National Aeronautics and Space Administration

“What’s happening?”

The Loss of Air France Flight 447

Senior Management ViTS Meeting

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Source: BEA

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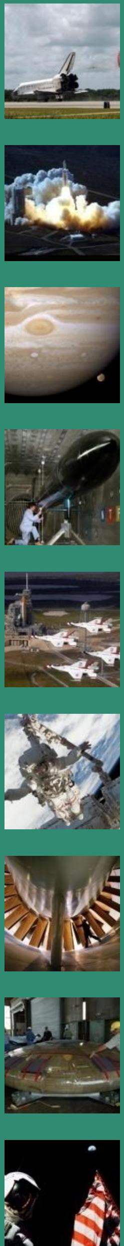


BACKGROUND

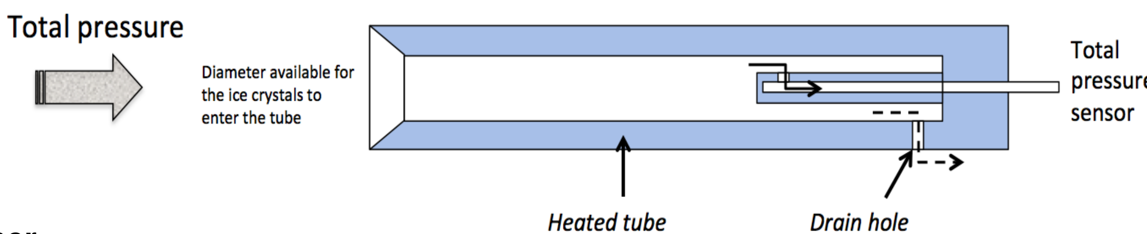
May 31, 2009: Air France Flight 447 (AF447) departed from Rio de Janeiro for Paris with 216 passengers and 12 crew members. The crew maintained contact with Brazilian flight controllers until one hour 36 minutes after takeoff, when the crew transmitted a position message, the last communication from the flight. A day later, Air France officially informed the Bureau d'Enquêtes et d'Analyses (BEA), the French aviation safety agency, that AF447 had been lost over the Atlantic Ocean. French and Brazilian search efforts began discovering bodies and floating aircraft wreckage on June 6, 2009. There were no survivors. Inflight maintenance data transmitted real-time from the aircraft indicated airspeed sensor problems but nothing more serious. How such a capable aircraft went down was a mystery until the final BEA report was published on July 5, 2012.

The Aircraft

- The Airbus A330 is a long-range, wide-body passenger jet incorporating fly-by-wire controls and redundant computers through which all human, hardware, and software commands pass. **Programmed "laws" govern how the aircraft actually responds in normal flight and when systems malfunction or fail**.

- The mishap aircraft received all required maintenance for flight by Air France and was certified as airworthy, but awaited installation of a new set of three pitot probes in weeks.

- Pitot probes project into the flight path to detect ram air pressure, used to measure airspeed. Incidents of Airbus pitot probe icing, despite electrical heating, were reported to airline operators, Airbus, and international regulators as a safety issue. **Since the equipment met standards**, the hazard was not rated as critical to safety of flight. The failure mode involved high-altitude ice crystal icing accretion inside the pitot probe.



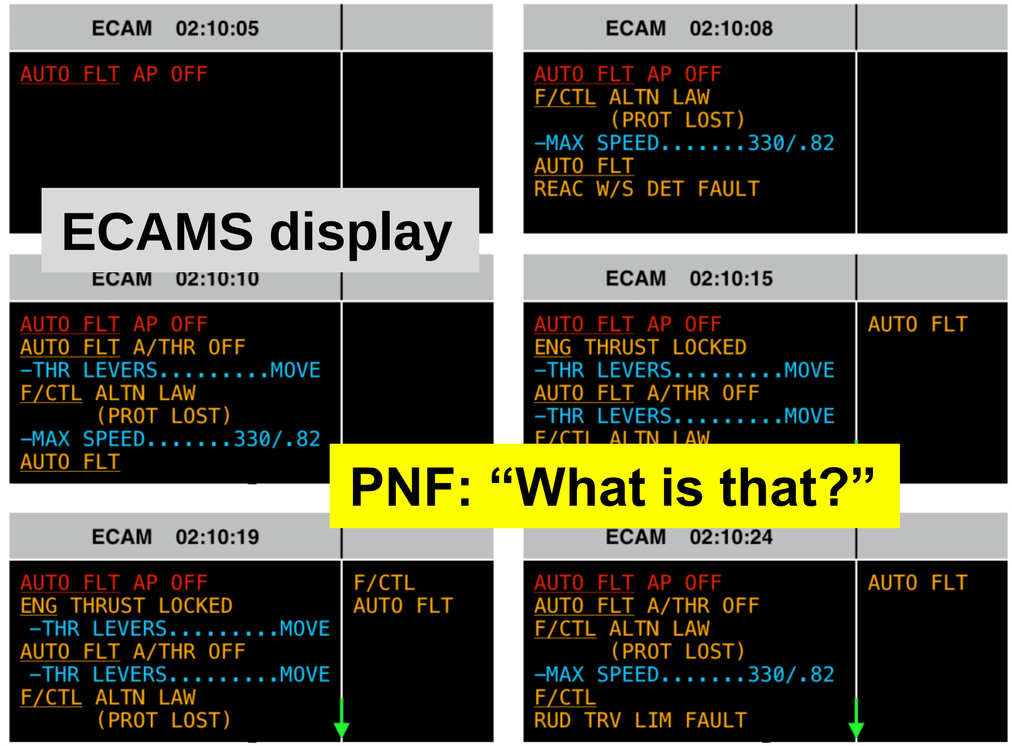
The Weather

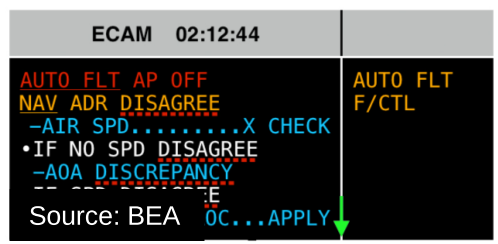
- Forecast weather for the planned route of AF447 included convective storms and high-altitude icing conditions within an Atlantic region called the Inter-Tropic Convergence Zone (ITCZ) typical for the month of June.

MISHAP EVENT SEQUENCE-CLIMB

- The Captain leaves the cockpit to rest. The Pilot Flying (PF) and Pilot Not Flying (PNF) remain to navigate storms at 35,000'. It is night. **Only cockpit instruments and alarms inform the crew on aircraft state.**

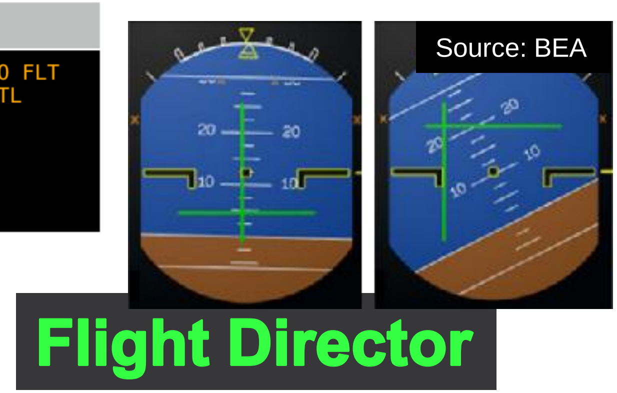
- AF447 enters icing. PF reduces thrust for passenger comfort. Ice crystals block all three pitot probes, sending erratic data to computers, which impose "Alternate Law" to disconnect autopilot, and cancel automatic stall protection. Many warnings appear on Electronic Centralized Aircraft Monitoring (ECAMS) display. Green needles on Flight Director (FD) disappear and then reappear, calling for climb. Airspeed indication climbs also due to erroneous data. Confused by conflicting cues, PF ***raises aircraft pitch to climb***.





Unknown to the crew, the actual speed of the A330 now drops dangerously close to stall, in conditions the crew has never trained for.

Manual controllability is poor in the thin air, and AF447 climbs 2,000 ft. in seconds under still-reduced thrust. The aircraft is about to stall, but the pilots struggle to interpret many cockpit cues and cannot comprehend actual state.



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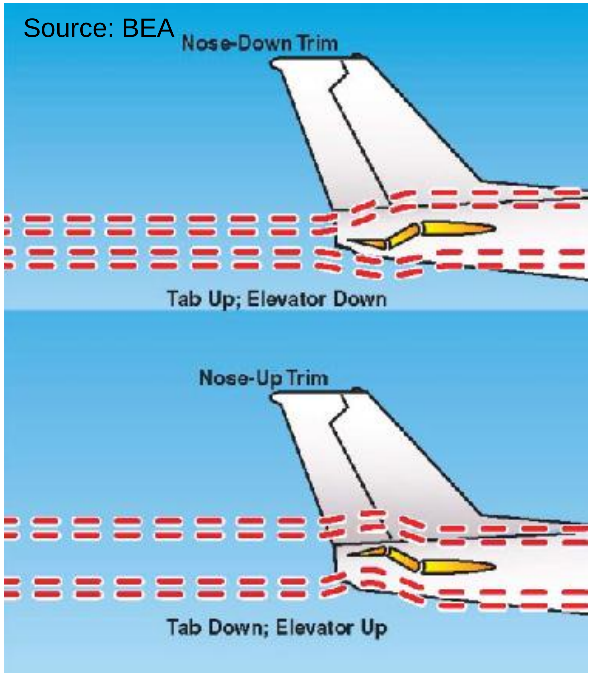
MISHAP EVENT SEQUENCE-STALL

- Onboard Angle-of-Attack (AOA) sensors alert the computer to impending stall AOA (critical angle between the aircraft path and the relative wind). In the mishap aircraft, **AOA was not displayed to the pilots**, only the computers. Impending stall AOA would trigger an aural tone and red MASTER CAUTION light.

- Still confused, the crew tries to control the flight path. Flight Director needles disappear and re-appear, this time in vertical speed mode, not altitude capture mode; pitch down is called for and PNF says, “according to all three you’re climbing.” **PF reduces pitch but does not descend**.

- **ECAMS cues and classroom training would imply the need for the Airbus/Air France emergency procedure “Unreliable Airspeed Indication” but the crew still fights to understand what is wrong and keep the plane from apparently overspeeding**. Actual airspeed decays for 46 seconds from autopilot disconnect until the STALL warning tone sounds for 34 seconds. The cockpit is now saturated with sound and visual alerts, but only the tone warns of approach to stall. The aircraft would have encountered aerodynamic stall buffet which the crew could have misinterpreted as weather turbulence. **They do not acknowledge the tone.**

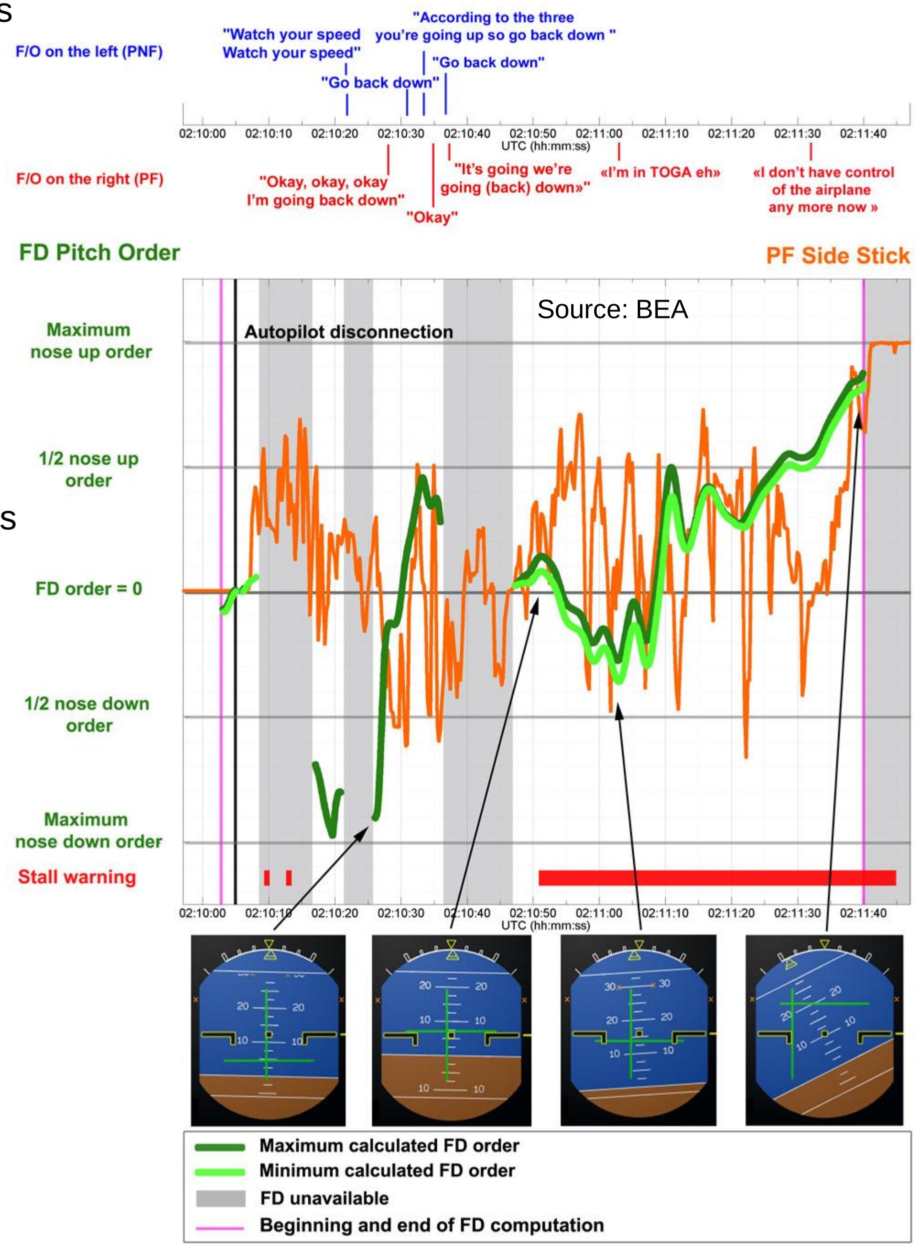
- Departing controlled flight into a full stall condition, still nose-up, the A330 flight control system automatically “trims” the elevator to maintain the commanded high-pitch attitude because the Alternate Law has removed stall prevention controls. **Now, AF447 is stalled and configured to stay that way without an aggressive nose-down command from the pilot.** When the crew increases engine thrust, the moment arm from the underwing engines only serves to force the stalled aircraft’s nose higher**.**

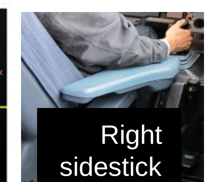


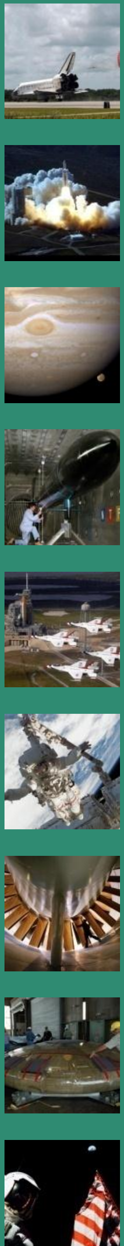
Source: BEA

MISHAP EVENT SEQUENCE-DESCENT/IMPACT

- Chart shows PF sidestick inputs in orange, and Flight Director needle orders in green. Red band is stall warning.
- Voice recording indicates the crew remains confused to the end. The PNF and Captain (who returned one minute into the over 4-minute descent) never realize the PF had his sidestick commanding nose-up until he tells them at 50 seconds before impact, **"but I've been at maxi nose-up for awhile."**
- Airbus A330 sidestick controllers are not cross-connected. The PNF cannot feel PF inputs via the other sidestick.
- AF447 pancakes into the Atlantic at over 100 mph. The passengers had received no word from the crew of any problem.







PROXIMATE CAUSES FOUND BY BEA

- Temporary inconsistency between the airspeed measurements, likely following the obstruction of the pitot probes by ice crystals that, in particular, caused the autopilot disconnection and the reconfiguration to Alternate Law
- Inappropriate control inputs that destabilized the flight path
- The failure to identify the loss of indicated speeds called out and the appropriate procedure
- The late identification of the deviation from the flight path and the insufficient applied correction
- The failure to identify the approach to stall, the lack of immediate response and the exit from the flight envelope
- The crew's failure to diagnose the stall situation and consequently a lack of inputs that would have made it possible to recover from stall

UNDERLYING ISSUES

- **The feedback mechanisms on the part of all those involved that made it impossible to**
  - Identify the repeated non-application of the loss of airspeed information procedure and to remedy this
  - Ensure the risk model for crews in cruise included icing of the pitot probes and its consequences

- **The absence of any training, at high altitude, in manual airplane handling and in the procedure for Unreliable Airspeed Indication.**

- **Task-sharing that was weakened by**
  - Incomprehension of the situation when the autopilot disconnection occurred
  - Poor management of a “startle effect” generating a highly charged emotional factor for the crew

- **The lack of a clear display in the cockpit of the airspeed inconsistencies identified by the computers**

- **The failure of the crew to account for the stall warning, which could have been due to**
  - A failure to identify the aural warning, a result of low exposure time in training to stall phenomena, stall warnings and buffet
  - The appearance at the beginning of the event of transient warnings that could be considered spurious
  - The absence of any visual information to confirm the approach-to-stall after the loss of the limit speeds
  - The possible confusion with an overspeed situation in which buffet is also considered as a symptom
  - Flight Director indications that may have led the crew to believe that their actions were appropriate, even though they were not
  - The difficulty in recognizing and understanding the implications of a reconfiguration in Alternate Law with no AOA protection

AFTERMATH

- The BEA investigation and analysis spanned 3 years, largely due to challenges locating the wreckage including the Flight Data Recorder and Cockpit Voice Recorder, which were key to many findings.

Flight Data Recorder

Cockpit Voice Recorder

- The BEA final report of July 5, 2012 published 41 recommendations, including
  - Improve capture of flight data by recorders and real-time transmission
  - Improve international search, rescue and recovery procedures and resources
  - Improve flight following procedures by air traffic control
  - Strengthen equipment certification criteria to match environmental hazards
  - Improve training for aircraft handling and crew coordination
  - Standardize commercial aircrew instructor certification and evaluation

- In addition, BEA provided six recommendations for the Civil Aviation Authorities to assess overall aircraft design requirements for AOA indicators, stall warnings, and ECAM message displays to improve the flight crew's comprehension of aircraft performance.

- Multiple findings from interim reports in 2010 and 2011 were acted upon by Air France, the European Aviation Safety Agency, the Federal Aviation Administration, Airbus, and other industry organizations.

RELEVANCE TO NASA

Design of human-operated, complex systems can easily surpass operator capabilities. When the operator is the safety feature of last resort, the operator's systems knowledge should surpass the "how" behind normal and irregular procedures, and explain the "why" of system behavior. Good design allows the operator to troubleshoot problems with speed and confidence.

- No A330 pilots could even practice full stall recoveries in the simulator under accurate conditions because test data for actual A330 stalls were never required to be collected. Planning to collect test data for the worst credible scenarios—not just the most likely—is a wise investment for high-value, low-risk projects.

- Cockpit AOA indicators were an optional, not standard, feature offered by Airbus. Involve the operators early to determine instrumentation requirements.

- Extensive reliance on automation for normal operations can undermine a time-critical, successful operator recovery from an off-nominal event. If there is a manual mode, operators must become and remain proficient in its use.

- There is no single right answer to the issue of human control versus machine control in human-machine interfaces. But as the need for human intervention follows the value of the system, the need for high-fidelity experience in compound failure scenarios, not just a single component or feature, becomes essential to timely action.