercept from above. Although not inherently unsafe, this condition placed pressure on the cockpit crew to complete pre-landing tasks in a short time and required rapid dissipation of altitude and airspeed energy with a very low thrust setting. Weather conditions added to approach difficulty; cloud cover obscured outside visual cues of descent rate and altitude.

The crew configured the Boeing 737 for an ILS approach with autopilot and autothrottle engaged, flaps at 15 degrees, and landing gear down. Despite lowering and locking the landing gear, at 2,000 feet the landing gear warning sounded. According to the flight log, the left hand radio altimeter displayed an input of -8 feet. This input—not identified as erroneous by the LRRA—was routed to the autothrottle. Thrust was already near idle because of the higher/closer than normal approach path. The first officer (flying pilot), in his right side seat, observed correct altitude input from his fully accurate right side radio altimeter. Even if the pilots noticed this discrepancy, neither Boeing nor Turkish Airline manuals contained off-nominal procedures for a radio altimeter mismatch encountered in-flight.

The crew continued the approach and, as the aircraft descended, the faulty left side radio altimeter input commanded the autothrottle into "retard flare" mode, a selection normally applied during the final landing phase below altitude of 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. Normal approach flap configuration of 15 degrees allowed this automatic switch to retard flare mode.

Neither cockpit voice recorder nor flight recorder data indicate the pilots were aware of the appearance of the RETARD flight mode annunciation and the speed reduction below the value selected on the mode control panel or below the reference landing speed. According to the flight recorder, the crew was intent on completing the landing checklist—postponed by late glidepath entry.

The right hand auto pilot, using correct altitude input from the right radio altimeter, 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.

Stall Event

The first officer's stick-shaker device warned of imminent stall at 460 feet. As trained, the first officer reacted by pushing the nose of the aircraft down and thrust levers forward—overpowering the autothrottle to regain airspeed and control. Then, the captain called for and took control of the aircraft. In response, the 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.

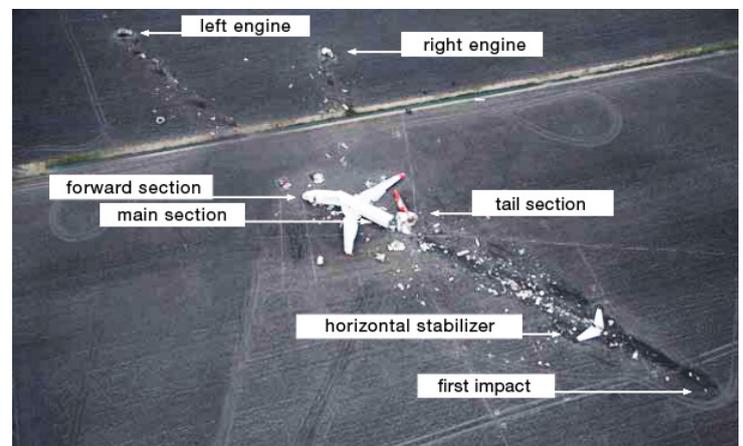


Figure 4: The crash site and wreckage of TK1951.



Figure 5: Remains of Turkish Airlines Flight TK1951. Runway lights of the Polderbaan can be seen in the distance.

Flight TK1951 struck farmland and was destroyed, breaking into three main sections. Survivors escaped through emergency exits and through openings in the fuselage where the aircraft was torn or broken (Figure 6). 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 LRRR 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 pilots reporting only a few as minor technical incidents. 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 there was a possibility that Turkish Airline pilots had not been reporting radio altimeter errors if they perceived low safety impact on aircraft operations.

After the accident, four similar incidents from multiple airlines were brought to the attention of the DSB. Each took place after February 25, 2009 and crews landed the aircraft safely. In all cases the aircraft was already on the glide path on a stabilized approach when the retard flare mode moved the thrust levers to idle. This was easily recognized and autopilots and autothrottles were disengaged.

Communications to resolve the altimeter issue occurred between Boeing and Turkish Airlines. From 2001 to 2003, Turkish Airlines made regular complaints to Boeing concerning fluctuating and negative radio altimeter heights. Multiple measures to mitigate this issue occurred over the years. In one instance, Boeing initiated a "fleet team resolution process" in 2002, and the Boeing Fault Isolation Manual was changed concerning the flight altimeter system in response. Between 2002 and 2006, Boeing asked Turkish Airlines to provide data from the fleet flight recorders for analysis. The cause of the problems, however, could not be discovered. Later, the communications between Turkish Airlines and Boeing shifted to a focus on the antenna supplier and manufacturer. A possible unintentional "direct coupling" of radio altimeter transmitter to receiver (bypassing reflection from the ground below) was presented as a possible issue, given the presence of water and corrosion in the aircraft's belly (where the receiver and transmitter reside). Although evidence was lacking, Turkish Airlines sought Boeing's permission to protect the antennas from moisture by using gaskets. Boeing wrote that there was "no objection" to this practice.

Between April 2004 and December 2008, all Turkish Airlines 737-800 aircraft were fitted with gaskets, with the mishap aircraft fitted in October 2008.

Redundancy Compromised

The mishap aircraft was equipped with a Smiths (now GE Aviation) autothrottle linked to two Honeywell flight control computers. While software updates for the Smiths autothrottle were periodically developed and available, the mishap aircraft's original autothrottle software was not subject to further update after 2003. From a

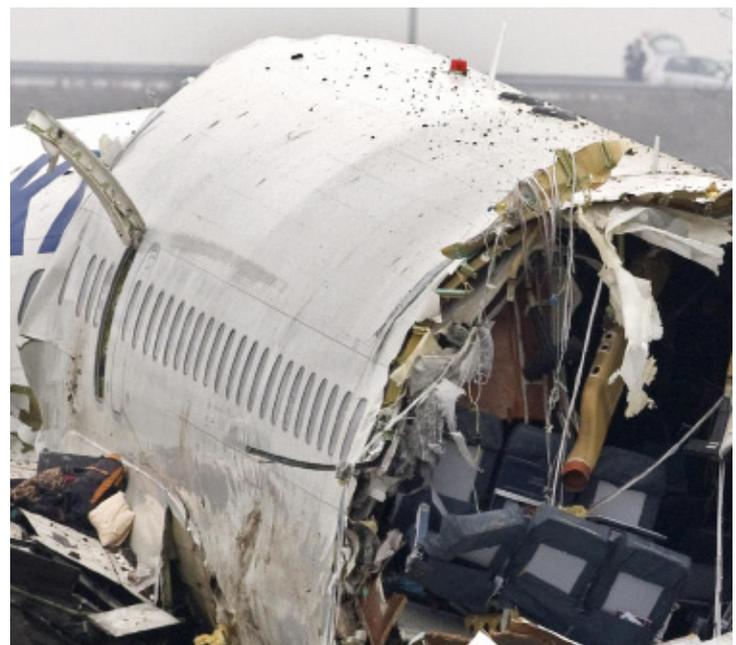


Figure 6: Section of fuselage from the Flight TK 1951 crash site.

regulatory standpoint, such updates were optional: no requirement existed from Turkish Airlines, the Federal Aviation Administration (FAA), other aviation authorities to update autothrottle software.

From 2003 forward, Boeing incorporated the Rockwell Collins Enhanced Digital Flight Control System (EDFCS) with integrated autothrottle in new 737s. Software updates occurred four times until 2009, one being FAA mandated. 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, although radio altimeter hardware direct coupling remained unresolved. 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 the means to acquire the EDFCS with integrated autothrottle and comparator. However, no requirement existed for this action from the FAA or other aviation authorities.

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

In 2010, the DSB warned that older certified Boeing 737 models may respond similarly to erroneous radio altimeter signals. 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 to preliminary findings of Dutch investigators. The message recommended that airlines inform flight crews of the investigation details and the DSB interim report and 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. The DSB also cautioned 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 was unclear and insufficient.

FOR FUTURE NASA MISSIONS

Despite careful design and exhaustive testing 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 alone 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), NASA must

Questions for Discussion

- How can tightly coupled systems be buffered to avoid creating hazardous situations?
- What can be done to ensure vigilance and anticipate unintended consequences when triggers are not immediately visible?
- How does social complexity alter technical progression on NASA programs?
- Are the man-machine aspects involved in automation dependency given enough attention during the initial and recurrent training of pilots?

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. The Constellation Program included recent exploration of a careful systems approach, that integrated technical, social, and organizational risks. Heeding recent lessons captured by both the Constellation Program and the Shuttle Program will benefit future NASA and commercial space exploration efforts by cautioning against deadly combination of complex interactions and tight coupling.

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Special thanks to John P. Lapointe and Munro G. Dearing for an insightful peer review.
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