How is it you can follow every movement of an unmanned rover that wanders the Martian landscape some 225 million kilometers away, yet here on Earth a passenger jet equipped with advanced navigation and communication systems can disappear without a trace? This is a question that has vexed the flying public since two recent incidents occurred:

- Air France flight 447 (AF 447), an Airbus A330 twin engine wide body passenger aircraft on a regularly scheduled flight from Rio de Janeiro to Paris that departed on 1 June 2009 with 228 people on board that crashed in the mid-Atlantic Ocean; and
- Malaysia Airlines flight 370 (MH 370), a Boeing 777 twin engine wide body passenger aircraft on a regularly scheduled flight from Kuala Lumpur to Beijing that departed on 8 March 2014 with 227 people on board that flew off course before crashing in the south Indian Ocean.

In each flight:

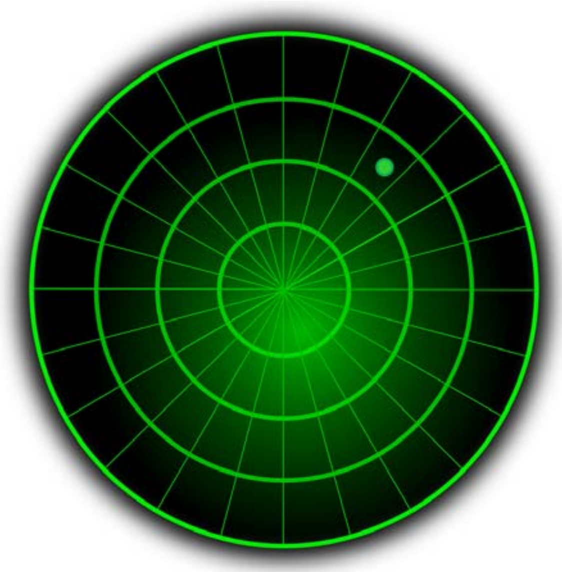
- the aircraft was a modern design with an excellent safety history;
- all passengers and crew went missing, and are presumed dead; and
- the aircraft flew over open ocean before crashing, where no air traffic control (ATC) surveillance was available to track the aircrafts' final position and progress.

As rescue workers did not know the aircrafts' last positions, they had no idea where to look. Nearly two years after it crashed, searchers located the wreckage of AF 447 at a depth of 13,000 feet following an exhaustive and costly sidescan sonar survey of the mid Atlantic Ocean floor. MF 370 has never been recovered, save a single fragment of a flaperon (a moving part of the wing) that was discovered on Reunion Island on 29 July 2015.

This lack of ATC surveillance has been a heated topic of discussion among aviation regulators, operators, and passengers. The general public finds it baffling that an aircraft equipped with advanced navigation and communication systems do not always report their position. This bewilderment appears to be due to an overestimation of the ATC surveillance capabilities. Before the above two incidents occurred, most of the flying public was unaware that there is no ATC surveillance during segments of trans-oceanic flights. The aircraft literally disappears from the ATC radar display, and during these surveillance dark periods, ATC centers rely on hourly radio reports from the pilots to track their position and status.

The question we hear is: why can't modern aircraft report their position to ATC when they are over the ocean? After all, the aircraft's navigation system knows exactly where it is. And don't these aircraft have satellite communication systems that let passengers check email on their smart phones? This lack of position reporting seems incredulous given the highly interconnected world we live in. The answers to these understandable questions become complicated and technical. I will try to explain the answers plainly and clearly.

First, a primer on ATC surveillance systems, starting with radar. Radar is an acronym for **RA**dio **D**ection **A**nd **R**anging. There are generally two kinds of ATC radar systems: primary radar and secondary surveillance radar. When it comes to ATC, most people think of primary radar. A primary radar system sends a signal in a specific direction, and a portion of the signal reflects off a distant target, and the radar receiver detects the reflected signal. By measuring the time the signal takes to travel from the emitter to the target and then back to the receiver, the radar system can calculate the distance to the target. A reflected primary radar signal appears as a blip, or a dot on the ATC display that represents the location of the aircraft.



In primary radar, the ground antenna transmits a directional signal that reflects off the target. By measuring the time the signal takes to reach the target, and then reflect back to the radar antenna, the ground station computes the distance to the aircraft. The primary radar display shows the position of the aircraft as a dot on a display.

Primary radar was first used to control aircraft in 1939 during World War II. The Royal Air Force built its first radar facility on the south eastern coast of Britain as an early warning system against enemy aircraft. The ground based radar detected German bombers advancing over the English Channel, and the radar operators dispatched the RAF fighter squadrons to intercept the Luftwaffe before they made landfall.

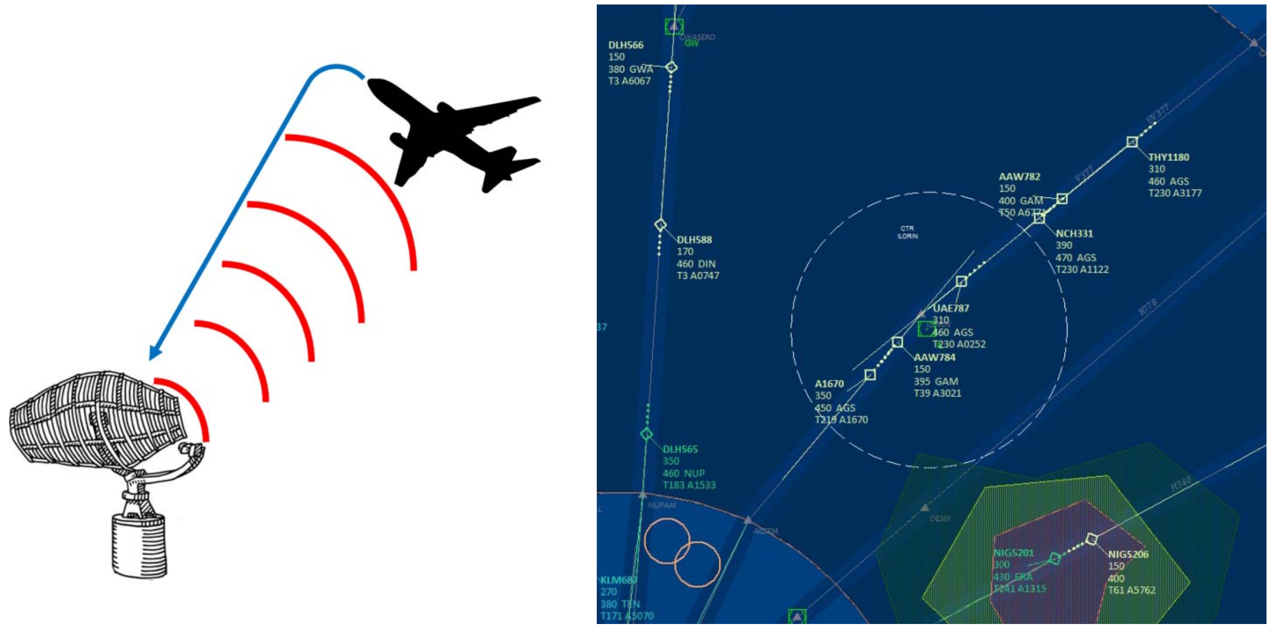
Modern commercial aviation no longer uses primary radar, although it is still used in military environments. Civilian ATC systems use a system called secondary surveillance radar (SSR), or more commonly, just secondary radar. In secondary radar, the emitter sends out a signal in a specific direction, just like in primary radar, but it does not capture the reflection of that signal – the signal is one-way. A special device onboard the aircraft, called a transponder, detects the incoming radar signal, and it immediately responds by transmitting its own reply bearing an encoded message. The encoded message includes a serial number unique to that aircraft, the flight call sign, and the altitude.[1] The ground system still measures the elapsed time from transmission of its signal to the return of the transponder message to calculate the distance to the aircraft. The secondary radar display shows the aircraft call sign (such as AF 447) as well as the aircraft's reported altitude beside the dot that indicates its position. The ATC ground computer also calculates the aircraft's speed and heading based on sequential radar position samplings, and it displays that information as well.

A primary radar display shows a dot indicating the aircraft's current position. A secondary radar display shows the same dot, but beside that dot it displays the aircraft's call sign, altitude, heading, and speed. Clearly the information rich secondary radar is preferred when a controller is responsible for several aircraft in her airspace.

The aircraft's transponder also returns a coded signal called the transponder code. A transponder code is a four digit number, with all digits ranging from 0 to 7. The pilot onboard

[1] This discussion refers to Mode S transponders.

the aircraft can set the transponder code by typing in the four digits on a panel or keyboard. Some transponder code values have special significance. For example, if an aircraft transmits a transponder code of 7500, that aircraft has been hijacked. This protocol allows the pilot to covertly alert an ATC operator his aircraft has been hijacked without announcing his status over the radio while the hijackers stand nearby. If the transponder code reads 7600, then the pilot has indicated his radio has failed. A transponder code of 7700 indicates an emergency.



In secondary radar, the ground antenna transmits a directional signal. A transponder on board the aircraft returns a coded signal containing the aircraft's call sign, altitude, and transponder code. The ATC system displays this information, together with the aircraft's speed and heading beside the dot indicating the aircraft's position.

The secondary radar became mandatory for most civilian ATC systems in 1960, and is still the standard surveillance system for civilian ATC. More recently, a third type of ATC surveillance system has gained wide acceptance, and is mandatory in some airspaces. Automatic Dependent Surveillance – Broadcast, (ADS-B), builds upon secondary radar capabilities, but ADS-B has several important differences.[2]

First, the ADS-B signal transmitted by the aircraft is completely self-contained, which is not the case with secondary radar. In secondary radar, the ATC ground station computes the aircraft's position based on the elapsed time from radar signal transmission to transponder signal reception. In ADS-B, the aircraft's onboard navigation system uses its Global Positioning System (GPS) to determine its location, and the ADS-B transponder includes the aircraft's position in its encoded message.

[2] This paper primarily discusses ADS-B Out, and briefly mentions one feature of ADS-B In.

The ADS-B transmission includes:

- aircraft serial number;
- the flight call sign;
- altitude (both barometric and geometric/GPS);
- heading;
- position;
- speed (both indicated airspeed and ground speed/GPS); and
- transponder code.

A second important distinction is an aircraft broadcasts its ADS-B information every second, regardless of whether it receives an incoming radar pulse or not. This means every ADS-B equipped aircraft continuously transmits its information every second.

Because ADS-B transmitters broadcast their own position, the ADS-B ground stations are vastly simplified compared to secondary radar ground stations. A secondary radar must transmit a rotating directional signal and compute the aircraft's distance based on the interval to the returned transponder signal. Radar ground stations are expensive to build and maintain, and their complex design includes a rotating high-power directional radio transmitter. ADS-B, on the other hand, requires nothing more than a simple pole antenna and a radio receiver tuned to the aircraft's ADS-B broadcasts. Consequently, ADS-B ground stations are simple, inexpensive, small, reliable, and low power compared to secondary radar ground stations.

ADS-B has some special advantages over secondary radar. Because the ADS-B transponder transmits position, altitude, speed, etc. every second, every aircraft can listen to every other aircraft's ADS-B broadcasts. Each and every aircraft's computer will then generate its own three dimensional picture of all air traffic around it. Should two or more aircraft appear to be on a potential collision course, the ADS-B system in each affected aircraft can alert its pilots to take evasive action long before the situation becomes a serious problem.[3]

The ADS-B transponder broadcasts its call sign, position, altitude, speed, heading, and transponder code to both the ADS-B ground station and to other aircraft in the nearby airspace. The ATC controller views an enriched data display, and the aircraft displays nearby airspace traffic to the pilots.

[3] The in-cockpit ADS-B display that shows other aircrafts' positions is not a mandatory requirement. Mid-air collision avoidance systems, such as TCAS II, are already mandatory in all commercial aircraft. Eventually, TCAS will incorporate ADS-B information from nearby aircraft to provide enhanced collision avoidance capabilities.

ADS-B also works when the aircraft is on the ground. Ground and tower controllers will be able to see aircraft on every taxiway, runway, and apron on their ATC display without requiring expensive ground radar systems. This capability significantly increases ground safety, especially in poor visibility conditions.

You can watch live airborne ADS-B surveillance tracking for actual flights by visiting the FlightAware website (*https://flightaware.com/live*), which displays every ADS-B enabled aircraft in flight around the world in (almost) real time.[4]

ADS-B is mandatory for all commercial aircraft that currently operate in Australia and in parts of Canada. By 2020, ADS-B will be required throughout North America and Europe, and it will replace secondary radar as the ATC surveillance system. Over 90% of all commercial aircraft are already equipped with ADS-B transponders.

The ADS-B Cockpit Display overlays information about nearby aircraft, including their position, altitude (+ or -), whether it is climbing or descending (up arrow or down arrow), and the direction the other aircraft are travelling relative to this aircraft. The Cockpit display is not a mandatory ADS-B requirement.

All three surveillance methods – primary radar, secondary radar, and ADS-B – are terrestrial based systems, meaning they require a ground base to receive the aircraft's reflected or transponder signal. And therein lies the rub. As an aircraft crosses a trans-oceanic route, it flies out of range of the ground radar and ADS-B stations, and the aircraft literally disappears from the ATC display until another ATC system captures the aircraft on the other side of the ocean.[5] Both AF 447 and MH 370 flights were in this mid-ocean ATC dark zone when they crashed, and their final positions were not known by any ground controllers.

Recent studies investigated the feasibility of using satellites to receive ADS-B information globally. The most comprehensive study piggy backed an ADS-B receiver on a PROBA-V satellite. The PROBA-V satellite's primary purpose is to observe vegetation to monitor naturally occurring vegetation health, crop health, urban encroachment, and other factors. The satellite launched successfully in 2013, and the experimental ADS-B receiver went to work beside the vegetation monitoring sensors. In early 2015 the study concluded there were several technical issues to address before ADS-B over satellite becomes viable. First, ADS-B is designed for a signal range of 150 nautical miles (280 Km), however the distance to low earth orbiting satellites

[4] Flight aware conceals some flights' positions for security purposes.
[5] Even if an aircraft is ADS-B enabled, most ATC centers do not display ADS-B information. The majority of ATC centers still use secondary surveillance radar only.

is typically 800 Km or more, so by the time the signal reaches the satellite, it may be too weak for some receiver technologies. Second, a ground station will receive hundreds of ADS-B signals at once, but because satellites have much wider horizons, each satellite will receive thousands of ADS-B signals simultaneously, and too many signals on the same frequency coalesce into a garbled mess. Third, aircraft antenna are designed and positioned to transmit ADS-B signals downward to the ground station, creating what is coined as a cone of silence, in which the region directly overhead the aircraft is ADS-B quiet.

The PROBA-V/ADS-B study concluded that ADS-B over satellite is possible, but only through the implementation of improved satellite signal reception, steerable satellite antennas, and enhanced signal processing. All these technologies already exist – it is simply a matter of applying them to a satellite based system.

ADS-B over satellite is identical to terrestrial ADS-B, except a satellite receives the transponder emission when the aircraft is not in range of a terrestrial ADS-B ground station. Ground stations are still available to receive the ADS-B signal when the aircraft is not overflying an ocean.

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A major advantage of ADS-B over satellite is the system requires no modifications to existing aircraft. Even the cone of silence is manageable with sufficient satellites. Another benefit is trans-oceanic flights can be spaced closer together without comprising safety. Currently, pilots report their position over radio every hour while overflying the ocean. ATC centers add extra spacing between aircraft to account for reporting errors or flight path deviations between reports. ADS-B over satellite will permit ATC centers to monitor and control trans-oceanic air traffic no differently than any other type of air traffic, thus eliminating the need for extra spacing between aircraft. This decreased aircraft separation will significantly increase trans-ocean traffic volume capacity with no compromise to flight safety.

A small detail remains. Someone needs to launch and maintain a constellation of low earth orbit satellites equipped with redesigned ADS-B receivers and antennas. Enter Aireon Inc. Aireon is a joint venture between the Canadian, Danish, Irish, and Italian civilian aviation regulation authorities together with Iridium Communications. Iridium owns and operates an existing constellation of 66 low earth orbit satellites[6] for commercial communications, including satellite telephones and satellite pagers.

Satellites fail over time, and any constellation requires constant upkeep. Iridium launches replacement satellites regularly. Under the Aireon joint venture, all future Iridium satellites will

[6] Iridium presently has 72 working satellites in orbit, but 6 of those are held in reserve as orbiting spares.

include redesigned ADS-B receivers. ADS-B over satellite is scheduled to go live in 2018. Once ADS-B over satellite becomes fully operational, ATC surveillance will have a global reach.

It is worth noting that ADS-B over satellite is more of an operational issue than a safety issue. ATC surveillance would not have saved anyone onboard AF 447 or MH 370, but it would have greatly simplified the search efforts for AF 447.

In the case of MH 370, it would appear at least one of the flight crew deliberately veered the aircraft off course and cruised over open water for over seven hours until the engines flamed out from fuel starvation. The doomed jet dove unnoticed into the Indian Ocean, coming to rest in a yet undiscovered watery grave. Whoever executed this death sentence could defeat the ADS-B system by disabling the transponder. There is evidence that is exactly what happened – ATC surveillance records indicate the transponder stopped transmitting 39 minutes into the flight.

Every electrically powered device onboard an aircraft is a potential fire hazard, and every electrical system must therefore be protected by a circuit breaker. Resetting the transponder circuit breaker is one way to disable the ADS-B. There is discussion in the aviation industry calling for tamper-proof circuit breakers, but this introduces new problems, and it doesn't fix this one. The pilot need not reset the circuit breaker to defeat the transponder. The flight management computer on the Boeing 777 has a transponder switch setting – a few presses on the keyboard is all it takes to deactivate the transponder.

Even if refitting the aircraft with tamper-proof circuit breakers was the answer, it is an expensive order. No one wants to bear a large retrofit cost that does nothing to increase flight safety. Tamper-proof circuit breakers will not save the passengers when a deranged pilot commandeers the flight deck while consumed with a crazed obsession to destroy the aircraft. Furthermore, aircraft manuals call on pilots to cycle circuit breakers in mid-flight to isolate and diagnose equipment problems. Pilots also reset circuit breakers to power down non-critical systems they suspect are faulty before the affected system becomes a safety problem.

The ugly truth is, if an otherwise normal pilot goes rogue and decides to end it all, there is precious little any person or technology can do to prevent it. As distressing as that thought might be, the fact is suicidal pilots are not a priority in aviation safety. In the past thirty five years, there have been seven commercial flights ending in fatalities where a suicidal pilot was the determined or suspected cause.[7] Suicidal pilots account for fewer than 1% of all commercial airline fatalities. Meanwhile, pilot error is responsible for 66% of all commercial aircraft accidents. It is understandable why the airline industry resists calls to implement costly measures, such as tamper-proof circuit breakers, that will do nothing to prevent pilot suicide related deaths.

While we are waiting for ADS-B over satellite to become a reality, why not transmit ADS-B data over the satellite communication (satcom) channel? It seems a reasonable question to ask, but that solution requires substantial modifications to the aircraft. Remember ADS-B over satellite requires no changes to the aircraft. The cost of retrofitting ADS-B over satcom on every aircraft would be an order of magnitude higher than adding tamper-proof circuit breakers, which already cost more than their worth. Moreover, satcom is an optional capability – not all aircraft have

[7] Japan Airlines 350, 9 February 1982, 24 killed; Royal Air Moroc 630, 21 August 1994, 44 killed; Silk Air 185, 18 December 1997, 104 killed; Egypt Air 990, 31 October 1999, 217 killed; LAM Mozambique 470, 29 October 2013, 33 killed; Malaysia Airlines 370, 8 March 2014, 239 killed; Germanwings 9525, 24 March, 2015, 150 killed

satcom antennas, and not all airlines subscribe to a satcom service. Airborne satcom systems have a lower design assurance certification than ADS-B, meaning satcom is not designed to be as robust and reliable as the ADS-B system is required to be. This is because satcom is not a critical system, whereas ADS-B is mandatory for some existing and all future ATC surveillance, making ADS-B a more critical system. Aviation safety regulations therefore forbid the transmission of ADS-B data over the less reliable satcom system for ATC surveillance purposes. Finally, it would take years to design, implement, and certify ADS-B over satcom, and by then ADS-B over satellite is scheduled to be live. In short, it is a non-starter.

In summary, the current ATC surveillance system does not track aircraft in mid-oceanic segments of flight because all civilian ATC surveillance technology requires a ground base to receive the signal from the aircraft. A joint venture, called Aireon Inc., is looking to support ADS-B over satellite using a global constellation of satellites that will receive ADS-B transponder signals worldwide. Aireon is scheduled to go live in 2018. The ability to track all aircraft all the time will significantly reduce search times and costs when aircraft are lost in the open ocean, but it will not prevent the rare situation where a pilot deliberately destroys the aircraft. ADS-B offers additional benefits, such as it can be implemented without modification to existing aircraft, it optionally allows pilots to visually monitor all air traffic around them, and it will increase trans-oceanic air traffic density without affecting safety.