Recurring Failure Modes in Aircraft Disappearances: Improvements in Location Tracking Requirements and Review of Solutions

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Abstract— **In this work, we analyze various solutions to recurring failure modes in aircraft location tracking. Improved tracking systems are vital for continued growth, not only for flight safety, but also for an increase in reliability and precision that would allow for planes to fly closer together, improving the efficiency of routes in terms of flight time and fuel consumption among other parameters. We examine five selected cases of commercial and military aircraft and identify the recurring tracking failure modes that were present. These modes violate safety principles and include radar dead-zones, transponder malfunctions, imprecise and infrequent location tracking, and Emergency Locator Transmitter (ELT)/Underwater Locator Beacon (ULB) failures. These violations are the foundation for a set of requirements that were developed to improve the flight tracking standards. The requirements included increasing the frequency of data transmission, breadth of data transmitted, ubiquitous map coverage, functional and dependable transponders, reliable post-crash tracking, and practicality (i.e. installation and cost considerations). We then analyze existing and potential solutions in terms of their ability to meet the set requirements and limitations each exhibit. The analysis upon implementation would improve in-flight aircraft tracking by increasing the frequency of data transmissions and breadth of information communicated. It also establishes that specialized procedures need to be in place during flight distress mode, like increasing the frequency of transmission to once every minute. Improving post-accident tracking will also have many benefits like decreasing the search area and therefore being more efficient with resources. Implementation of the requirements will demand organizations and governing bodies to coordinate between each other, but the positive outcomes of this implementation will be well worth it, although there is still plenty of future work to be done.**

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1 INTRODUCTION

1.1 Motivation and Objectives

A fundamental feature in the aircraft industry is confidence, confidence in the safety and reliability of the aircraft's systems. When an accident occurs, not only are the people associated with the passengers looking for answers, but all of the customers are doing so as well. Answers help restore confidence, and these can only be discovered if the aircraft is recovered. As the ATTF states, "In the absence of confirmed facts, speculation defines the incident" [1]. Therefore, an essential system for passenger confidence is tracking. Air traffic passenger demand has increased ~7% every year over the past decade supporting the urgency of ensuring safe and reliable air travel [2].

The current state of tracking is very inadequate, particularly in low-density (oceanic or remote) airspace. Air traffic control generally uses two radar systems for tracking. The primary system is antiquated and detects the approximate location of an aircraft from reflected radio signals. This form is one-sided and does not require any action by the people or systems on board the tracked aircraft to track location. The secondary system uses a transponder and is a two-sided form of location determination where a radio signal is received by the aircraft and a flight/aircraft specific code is returned to air traffic control which contains vital tracking information such as flight identification, altitude, speed, and direction [1].

The main drawback of these previously used methods is that radar does not work when an aircraft is more than 240 km (150 miles) from land. Location tracking beyond this range originally was only possible through airband radio transmissions sent from the aircraft at regular intervals, which only works when the aircraft is in the line-of-sight a receiver. This system was later augmented in the 1978 to include satellite data transfer when airband communication fails [4]. Similarly, emergency location tracking began in the 1930's and utilized radio beacons to transmit information. In 1979, the International Cospas-Sarsat

Program integrated satellite technology to relay radio distress signals to ground stations, but even this system only covers about 70% of the Earth's surface [4]. While GPS technology is reliable and extensively developed, global air traffic control systems are currently primarily radar based. The GPS-compatible ADS-B system created in the early 2000's and planned to be fully implemented in the 2020's [4].

This paper is motivated by a desire to implore technologically advanced systems to improve the depth and value of tracking information, pre- and post-crash, since these systems are so vital to aircraft safety and public confidence. Additionally, looking at these systems through the lens of safety principles provides an opportunity to understand intrinsic problems with flight tracking systems and allows for informed decision-making with respect to solutions.

The objectives of this report are threefold. First, through a case series of accidents, we aim to identify recurring failure modes in diverse aircraft flight tracking situations and conditions. This will identify major deficiencies of current systems. Second, in light of these failure modes, we suggest requirements for improvement along all stages of the accident sequence, emphasizing the most critical and repairable options. These requirements are derived from safety principles and are intended to encompass all failure modes. Third, we will analyze the solution space of existing and potential solutions for improved flight tracking based on the derived requirements. An important distinction that will be made throughout the paper is between normal in-flight tracking and distress tracking, since both are vital and have distinct solutions.

The objectives provide a road map for this paper, and the rest of the paper is organized as follows. Section 2 discusses the data sources for the case studies, the methods used to meet our objectives, and common patterns of tracking failure. In Section 3, we analyze the recurring failure modes found in Section 2 through the lens of safety principles. In Section 4, we develop a set of requirements for future tracking systems that is rooted in the . We then analyze existing and potential solutions based on their ability to meet the requirements set.

1.2 Acronyms and Terminology

ATC/ATS - Air Traffic Control/Air Traffic Service
PSR/SSR - Primary/Secondary Surveillance Radar
TCAS - Traffic Collision Avoidance System
ELT - Emergency Locator Transmitter
ULB - Underwater Locator Beacon
ACARS - Aircraft Communications Addressing/Recording System
ADS-B - Automatic Dependent Surveillance-Broadcast
ADS-C - Automatic Dependent Surveillance-Contract
ANSP - Air Navigation Service Provider
HF/VHF - High frequency/very high frequency radio
OCC - Operations Control Center
SAR - Search and Rescue
SATCOM - Satellite communications
FDR - Flight Data Recorder
CVR - Cockpit Voice Recorder
TPL - Towed Pinger Locator

Investigative and Regulatory Organizations by Nation

FAA - United States, Federal Aviation Administration
NTSB - United States, National Transportation Safety Board
BEA - France and Fr, Bureau of Enquiry and Analysis for Civil Aviation Safety
ATSB - Australia, Australian Transportation Safety Board
ICAO - United Nations, International Civil Aviation Organization

2 Data & Methods

2.1 Methodology for case selection

Location tracking failures expose themselves in various ways and in diverse conditions which is explored through a number of case studies which shed light on the common factors that characterize location tracking failures. General and commercial aviation accidents and incidents are well documented via a number of open access databases recorded by agencies around the world; however, location tracking failure is not directly searchable in any database. In order to find pertinent cases, four online databases were queried for any case that involved a partial or complete failure of a component related to the location tracking system. Specifically, the National Transportation Safety Board (NTSB) Aviation Accident Database & Synopses, the Federal Aviation Administration (FAA) Accident & Incident Data, the Australian Transport Safety Board (ATSB) National Aviation Occurrence Database, and the Aviation Safety Network (ASN) Accident Database were used to search for cases of international aviation accidents.

Location tracking technology, for both nominal flight conditions and emergency situations, was developed gradually as the aviation industry developed, making it difficult to identify a single date at which to begin investigating cases. For the purposes of this investigation, only accidents which occurred after the 1973 FAA technical standard order (TSO-C91) are considered. This mandate required the installation of ELTs in general aviation accidents, marking the beginning of reliable data on emergency location tracking. While location tracking for nominal flight existed prior to 1973, these cases are not necessarily relevant due to the improvements and development of avionics equipment since then. Thus, this analysis restricts the cases considered to those of nominal flight and emergency location tracking failures since 1973.

Intuitively, the first set of data consisted of cases of aircraft that were unrecovered following an accident and had been deemed 'missing.' However, the conditions which characterize location tracking failures are complex and nuanced. In order to collect as many pertinent cases as possible, any case that included a failure or malfunction of the PSR or SSR (on the pilot's side or ATC side) and transponder failures (including the malfunction of transponder-based systems such as TCAS, ADS-B, etc.) are considered. Furthermore, in the spirit of redundancy and to avoid missing incidents that were not primarily caused by location tracking failure, cases classified as a loss of communication, in-air collision, runway incursion, near miss, loss of separation, airspace infringement, and accidents that occurred over bodies of water were also considered as they in some way partially depend on accurate location information and communication.

Given these constraints, 2259 cases of possible location tracking failure were found across the four databases queried. Each case was considered individually to determine whether the tracking system played a role in the accident or post-accident analysis. The majority of the cases were easily filtered out as they either were clearly not tracking related (i.e. crashed due to pilot error, component malfunction, maintenance errors, etc.) or did not contain sufficient documentation to make a definite decision (i.e. accidents involving small planes and very low-visibility crashes). Of the remaining cases, 73 involve accidents that are considered to be directly caused by, or heavily exacerbated by a component of a location tracking failure.

It is important to note that tracking failure is not necessarily the primary cause of an accident. Apart from in-flight collisions, location tracking is not as critical as other systems such as an aircraft's controls. Emergency location tracking systems do not influence the operation of an aircraft and serve as an air to SAR teams to recover lost aircraft, humans, and flight data. As a result, the failure of an ELT or ULB is in no way causes an accident or incident, but still is considered a system failure (or in some cases a design failure) due to an inability to function properly and relay valuable location data. Also, it is reasonable to presume that some flights may experience temporary, localized failures of a given aspect of the location tracking system in the form of a transponder malfunction or loss of radar contact, especially in low-density airspace and still continue with no adverse consequences. Unfortunately, data on the frequency of these types of occurrences is not well documented. **Nevertheless, location tracking failures are accident pathogens that lie dormant and severely exaggerate the consequences of an incident or accident.** In the event of an accident over the ocean, for example, the consequences of tracking failure would be an increased search area and which limits the opportunity for search and rescue by increases the time to locate the aircraft and the expenses associated with aircraft recovery.

The 73 cases identified are expanded upon in Appendix A. From these events, five cases are chosen to discuss in detail distinct aspects of the failure modes present in location tracking procedures and equipment. The following five case studies depict aircraft incidents in which the flight was partially recovered or never recovered due to the failure in operation and/or design of the location tracking system for both normal and abnormal flight. Even more aircraft have had accident recovery hindered due to tracking failures, but since those failures did not propagate as far in their accident sequences, this investigation only focuses on cases that were heavily affected by tracking failures. Despite technological advancements and regulations instituted by the FAA and other regulating bodies over the past decades serving as defenses against tracking failures, holes in these defenses can result in large scale loss of life and even the disappearance of entire aircraft, well in the 21st Century.

The demographics of the cases discussed in this report include three civilian and two military aircraft to show that the problems discussed are present even in the most sophisticated aviation technology in the world; however, due to the limited level of transparency in military incidents, civilian aviation accidents are the predominant focus of the report. Despite tracking technology existing for decades, the five studies discussed occurred since 2009 to highlight the continued presence of these failure modes and the urgency with which these problems should be addressed. Additionally, all of the cases presented are similar in they resulted in total loss of occupants with two instances of high-visibility accidents with over 200 fatalities. Furthermore, all the aircraft involved in these cases were equipped with some level of tracking or flight recorder technology which is fully discussed later. Brief summaries of the cases are presented in Table 1 for reference and are discussed in more detail afterwards.

2.2 Discussion of Case Studies

2.2.1 Malaysian Airlines Flight 370 (MH370)

On the evening of March 7, 2014 Malaysia Airlines Flight 270 took off from Kuala Lumpur International Airport en route to Beijing [13]. The Boeing 777-200ER with 239 occupants last made contact with ATC radar over the South China Sea before straying from its intended flight path and making last known contact over the southern Indian Ocean. The aircraft last made voice contact with ATC at 17:19 UTC before disappearing from ATC radar at 17:22 UTC. Military radar continued to track the plane as it flew west from its intended flight path towards the Indian Ocean. The aircraft left the range of military radar at 18:22 UTC. At this point, no PSR or SSR tracked the aircraft, but there was an hourly SATCOM connection which, although was not intended to be a tracking system, offered minor location inferences through handshakes with a satellite that happened to be overhead. This allowed the location of the plane to be imprecisely reduced to somewhere along a large arc on the Earth's surface. Using SATCOM information, the plane was observed to fly directly south across the Indian Ocean until its last SATCOM transmission at 0019 UTC. After this, the aircraft failed to respond to a SATCOM transmission at 0115 UTC at which point it had presumably run out of fuel.

To better understand exactly how the series of failures transpired, it is important to understand the setup of the tracking systems on the aircraft, all of which are described in detail by in the accident reports produced following an extensive investigation. First, the flight was fitted with four ELTs that were interfaced with the Cospas-Sarsat satellite constellation for SAR. The satellites relay emergency signals to the nearest Mission Control Centre (MCC) in Canberra, Australia. Of the four ELTs installed on the flight, a fixed ELT was operated through the cockpit, a portable ELT was locked in a crew closet, and two slide ELTs were installed in the two slides and were only activated if they were deployed. ELTs in general are not designed to function underwater and even though some are water activated, they must remain undamaged with the antenna above water to transmit a signal. This would be unlikely for any of the four ELTs on board due to the fact that three were locked within the plane and one was only cockpit controlled. Unsurprisingly, no ELT signal was ever received. Furthermore, **Cospas-Sarsat does not offer ubiquitous coverage of the globe, only covering about 70 percent of the Earth at a time**. The importance of ubiquitous coverage will be further elaborated on in Section 3.

To compensate for ELTs' inability to operate underwater, ULBs are used to send pings following a crash over a body of water. MH 370 had two ULBs installed in the flight data recorder and cockpit voice recorder, respectively. Each could transmit 37.5 kHz pings for at least 30 days from a maximum depth of 20,000 ft.; however, according to the accident report, the ULB in the flight data recorder had batteries that had expired in December 2012, and the voice recorder ULB was set to expire in June 2014. Due to improper maintenance, on the ULBs, the likelihood that they would operate nominally in this accident is severely decreased.

Apart from emergency tracking failures, the normal communications system contained numerous accident pathogens that could exacerbate failures in certain conditions. MH370 was outfitted with two Collins HFS-900 HF Systems for high frequency radio communication with ATC. These two separate HF systems used a common HF antenna on the vertical stabilizer. To communicate with ATC and use TCAS, the plane had an ATC/Mode S transponder system with two separate transponders that provided GPS data. However, both transponders were only accessible through the cockpit and designed to not automatically switch to the other transponder if one fails. Additionally, the transponders can be easily deactivated manually. Since the secondary surveillance system depends on cooperative information exchange between ATC and the aircraft through the transponder, once the transponder was deactivated (whether manually or due to a malfunction), MH370 disappeared from ATC radar screens and there was nothing that could be done outside the aircraft to track and receive information from the airplane other than basic location tracking using PSR.

The flight was equipped with an ACARS datalink system which used VHF radio or SATCOM to relay information in-flight every 30 minutes. If ACARS is silent for 30 minutes, a ground station attempts to contact the cockpit via text or SATCOM call. The system defaults to VHF transmission which only works at line-of-sight distances. If VHF transmission fails, the system automatically switches to SATCOM. This particular terminal used the Inmarsat Classic Aero system which does not have ubiquitous coverage globally, specifically at the poles which is where the last known location of MH370 was. If there has been no communication for an hour, the SATCOM system sends the aircraft a 'log on interrogation' to check if it is at least still logged on to the network. This is known as a 'handshake' [14]. The last log on acknowledgement returned by MH370 was at 0019 UTC. This method of communication theoretically allows for reverse calculation of the plane's position given the position of the satellites at the time, but still requires cooperation to get location information and is not the intended purpose of the system at all.

Though what happened on board MH370 is unknown, **the limitations in the design and usage of PSR and SSR systems; the poor design, maintenance, and implementation of ELTs and ULBs; and the reliance on an inadequate satellite system** contributed to the inability to locate the aircraft and ensured that the world will never know what really happened to the flight.

2.2.2 Air France Flight 447 (AF447)

After departing from Rio de Janeiro en route to Paris on May 31, 2009, Air France Flight 447 stalled over the Atlantic Ocean. **In this case, unlike MH370, the primary tracking systems did not fail**. The failures of interest occurred after the aircraft had crashed into the ocean and all the 228 occupants had perished. The flight path of AF 447 crossed the Atlantic Ocean with a brief length in time in which the aircraft was out of range of any ATC. After taking off at 22:29 UTC, the last voice contact via radio with the plane had occurred at 01:35 UTC as the flight left Brazil and began to cross the Atlantic Ocean. At 01:49 UTC, the aircraft left Brazilian radar surveillance and was expected to be in a radar dead zone until 02:20 UTC when it was due to enter Senegalese airspace. Senegalese ATC had noticed AF 447 was not following its flight plan, but it wasn't until the morning of June 1 that the plane had been deemed missing by ATC [14].

The crash itself is not of particular relevance to the failure of the tracking system, so it will not be covered in as much detail. Following an autopilot disengagement and improper pilot correction, the plane stalled at approximately 02:10 UTC and crashed into the ocean. Since the plane was out of radar contact, no ATC was notified of the emergency and the only tracking data received was an ACARS satellite message at 02:10 UTC sent to Air France via the ACARS network every ten minutes. The position provided in the ACARS report was used as a reference for SAR operations; however, since the plane was near its maximum flight ceiling when the position was recorded, the search area was very large. Although ACARS was operating nominally, this large search area suggests that more frequent transmission of location data, especially in distress modes, would narrow the search area and simplify SAR efforts.

Recovery efforts found portions of wreckage in the weeks following the crash; however, despite employing two Tower Pinger Locators (TPLs) from the United States, the data recorder and cockpit voice recorder were not recovered in the thirty days following the crash and the batteries were presumed to have died. The TPLs had been towed over all area within 40 nautical miles of the initial wreckage that was found. Nearly two years later, using a probabilistic crash area, the remainder of the wreckage was found, including the FDR and CVR which each contained a ULB. The Final Report by the BEA noted that the TPLs had passed near the ULBs on two occasions in June 2009 and failed to detect any signal. Assuming normal operation, ULB detection depends on a towed locator attached to a ship or submarine to pass near a ULB and detect its signal within 30 days of an accident. This process requires a significant amount of coordination and is a resource intensive effort which even in optimal conditions is difficult to execute. In the case of AF447, the failure to locate the ULBs in 2009 could be due to a malfunction of the ULBs or the TPLs, but regardless it cost two years of time and resources in order to find the airplane wreckage and recover data about what had happened during the flight.

Due to the remote location of the accident and design flaws in the locational and data recovery systems, the AF 447 tragedy resulted in a slow, expensive, and uncoordinated search and recovery of the aircraft wreckage

Flight Name	Aircraft	Date	Failure Description	Value as a Case Study	References
MH370	B777	3/18/14	- SSR tracking failed (transponder turned off) in-flight. -Military PSR then tracked the aircraft before losing line-of-sight connection, -SATCOM tracked the flight even further but was poor at tracking by design. -ELTs and ULBs had expired batteries and/or were not as effective as they were intended.	-Largest and highest visibility incident. -The aircraft completely disappeared and experienced failures in the operation and/or design of the PSR, SSR, and emergency tracking system.	Accident reports by a number of agencies, many in English
AF 447	A330	6/1/09	-Accident took place over an isolated region and radar dead zone of the Atlantic Ocean -ELTs and ULBs took two years to locate and recover.	-High visibility case with many casualties. -Shows reliability issues with emergency location tracking following an accident that was not caused by tracking failures	BEA Accident Report (in French and in English)
Senegalair 6V-AIM	HS-125	9/5/15	-After a mid-air collision, the plane flew for 55 minutes across the entire radar field of Dakar's ATC and crashed in the Atlantic. -The aircraft was never recovered and no information other than PSR was collected.	-Combines elements of emergency and primary location tracking limitations for small civilian aircraft. -Small aircraft, which is distinct from the first two cases, showing the depth of the problem -While the TCAS failure is not the focus of this investigation, the failure to locate the aircraft afterwards reveals design limitations	BEA Accident Report (in French)
IAF K-2743	An-32	7/22/16	-Disappeared from radar -ELTs failed to function -Aircraft was not equipped with ULBs	-High visibility incident in India which involved a military transport aircraft unlike the other cases. -Despite being a recently renovated Soviet-built aircraft, contact was lost, and the aircraft was never recovered -Discusses both primary tracking failure and emergency tracking failure	-Military crash, so a full report is not available. -Eight Indian news articles - Government statements
AX-6	F-35A	4/9/19	-Pilot aborted a training mission and mentioned a problem before the aircraft disappeared from radar -Recovery operations were hindered by the design of the emergency tracking system	-Tracking failures are present in one of the most sophisticated systems ever produced. -Failure modes are present in military fighter aircraft -Discusses both primary tracking failure and emergency tracking failure	-Military crash, a full report is not available. -Ten news articles - Government statements

2.2.3 Senegalair 6V-AIM

The next case is of an aircraft type which is distinct from the first two cases and this shows the depth of the problem as also affecting small aircraft. Although this accident involved a TCAS failure, the main focus for this investigation is the failure to locate the aircraft afterwards.

On September 5, 2015, a Hawker Siddeley HS-125 (6V-AIM) operated by Senegalair as a medical evacuation aircraft was flying west from Ouagadougou, Burkina Faso to Dakar, Senegal carrying 7 occupants [15]. Meanwhile, a Boeing 737-

800 operated by CEIBA Intercontinental was flying east from Dakar to Cotonou, Benin. The 737 was cruising at 35,000 ft. in good weather, and the HS-125 had been cleared to fly at 36,000 ft. While flying over eastern Senegalese airspace, just outside of radar contact with the Dakar ATC and radar contact with any nearby airport, the HS-125 medical evacuation plane collided with the 737's wingtip. The HS-125 involved in the incident had multiple reports of altimeter malfunctions in the months prior to the accident, including an instance of the altimeter reporting an altitude 1000ft above the actual flight level. The interaction between the planes was initially documented as a "near-miss collision," and the 737 continued to fly for three hours to Malabo, Equatorial Guinea, where it was discovered that one meter of the right wingtip was severed. The HS-125 was unresponsive as it entered Dakar's airspace, and flew for 55 minutes past Dakar into the Atlantic Ocean as it presumably ran out of fuel and crashed. The accident report conducted by the Senegalese Bureau of Enquiry and Analysis for Civil Aviation Safety (BEA) presume the HS-125 was damaged and lost cabin pressure, leaving the crew inert as the plane flew until crashing.

As 6V-AIM flew in Dakar ATC airspace, ATC repeatedly attempted to contact the flight crew with no response. According to the BEA accident report, the ATC reached out to Senegalair to see if there were any way to contact the plane, but there unfortunately was not. As the plane flew west over the Atlantic Ocean and disappeared from Dakar radar, the controller initiated the distress phase of SAR, DETRESFA at 19:08 local time. This is an ICAO Emergency Phase that indicates "there is a reasonable certainty that an aircraft and its occupants are threatened by grave and imminent danger and require immediate assistance" (ICAO Chicago Convention). By 19:18, the French Elements in Senegal (EFS) sent a Falcon 50 to search the last known location of 6V-AIM and the Navy is directed to divert ships towards the area to search for the aircraft. A multinational effort sent ships and aircraft patrolled the probable area, including a Spanish CASA CN-235. On September 7, the EFS Falcon 50 detected a 243 MHz which is an aircraft emergency frequency that has been phased out over the past decades. This signal was confirmed by another search party. The report mentions that the recovery efforts searched the area near the signal for several days before pronouncing 6V-AIM as disappeared.

While this investigation does not aim to focus on collision avoidance systems such as TCAS, which is the primary cause of the mid-air collision in this case, it is valuable to look at the failure of the transponder as a unit since the SSR relies heavily on transponder operation. The B737 TCAS system did not warn the flight crew of a potential collision since it relied on cooperative communication with nearby aircraft transponders. The HS-125 suffered an instrument malfunction (before the crash), which affected the plane's transponder and consequently TCAS system. Since the TCAS systems indicate warnings by communicating with other aircrafts' transponders and TCAS systems, the 737 TCAS failed due to inaccurate readings from the HS-125 transponder [15]. Nevertheless, the main focus of this case is what occurred following the mid-air collision. **The lack of observability by ATC into the state of aircraft and the inability for SAR teams to recover the aircraft are the results of a poorly designed emergency location monitoring system and highlights the importance of functioning transponders for location tracking in normal flight.** This will be elaborated upon further in Section 3.

2.2.4 Indian Air Force An-32

The next two cases are based on military aircraft, unlike the other cases.

On July 22, 2016, an Indian Air Force An-32 transport aircraft lost radar contact over the Bay of Bengal 42 minutes after takeoff from Chennai [14]. The 29 passengers consisting of Indian military personnel and eight defense civilians were presumed dead. The aircraft took off at 08:30 local time from Tambram Air Force Base on an intended 3-hour flight to the archipelago of Andaman and Nicobar Islands off the western coast of India. The aircraft reportedly experienced a sudden drop in altitude at 23,000 ft after executing a left turn before losing contact with Chennai ATC at 08:12 while about 300 km east of Chennai. Following the accident, over 30 naval vessels, C-130J's with EO/IR sensors, a P8i (Poseidon variation) with Synthetic Aperture Radar, several Dorniers, and a submarine to locate Emergency Locator Beacons (ELBs). Additionally, satellite imagery was used extensively in an effort to locate any debris.

The Indian Air Force fleet of Soviet-era An-32's was originally purchased from Ukraine and the fleet was highly regarded--even after the accident--as the "safest aircraft in the IAF." The aircraft involved in the accident was upgraded with modernized avionics equipment in September 2015; however, by the time of disappearance, the An-32 had logged only 279 flight hours since the upgrade and had been grounded multiple times for "different safety concerns." In updates on the search mission, an Indian Air Force representative said that the ELB and transmitter "may not have properly activated," and the search teams had numerous false leads from misleading pings and ocean floor surveying. After surveying the search area, the search teams identified 70 locations of high reflectance that could either be debris or ocean floor protrusions. The locations of interest were between 3 and 6 km in depth, and only a single remotely controlled vehicle could operate at that range of depth.

The aircraft presumably crashed due to an unknown system failure, in which case the ELTs should have begun to transmit information; however, it is likely that upon crashing into the ocean, the ELTs were inoperative. **While this particular aircraft was outfitted with ELTs, it did not use any ULBs which severely limited underwater search efforts and was a lack of redundancy and poor imagination of failure by the aircraft designers.** Two similar instances of the IAF losing An-32 aircraft occurred in 1986 and June 2019. Both of these cases exhibit similar patterns of failure in location tracking and ELT design and suggest a pattern of failure in the IAF's tracking procedure and technology. Not much public information is available on the IAF's long-term response to these failures, but not only do they fail to address the safety problem, but they also appear to have a tracking failure mode that is activated by reasonably common flight conditions.

2.2.5 Japanese Air Force F-35A

During a training mission of the Japan Air Self-Defense Force (JASDF) on April 9, 2019, an F-35A was lost 85 miles off the coast of northeastern Japan [15]. A comprehensive joint US-

Japanese search recovered portions of the aircraft including part of the flight recorder system which was severely damaged. The F-35A was the first from the production line of the Japanese's fleet and had only 280 flight hours. During a four aircraft training mission, one pilot signaled to abort the practice mission before disappearing from radar. Specifically, the aircraft lost radar contact at 29,000 ft, and, as a result, the location of the plane and other flight information were immediately lost. The aircraft hit the water at a high velocity after what was later determined to be the result of pilot spatial disorientation, and parts of the horizontal stabilizers were found the next day floating on the surface. An extensive international search effort consisting of a P8 Orion maritime patrol aircraft, a U2 spy plane, and numerous recovery vessels had difficulties recovering the FDR and cockpit of the aircraft. In early May, portions of the cockpit and FDR were recovered at 1500 m, but the FDR memory was critically damaged, and most information was lost.

Since the F-35 is a heavily classified vehicle, details on the failures and investigation are not publicly available. This paper though does not aim to speculate on this case, but rather solely use it as an example that **location tracking failures are still present in 2019 on even the most advanced flight systems**.

In terms of ELT and ULB performance specifically, a few studies have been conducted which uniformly show that these systems are not as reliable as they are intended to be. An analysis by Honeywell Aerospace, a large producer of avionics equipment, found that 83 aircraft have been reported missing since 1948 and modern ELTs have only activated in 40% of accidents. Further analysis of the specific failures of ELTs finds that the most common reasons for these failures are "incorrect installation, flat batteries, lack of water proofing or fire protection, damage to the antenna, or an aircraft coming to rest inverted after impact" [8]. Furthermore, this 2014 study prompted a number of additional analyses including a NASA experiment to test ELTs by dropping a Cessna 172 to better understand which portion of the ELT system is failing [18]. NASA found that 9 of 14 ELTs were actually activated in the crash itself and antenna/cabling failures were observed especially in cases where best installation practices were not used. These findings depict location tracking as a multidimensional problem which is affected by numerous aspects of aircraft design, operation, and maintenance. Furthermore, representatives from the USAF Rescue Command Center corroborate these failure rates with incredibly high false alarm rates, which can be equally as limiting due to Cospas-Sarsat satellite's low processing capabilities [19][20].

3 Discussion of Failure Modes Using Safety Principles

Across the five cases, there were a range of failures across the entire sequence of the accident spanning from nominal flight operations to the search and rescue after the aircraft disappeared. From this, four distinct failure modes stood out: imprecise and infrequent location tracking, the presence of radar dead-zones, failure of the transponder and transponder-dependent systems, and ELT/ULB failure. The first two failure modes involve failures in operations involved with aircraft tracking, while the last two failure modes focus on equipment failure.

Imprecise and infrequent location tracking focuses on the data transmission of information from both radar and satellite sources. Imprecise tracking means that the data given during this transmission is limited in information and lacks important details such as identification of aircraft, 4D location (latitude, longitude, altitude, time), and velocity/heading. This information is crucial for proper flight tracking, and hence making sure that it is transmitted in a frequent manner is also critical for the prevention of aircraft tracking failures.

Radar dead-zones are where traditional SSR does not have extensive reach due to low-density airspace over large bodies of water and includes considerations of diverse technology and operations across different sovereign bodies. As planes fly to their destination, their tracking is typically transferred from one ATC to the next and their location is closely monitored on a radar screen. However, over low-density airspace, plane tracking deviates away from real time tracking and instead information is provided by periodic position reports and voice communications between the flight crew and the ANSP. Therefore, in these dead-zones, aircraft temporarily disappear from radar screens while they are out of range of any ATC. If an accident occurs in these dead zones, such as with AF 447, then ATC is unable to determine exactly where an accident occurred, and only notices that the aircraft failed to appear on the next radar screen in its flight path. Therefore, these radar dead-zones represent a fundamental failure within the operational scope of aircraft tracking, and hence are reflected in all the cases as they all involved aircraft disappearing over a body of water.

Transponders are a crucial piece of equipment within many flight tracking avionics equipment, and so their failure often leads to failures in many other systems such SSR, TCAS, ADS-B, etc. Failure occurs when one becomes inoperable due to an equipment malfunction or when one is manually turned off. Often times, as in the case of MH 370, you cannot distinguish between these two cases but instead you are just aware that a transponder failure occurred due to the disappearance of the aircraft from radar. Therefore, the importance of transponders to aircraft safety cannot be underestimated and measures to ensure proper redundancy and operational procedures should be explored more. Pilots are able to turn off transponders for various reasons First, in the event of a malfunction, disengaging the transponder prevents inaccurate transmissions. Second, in the event of a fire or short circuit, the transponder can be turned off to separate it from the rest of the plane's electrical system [16]. The type of transponder failure is diverse in nature and consequences and is beyond the scope of this investigation, for a more comprehensive discussion of transponder failure, the reader is encouraged to reference EUROCONTROL's analysis of the topic [16]. Ultimately, transponders are disengaged (accidentally and intentionally) with relatively high frequency as a safety barrier to prevent failure propagation; however, many tracking systems are designed to depend solely on transponder function which introduces new problems.

ELT and ULB failures occur at the later stages of the accident sequence and greatly impact SAR efforts [24]. These failures occur when the ELTs and ULBs do not function as expected, such as not being properly activated (e.g. due to internal damage or external component failure) or sending misleading pings. This has major consequences such as severely limiting underwater search efforts and preventing the recovery of the flight data recording system.

The cases in the series exhibited a range of these failure modes. The first case, MH 370, encompassing all of the four failures: radar dead-zone, transponder failure, ELT/ULB failures, and imprecise and infrequent tracking. Case 2, AF 447, encountered two failures: the radar dead zone and ELT/ULB failures. Case 3, the Senegalair 6V-AIM, had a transponder failure and an ELT/ULB failure. Finally, cases 4 and 5, the IAF K-2743 and AX-6, involve radar and ULB failures.

To offer a new perspective on these cases in addition to their common failures, these different failure modes can be mapped to different system safety principles. These principles are concepts introduced by Joseph H. Saleh, Karen B. Marais, and Francesca M. Favaro in their paper 'System safety principles: A multidisciplinary engineering perspective' [17]. Their work has provided the basis for this section in which we elaborate on the significant ties between the location tracking failure modes and the governing system safety principles that were violated. These principles are summarized briefly, and we welcome the reader to read the referenced paper for a deeper understanding of them. Figure 1 maps the most prevalent failure modes to the safety principles violated by each for a visual representation of the connections made in this section.

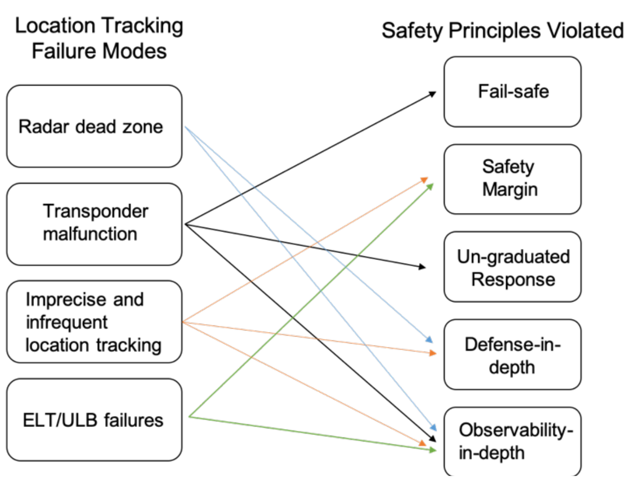

Figure 1. Failure Modes mapped to Safety Principles Violated

The transponder malfunction is in direct violation of the fail-safe safety principle and un-graduated response which occurred on both Case 1, flight MH 370, and Case 3, Senegalair 6V-AIM. The **fail-safe principle** suggests that the failure of an item in a system should result in conditions that block the accident sequence from further advancing or freeze the hazard escalation. Subsequently, the **un-graduated response principle** suggests that the 'kill first' military method or 'eliminating the hazard all-together' must be used prior to adopting 'softer stances' to safety. This provides a methodology for approaching system safety hazards. Perhaps the most critical piece of evidence tying these safety violations to MH370 is that both transponders were only accessible through the cockpit and not designed to automatically switch to the other transponder if one fails. However, the SSR tracking failed, suggesting the transponder was turned off in-flight. As a whole, the transponder is a critical system for determining the relative and absolute locations of aircraft. The fact that multiple systems (TCAS, ADS-B, SSR,etc.) converge at the transponder level indicates the system might benefit from an appropriate fail-safe mechanism. Additionally, while the ability to manually disengage the transponders prevents some types of failures from propagating, using an un-graduated response to not only block propagation but also prevent total system loss as a result. The un-graduated response offers a starting point to structure the system.

Next, the **safety margin principle** highlights how estimated critical hazard thresholds must be considered first and how features must be put in place to operate at some distance away from them. The imprecise and infrequent location tracking and ELB/ULB failure modes are in violation of this safety principle across the five cases. Primarily for the imprecise and infrequent tracking for flight MH 370, the last log on acknowledgement was returned at 0019 UTC as there had been no communication for an hour. Increasing the safety margin for the frequency of communication would have perhaps eliminated a situation in which the SATCOM system would even need to send the aircraft a 'log on interrogation' to check if it was still logged on to the network.

Next, the radar dead-zone failure mode seen in Cases 1and 2 and the imprecise and infrequent tracking failure mode seen in Case 1 are in direct violation of the **defense-in-depth principle**. The defense-in-depth principle proposes multiple lines of safety barriers placed along the potential accident sequences to prevent, block, and contain the damage. Here, an important nuance is that defenses are realized through the barriers and that a safety barrier is an embodiment of the defense. Safety barriers are well implemented and extensively used already which is why air travel is one of the safest forms of travel; however, the effectiveness of a depth of defenses is diminished in cases of radar tracking failure and infrequent/imprecise tracking. In normal operation, tracking is entirely dependent on aircraft operation and the regular communication of location. Even in emergency situations, the passive SAR systems rely on ELTs being manually activated in the cockpit, or automatically activated by the g-load of an impact. The latter of which is known to not be reliable, especially in the event of ditching, and does not provide a last-known location of the aircraft before the crash. **The state of current defenses is the result of a hodgepodge of technological advances that were haphazardly integrated into location tracking systems leaving critical holes in relatively common flight conditions**.

Finally, **observability-in-depth** contributes distinctly from the previous principles and highlights why the truncation of the accident sequence did not happen. Observability in depth allows for a more robust defense in depth strategy, which is dynamic and dependent on emerging risks. The value of observability reduces uncertainty in system failure, which is especially helpful for interactive systems such as location communication between an aircraft, various ATCs, and other aircraft over the course of a flight. Observability-in-depth allows for the full realization of the defense-in-depth principle introduced previously. The systems in question are ultimately human systems, and thus require an understanding of system function on multiple levels and from different perspectives. For example, the failure of a transponder, even in the relatively common case of unintentionally turning the device off, would immediately remove an aircraft from ATC SSR as well as from other aircraft TCAS with no explanation or ability for either side to communicate the failure. Thus, location systems ultimately serve as an interface between humans (in the form of ATC or SAR teams) and aircraft. As such, observability of the operation of various levels of components would mitigate the effects of a failure and allow for a better understanding of exactly how and why these failures occur.

4 Analyzing the Solution Space

4.1 Suggested Requirements in Light of Failure Modes

Current aircraft tracking systems are failing to keep the passengers and pilots safe and accounted for. Rather than working in a regional and national basis, a global network must be put in place to better track aircraft, especially over international waters. A plane should never be unaccounted for from the moment it takes off to the moment it lands. On account of these issues, this section of the paper will give recommendations for potential requirements that can be implemented to change these short-comings. The Aircraft Tracking Task Force (ATTF) and the International Civil Aviation Organization (ICAO) are two organizations working towards pushing these goals forward. The ATTF was established by the International Air Transport Association (IATA) after the disappearance of Malaysian Airlines Flight 370, and the ICAO is a United Nations specialized agency that focuses on supporting a safe, efficient, secure, economically sustainable, and environmentally responsible civil aviation sector.

These organizations have also proposed recommendations for how to go about implementing these changes. The requirements proposed in this section are derived from the ATTF and ICAO, but they are taken a step further by connecting and relating them to the case studies discussed in the previous section [1]. The existing requirements proposed by ATTF are the following: (1) The aircraft tracking functionality should track aircraft within potential areas of operation and range; (2) The tracking should be available and operating while the aircraft is airborne; (3) The information for aircraft tracking should include the aircraft 4D position and aircraft identification; (4) The tracking accuracy of the position should be at least 1 NM or better depending on the aircraft's navigation system capability; (5) The tracking should report at least every 15 minutes; (6) The tracking should be able to increase its reporting rate based on established triggering parameters; (7) Communications protocol must exist between the airline and the air traffic service to facilitate coordination during distress modes; (8) Operators who receive tracking information should ensure that procedures are in place to address instances where required reporting does not occur; (9) New airborne equipment or modification to existing equipment shall meet the appropriate airworthiness requirements.

It is important to note that while all of the requirements listed below may not be feasible with the current technology in the aviation industry, technology is continuously improving and it is imperative to seek design solutions that follow these requirements in order to improve aircraft tracking. The six main requirements noted below are the following: (1) Increase frequency of data transmission; (2) Aircraft tracking information; (3) Ubiquitous map coverage; (4) Functional and reliable transponders; (5) Reliable post-crash tracking; and (6) Practicality. These tracking requirements are mainly time based versus position based.

1. **Increase frequency of data transmission**: In oceanic and low-density airspace, aircraft location is generally tracked at 30 minute intervals [7]. The current 30 minute recording interval shall be decreased to 15 minute recording intervals. By increasing the rate at which airplanes are being tracked, the radius of the search area decreases, therefore increasing the **safety margin** of the tracking system currently in place. During situations of distress, the recording interval shall decrease to 1 minute intervals maximum. As noted from the case studies, a main failure mode is the **imprecise and infrequent location tracking**, so it is crucial to consistently track the aircraft during regular flight time and in distress mode to better prevent their disappearance. The main goal of this requirement is to attain real-time tracking of airplanes, continuously knowing where they are at all times.
2. **Aircraft tracking information:** The type and quality of information acquired from aircraft tracking is critical to understanding their location. The information that shall be recorded are the aircraft's 4D location - latitude, longitude, altitude, and time - as well as the velocity, heading, and identification of the aircraft. The accuracy of the position of the aircraft should be within a range of 1 nautical mile. This information is important to obtain in order to understand how the aircraft is performing and prevent **imprecise location tracking**.
3. **Ubiquitous map coverage**: The Pacific Ocean and Atlantic Ocean both have very low density airspace. These **radar dead-zones** cause a majority of the failure modes seen in the case studies. It is imperative to have extensive aircraft tracking that covers a minimum of 70% of the globe, focusing on the radar dead-zones that ground stations cannot cover [21]. The goal of this requirement is to never lose contact with an aircraft at all points in time, from take-off to landing.
4. **Functional and reliable transponders**: The current location tracking systems in the aviation industry have many components which are failing to fulfill their jobs, and their failures are aggregating accident pathogens. One of the main components creating failure modes are the **transponders malfunctioning**. The solution shall increase the redundancy of the secondary radars, and the transponders shall be redesigned to increase their safety margin. The goal of this requirement is to remove the known accident pathogens and to increase the reliability of the transponders.
5. **Reliable post-crash tracking**: A main cause of concern to the flying public has is that there have been

aircraft accidents that to this day have not been found. There are **ELT and ULB failures** happening at an alarming rate, and they have yet to be improved. Currently, automatic ELT's experience a 60% failure rate [8]. To reduce this failure mode, a large amount of redundancy should be added for the ELT's, as well as a redesign that takes into account waterproofing, fire protection, crash resistance, and adequate battery maintenance. The ULB's should also have added redundancy and should be able to work for 90 days after the accident, as opposed to the current time of 30 days [7]. The objective of this requirement is to improve aircraft tracking post-accident in order to retrieve the craft and its contents [23].

6. **Practicality**: The solution shall be easy to integrate and install on the aircraft and ground stations. A reasonable cost for the system shall also be taken into consideration. With these requirements, a large amount of data will be collected which needs to be parsed through and stored properly. The data collected from each flight shall be stored for a minimum of 6 months after the flight-time.

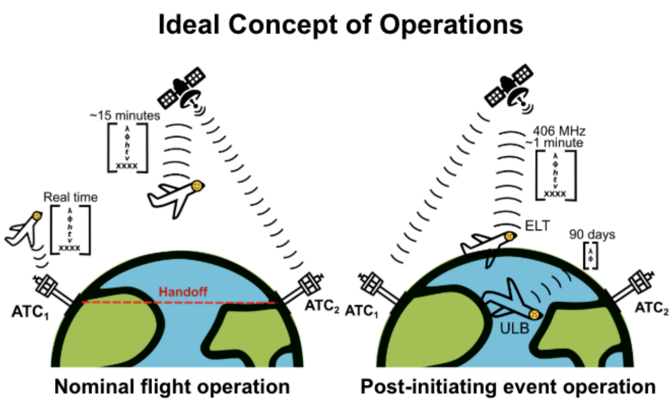

Figure 2: Ideal Concept of Operations

Since these requirements cover the entire timeframe of the accident sequence, they can be represented as an ideal concept of operations as seen in the accompanying Figure 2. This figure shows the data transmission exchange between the aircraft, ATC, and a satellite as it crosses over the ocean in low density airspace. Two ATCs are shown to represent the importance of a proper handoff between ATCs in different entities, and a satellite is shown to represent a possible solution to the lack of ubiquitous radar coverage. The full range of information and frequency intervals are expressed from Requirement 2, and two separate concepts of operations exist to show the difference in requirements between nominal operations and post an initiating event where the aircraft is in distress mode and ELTs are activated. In case of an aircraft crash, ULBs are included with their new 90 day designated time frame for operation. Overall, this figure emphasizes how the suggested improvements to the requirements focus on changing the operational procedures of location tracking in order to alleviate the effects and consequences of aircraft disappearance.

4.2 Analysis of Existing and Potential Solutions

This section analyzes the existing and near-term solutions in the context of the suggested requirements in Section 3.1. The six aforementioned requirements directly correspond to the benefits and limitations of the technologies highlighted in this section. The existing solutions include: Primary Surveillance Radar (PSR), Secondary Surveillance Radar (SSR), ACARS, and GNSS. The near-term solutions include ADS-B, ADS-C and most recently, Space-based ADS-B.

As seen in Table 2, the limitations of the existing solutions are primarily not meeting Requirements 1, 2 and 3. They do not have frequent, 4D and ubiquitous map coverage. While ADS-B and ADS-C have made strides to improve upon those limitations, and largely satisfy Requirement 2, Requirements 1 and 3 are still in question. Most importantly, ADS-B remains still not ubiquitous when operated from ground-based systems. Hence Space-Based ADS-B bridges the gap between the limitation and the evolution of technology. Space-based ADS-B is set to be fully operational by November 2020, operated by Aireon as a service provider to ANSPs at large. While it continues to make progress in being implemented, only Requirment 6, its practicality remains in question. Meanwhile, the expensive high frequency data transmissions from the ADS-C continue to serve the market and provokes us to believe that an entire untapped market of technological innovations is set to unfurl upon us in the next few years with more rows added of new, competing technologies. These will likely, improve upon and eliminate most limitations altogether.

5 Conclusion

This work brings together very important factors on how to improve aircraft tracking. The main objective of the work is to inform how in-flight aircraft tracking can be improved by increasing the frequency of data transmission and breadth of information, creating specialized procedures for tracking when the aircraft is in distress mode, and improving the post-accident tracking systems. Through a case series of accidents, the work identified recurring failure modes in aircraft tracking, encompassing the flight and accident sequence. The four main failure modes taken into consideration were radar dead-zones, transponder malfunction, imprecise and infrequent location tracking, and ELT/ULB failures. The focus was heavily put on radar dead-zones and imprecise and infrequent location tracking due to the broad scope of the failures, and the objective was not to go into specific details about particular avionics. In light of the failure modes, requirements were suggested along all stages of the accident sequence, emphasizing the most critical and fixable ones. A new concept of operations was also suggested for both nominal and post-event flight tracking. Furthermore, existing and potential solutions were analyzed based on said requirements.

There is an integral relationship between in in-flight aircraft tracking and post-crash aircraft tracking, because better in-flight tracking leads to better post-crash tracking. An increase in tracking data quantity from increased frequency of data transmission leads to a decreased search area. For example, an interval tracking every 15 minutes yields a search area of about 44,788 square miles, but compared to a tracking interval of 1 minute, the search area is reduced over 99 percent to approximately 154 square miles [10]. It is important to note that implementing the recommended requirements demands a vast amount of coordination between many organizations and governing bodies, and this should be taken into account for the future.

Table 2: Existing and Future Solutions

Technology	Description	Time to Market	Benefits	Limitations
Primary Surveillance Radar	Indicates the position of the targets Not transponder dependant	Existing	No on-board equipment in the aircraft is necessary (Req. 6)	Not ubiquitous (Req. 3) Does not identify target (Req. 2)
Secondary Surveillance Radar	Indicates position and identification Transponder dependant	Existing	Provides data link Available over long ranges (Req. 2)	Not ubiquitous (Req. 3)
ACARS	Position report every 10 minutes Increased reporting frequency in unanticipated altitude changes/ flight levels below a safe altitude	Existing	Redundancy to communication channels (Req. 4) Independent of ADS-C (Req. 2)	High cost of data transmission - can lead to less information and less frequent use (Req. 1 & 2) No real-time capabilities (Req. 2)
GNSS (ABAS) (RAIM)	Transmit info through satellite relay Small avionics devices attached to airframe	Existing	Global coverage (Req. 3)	Only 4 dominant providers - USA, Russia, China, Europe (Req. 3)
ADS-B	Broadcasts position, altitude, and vector by other aircraft, vehicles, and by ground facilities Transponder dependent	Near-term	Widely available (Req. 6) Breadth of information (Req. 2)	Not ubiquitous (Req. 3)
ADS-C (ANSB or OCC)	Explicit contract between an ANSP and an aircraft Most often employed in the provision of ATS over low density areas	Near-term	Breadth of information (Req. 2) Uses existing equipage (transponders) (Req. 6)	Expensive high-frequency data transmission (Req. 1)
Space-Based ADS-B	Projected to provide 100% surveillance of air traffic globally Transponder dependant	Near-term	Most ubiquitous option (Req. 3) Uses existing equipage (ModeS transponders) (Req. 6) Reliable post-crash tracking (Req. 5)	Full operational service planned for November 2020 (Req. 6) No current competition Only one current provider (Req. 6)

There is a fair amount of future work that needs to be considered. Although practicality is a requirement, cost considerations, competition, and ease of implementation are very distinct works which require a great deal of research and study. This work is unable to conduct a cost comparison of different solutions since Aireon is currently the only space-based ADS-B company attempting to create a solution. Further work also needs to be done to decide how and when an aircraft is in distress mode because this will affect how the aircraft is being tracked, such as the frequency of the data transmission. This decision should specify what events cause a plane to go into distress mode and what sensors determine this. There is also a problematic ability that allows the flight crew to disable avionics (transponder, ACARS) during an emergency which needs to be addressed. For example, during MH 370, it was noted that the transponder might have been manually disabled by a member of the flight crew which led to its disappearance from radar screens. While it is important to have the ability to manually turn off transponders in case of power issues and others, they are also crucial for ATC operations. This topic therefore is immensely complicated, and thus would be interesting to explore more in depth. This aligns with what the ATTF concluded in their report, as they stated that "any changes to the ability to deactivate equipment on board aircraft are a long term prospect owing to significant design, operational, certification, and procedural considerations" [1].

The relationship between flight tracking and flight data recording is another integral part of aircraft tracking that should be addressed in future work. Since ULB's are used to find Flight Data Recorders (FDRs), also known as black boxes, it would be easier to locate the aircraft and obtain the black box if more tracking data is available. Although, on a different note, if FDRs are stored in the cloud, then there would be less speculation about aircraft accidents leading to a decrease in strenuous search efforts for the missing aircraft.

To conclude this work, new technology such as Space-based ADS-B, High-Throughput Satellites, and ADS-C could be the future of aircraft tracking. Private companies such as One Web, ViaSat, and many more are reaching into the commercial airline data streaming market, which raises one question: if we can stream a movie or conduct high frequency trades on a flight over the ocean, why are we not able to track airplanes in real-time? There are many potential solutions in the work, such as the Black Box in the Cloud from Inmarsat aiming to use satellites to do just this, and space-based ADS-B from Aireon. There is still plenty of work to be done in this sector, and it could take years before solutions are implemented, but as new products and technology become available, it is important to remember the requirements needed to create these solutions and their roots.

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Appendix A: Instances of serious location tracking failure in aviation incidents and accidents since 1973

Aircraft	Date	Location	Failure Description	Consequence
B707	7/22/73	Papeete, Tahiti	Recorders never recovered	ULB failure
B707	1/30/79	Tokyo, Japan	Aircraft never recovered	Total ELT/ULB failure
DC3	10/3/80	Mediterranean Sea	Plane had no working radio equipment. This day a VHF radio was installed but not working	Loss of communication; plane never located
DC3	4/21/81	Mediterranean Sea	Radar contact lost over the Mediterranean Sea	Loss of communication; plane never located
C210M	8/9/81	Barrington Tops National Park, Australia	Crashed into sea, ELT failed to function	Plane never recovered
Learjet 35	2/12/83	Straits of Malacca	Lost radio contact, ELT failed to function	Plane never recovered
C172	7/30/83	Lake Tekapo, New Zealand	Presumed to crash in adverse weather conditions; ELTs failed to function	Plane never recovered
BN2A	9/2/83	Smithers, BC, Canada	No radar hit, visual search failed	Plane never recovered
DC47	10/31/84	Davao, Philippines	Lost radio contact, ELTs failed to function	Plane never recovered
Pitts S-2	9/16/85	Pacific Ocean	Crash during filming for *Top Gun*, ELT failed to function	Plane never recovered
IAI 1124 Westwind	10/10/85	Sydney, Australia	CVR had no ULB, FDR's ULB damaged on impact	ULB failed to function
An-32	3/25/86	Off Jamnagar, India	Indian Air Force ferry lost radio contact 1 hour and 18 minutes after takeoff	Plane never recovered
DHC6	8/3/86	St. Vincent and the Grenadines	Crash during inclement weather, ELT failed to function	Plane never recovered
B747	11/28/87	Mauritius	ULB failed to function	FDR never recovered
BN2A	12/4/87	Mount Waddington, BC, Canada	Difficult terrain to search, ELT failed to function	Plane never recovered
DC47	1/17/89	La Paz, Bolivia	Difficult terrain to search, ELT failed to function	Plane never recovered
F27	8/25/89	Himalayan mountain range	Plane presumed to have crashed in the Himalayan mountains	ELT failed to function
B727	9/11/90	Newfoundland, Canada	ULB failed to be recovered	Aircraft never located
DHC6	1/10/95	Molo Strait, Indonesia	Missing in bad weather, ELT failed to function	Plane never recovered
DC9	5/11/96	Everglades, Florida	FDR's ULB inoperative and CVR's ULB detached	ULBs failed to function
B757	10/2/96	Pasamaya, Peru	One ULB detached	ULB failed to function
B767	11/23/96	Moroni, Comoros Islands	Hijacking and subsequent crash	Aircraft never located; ULBs never located
C180	11/8/97	Waiatoto River, New Zealand	Went missing with no location transmitted	Plane never recovered
B737	12/19/97	Palembang, Indonesia	Both ULBs detached	ULBs failed to function
An-72	12/22/97	Off Côte d'Ivoire	Missing cargo flight over ocean, ELT failed to function	Plane never recovered

Aircraft	Date	Location	Failure Description	Consequence
MD-11	9/2/98	Halfax, Canada	ULBs almost detached	Partial ULB failure
B767	10/31/99	Nantucket, USA	CVR's ULB detached	ULB failed to function
A320	8/23/00	Muharraq, Bahrain	Both ULBs detached	ULBs failed to function
ATR72	12/21/02	Pengu Island, Taiwan	CVR's ULB detached	ULB failed to function
B727	5/25/03	Luanda, Angola	Plane stolen from airport, taxied and took off without turning on communications or contacting ATC	Plane never recovered
B737	1/3/04	Sharm el-Sheikh, Egypt	CVR's ULB detached	ULB failed to function
F15/E145	1/27/05	Bedford, UK	Mode C altitude disappeared from radar as F15 entered new airspace	Loss of separation
H25B/AS29	8/28/06	Smith, Nevada	Glider turned off transponder to conserve power	In-flight collision
B738/E135	8/29/06	Mato Grosso, Brazil	E135 crew inadvertently turned off transponder, ATC assumed it followed directions when it subsequently disappeared from the radar	In-flight collision, 154 casualties
Metro III	4/9/08	Sydney, Australia	FDR's ULB detached	ULB failed to function
Beechcraft 65A	11/1/08	Guyana	Crash in heavily forested terrain, ELT failed to function	Plane never recovered
A320	11/27/08	Perpignan, France	CVR's ULB detached	ULB failed to function
A330	**6/1/09**	**Atlantic Ocean**	**ULB search failed to find wreck, Bayesian search method eventually prevailed**	**ULB failed to function properly**
A310	6/30/09	Moroni, Comoros Islands	Both ULBs detached	ULBs failed to function
A320	10/21/09	Denver, Colorado	Pilots distracted by conversation failed to maintain radio contact with ATC for over an hour	Loss of situational awareness
B737	1/25/10	Beirut, Lebanon	CVR's ULB detached	ULB failed to function
R44	1/2/11	Argentina	Helicopter did not maintain radio contact; no ELT was found	Helicopter never recovered
TBM8	1/12/11	Birmingham, UK	Loss of radio contact resulted in loss of separation on landing	Near miss
B752	3/11/11	Atlanta, Georgia	PM did not set transponder frequency correctly; plane flew for 8 minutes with no secondary radar surveillance	Loss of Separation
B744	7/28/11	East China Sea	ELT activated but inoperative due to water immersion	ELT signal not received
C30J	3/15/12	Northern Sweden	ELT damaged in crash	ELT failed to transmit
B190	3/17/12	Blue River, BC, Canada	Impact forces below threshold for ELT activation	ELT failed to activate
F100/EC45	5/24/12	Bern, Switzerland	Failure to follow TCAS RA, STCA installed at Bern had been disabled for years	Near miss
C525/P180	3/22/13	Sion, Switzerland	Neither aircraft's ACAS issued collision warning, STCA partially effective	Loss of separation

Aircraft	Date	Location	Failure Description	Consequence
Beechcraft 1900C	4/7/13	Near São Tomé Island	Crash in ocean due to weather, ELT never found	Plane never recovered
A319	4/12/13	Mumbai, India	Radio failure after frequency change	Landing without clearance
S76	5/31/13	Moosonee, Ontario, Canada	Tailboom-sited external antenna severed in crash	ELT failed to function
B788	7/12/13	London Heathrow, UK	ELT lithium-metal batter caught fire when plane was unoccupied and unpowered	Airworthiness problems
A320/B738	9/2/13	Delhi, India	ATC error while below height where TCAS RAs are functional	Loss of separation
E190	11/29/13	Bwabwata National Park, Namibia	Broken co-axial cable that linked unit and antenna	ELT failed to function
B777	**3/8/14**	**Indian Ocean**	**Flight MH370 disappeared unexpectedly, ELTs and ULBs did not operate properly**	**Aircraft never located; ULBs never located**
B738/C172	7/20/14	Falsterbo, Sweden	C172 Mode C-capable transponder did not transmit altitude, invalidated ATC/TCAS safety barriers	Loss of separation in restricted airspace
MD83	7/24/14	Gossi, Mali	ELT damaged in crash	ELT signal not received
A320/B738	10/30/14	Córdoba, Spain	Ineffective monitoring of TCAS separation warning	Loss of separation
C130/C27J	12/1/14	Mackall AAF, North Carolina	Unnecessary over reliance on TCAS	Mid-air collision
BN2	12/28/14	Guyana	Plane failed to arrive with no radio contact, 21-day search found no ELT or ULB signals	Plane never recovered
E170/F900	6/30/15	Varna, Bulgaria	E170 failed to notice transponder reverted to Standby; slow ATC response due to handoff between stations	Loss of separation
F16/C150	7/7/15	Berkeley County, South Carolina	Failure of radar control on F16; failure of see-and-avoid	Mid-air collision, 2 casualties
HS125/B737	**9/5/15**	**Off Dakar, Senegal**	**Malfunctioning transponder resulted in collision with B737, HS125 continued until eventual crash due to loss of fuel**	**Mid-air collision, Aircraft never recovered**
UAV	2/29/16	Reims, France	Improperly manufactured co-axial cable assembly and software flaw	Loss of separation, crash
A319/AS32	6/27/16	Marseille, France	Helicopter operating with failed single transponder, loss of radio contact	Near miss
An-32	**7/22/16**	**Bay of Bengal**	**Disappeared east of Chennai, ELTs and ULBs never recover**	**ELTs and ULBs failed to function**
DH8D/DH8D	10/12/16	Sudbury, Ontario, Canada	Both crews ignored TCAS RAs	Loss of separation
DH8B/BN2P	10/12/16	Horn Island, Australia	BN2P aborted approach due to DH8B takeoff, the latter relied too heavily on TCAS for takeoff and did visually look for BN2P	Runway Incursion, Loss of separation
PA28	6/8/17	British Columbia, Canada	Two-week visual search failed to find wreckage, unknown if ELT was onboard, radio contact not maintained during flight	Plane never recovered

Aircraft	Date	Location	Failure Description	Consequence
EMB720	12/2/18	Brazil	Aircraft crashed deep in the Amazon rainforest	ELTs and ULBs failed to function
PA32	2/1/19	Palm Beach, Florida	Presumed crash in bad weather, equipped with Mode-S transponder, no ELT or ULB found	Plane never recovered
F35A	**4/9/19**	**Aomori Prefecture, Japan**	**High speed impact damaged emergency location and data recording systems; aircraft disappeared from radar before crash**	**Loss of radar contact, ULBs partially failed**