A System Theoretic look at Severe Weather Encounters

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Abstract

Each year passengers and cabin crew are injured or worse, and aircraft are damaged when encountering unexpected turbulence or hail when operating in the vicinity convective weather. In many cases the pilots did not appear to be aware of the presence of convective weather prior to the encounter. In addition, despite more knowledge and training, pilots are still encountering microbursts and downbursts. This is in the face of advances in automated onboard radar systems, ground and satellite-based systems and continuing research. Understanding and preventing future events requires moving beyond the superficial aspects and delving deeper into the decision-making process that led up to the encounters.

Most current accident causal analysis is based on linear chains of events, each event leading to the next one in the chain until the loss occurs. The events are caused not only by previous events but also by existing conditions. While the linear chain of events is usually identified in an accident investigation, some of the conditions that indirectly contributed to the loss are often omitted. These systemic or indirect causes may be among the most important to change in order to prevent losses in the future. In this paper, I will present a structured, organized way to find these factors.

This paper and presentation used the System Theoretic Accident Models and Processes (STAMP) Causal Analysis using System Theory (CAST) method to analyze several events. CAST is a new analysis method based on system theory and provides a path to understanding the entire socio-technical system involved in an accident or incident. Rather than just superficial errors, the CAST methodology is designed to identify the contextual factors that result in both human and software decision making.

From this framework, the paper and presentation explores new and recent research into the nature of convective weather that can result in radar signatures that may not present in the manner that pilots have been taught to expect. This will be examined for convective storms over various regions of the world as well as a discussion about some techniques that might provide a path forward to identify some of these threats.

1.0 Introduction

Most accident analyses are based on *ad hoc* approaches. Many formal analysis techniques have been proposed, but few are widely used. This case study shows how a structured process called

CAST (Causal Analysis based on Systems Theory), based on a more powerful model of accident causation, can improve the results of accident investigation.

CAST[1] is based on an expanded accident model called STAMP (Systems-Theoretic Accident Model and Processes) [1]. Traditionally, accidents have been thought of as resulting from a chain of failure events, each event directly related to the event that precedes it in the chain. For example, the baggage door is not completely closed, the aircraft climbs to a level where unequal pressure between the cargo compartment and the passenger cabin causes the cabin floor to collapse, the cables to the control surfaces (which run through the floor) are severed, the pilots cannot control the aircraft, and the plane crashes. The biggest problem with such a chain-of-events model is what it omits. For example, why did the design of the baggage door closure mechanism make it difficult to determine whether it was effectively sealed? Why did the pilots not detect that the door was not shut correctly? Why did the engineers create a design with a single point failure mode by running all the cables through the cabin floor? Why did the FAA certification process allow such designs to be used? And so on. While these additional factors can be included in accident investigation and analysis, there is no structured process for making sure that "systemic" causal factors are not missed.

STAMP extends the traditional model of accident causation to include the chain-of-events model as one subcase but includes the causes of accidents that do not fit within this model, particularly those that occur in the complex sociotechnical systems common today. These causes (in addition to component failure) include system design errors, unintended and unplanned interactions among system components (none of which may have failed), flawed safety culture and human decision making, inadequate controls and oversight, and flawed organizational design. In STAMP, accidents are treated as more complex processes than simple chains of failure events. The focus is not simply on the events that led to the accident, but *why* those events occurred.

The other significant difference is that, instead of focusing on failures, STAMP assumes that accidents are caused by a lack of effective enforcement of safety constraints on the system behavior to prevent hazardous states or conditions. Thus, safety becomes a control problem, not a failure problem. Controls are created to prevent hazards, such as a stall. Such controls clearly include pilot knowledge, but they also include the aircraft envelope protection system, the aircraft warning systems, pilot training, standards, government regulation and oversight, etc. Theoretically, the extensive controls that have been introduced to eliminate stalls should have prevented the accident. Why didn't they? How can we learn from the accident to improve those controls?

Because individual controls and controllers may not be adequate or effective, there are almost always many types of controls used. The goal of accident analysis should be not to identify someone to blame (in practice this is usually the flight crew) because they did not satisfy their particular role in preventing a hazard such as avoiding a thunderstorm, but to identify all the flaws in the safety controls that allowed the events to occur, to understand why each of these

[1] Unfortunately, the acronym CAST for this accident analysis approach has an important conflict in the aviation community. CAST has been used as an accident analysis technique for close to 20 years in the safety community and for about the same time in aviation to denote Commercial Aviation Safety Team, without either group being aware of the conflict. In this paper, CAST appears only as a reference to the accident analysis technique

controls was not effective, and to learn how to strengthen the controls and the design of the safety control system in general to prevent similar losses from occurring in the future.

Typically, the listed “Causes of the Accident” focus primarily on the flight crew behavior and the events in the event chain reflecting flight crew actions. A system’s approach looks not only at what human operators (such as pilots) did that contributed to an accident but, more important, *why* they believed it was the right thing to do at that time [2]. Although the latter may be addressed, a systems approach will look at these aspects more deeply in that the entire system for preventing the weather encounter is examined and not just the pilot behavior. How did the system design influence the events and the flight crew’s behavior? Why were the design controls to prevent the encounter not effective?

In this approach, safety is treated as a *control* problem, not a *failure* problem. Commercial aviation has many controls to prevent convective weather encounters. To maximize learning from the events, focus in CAST is on why the controls were not effective in this case and how they can be improved for the future. Most of the emphasis is on explaining why the flight crew and others behaved as they did, i.e., why it made sense to them to do what they did [2], and why the controls to prevent such behavior were not effective.

CAST tries to avoid *hindsight bias* by assuming that the humans involved (absent any contradictory information) were trying to do the right thing and did not purposely engage in behavior that they thought would lead to an accident. After an accident, it is easy to see where people went wrong, to determine what they should have done or not done, to judge people for missing a piece of information that turned out to be critical, and to blame them for not foreseeing or preventing the consequences [2]. Before the event, such insight is difficult and, usually, impossible. The Clapham Junction railway accident in Britain concluded: “There is almost no human action or decision that cannot be made to look flawed and less than sensible in the misleading light of hindsight” [3]. CAST attempts to eliminate hindsight bias as much as possible from accident analysis. Simply listing what people did wrong provides very little useful information about how to eliminate or mitigate that behavior.

CAST is most effective when used during an investigation to generate the questions that should be answered. Many of the questions generated during the CAST analysis are not answered in the official reports and therefore were left as questions in the CAST analysis.

A major advantage of the CAST methodology is completeness. While other methods, rely on finding a way to identify various failure modes that are then analyzed. This is true for Bow-Tie, Event Tree, Fault Tree, HFACs, and all other linear methods. By contrast, CAST enables both finding as well as analyzing failure modes that would otherwise not have been considered.

2.0 Statement of the problem

Turbulence injuries in air carrier operations can be broadly classified into two groups, one is generally attributed to clear air turbulence the second to convective weather (thunderstorms). Other sources involve orographic (wind over terrain) and wake turbulence from other aircraft.

Each of these categories has somewhat different mitigation strategies, but this paper will be limited in scope to convective weather.

Although accidents due to microburst/downbursts have diminished in recent years, the threat still exists. The implementation of microburst detection systems at many U.S. airports, coupled with onboard so-called predictive windshear systems and enhanced training have all contributed to this reduction, although accidents still occur, particularly at airports not protected by microburst detection systems.

Dr. Pam Knox, and her husband, Dr. John Knox study, teach and publish on topics involving atmospheric dynamics at the University of Georgia. Each have remarked to me that the turbulence, and intensity and quantity of convective storms will increase due to climate change providing more energy. This has been echoed by Dr. Julie Haggerty at the National Center for Atmospheric Research (NCAR) in Boulder, Colorado. This results in an increasing risk for aircraft encounters.

3.0 Convective Related Accidents and Incidents

Although there are many to choose from, for the purpose of this paper and presentation I am going to concentrate on just a few accidents and incidents. The specifics of the cases are not critical but will be used to build a generic model for cruise events and another for those occurring during the approach and departure phases.

3.1 Cruise Portion

The following accidents and incidents were used to examine events in the cruise phase of flight.

3.1.1 Air France 447

On June 1st, 2009, an Air France Airbus 330, flight 447, crashed after encountering high altitude ice crystals (HAIC) during cruise flight at night over the Atlantic ocean [4]. The complexities that the encounter created for the pilots is beyond the scope of this paper[2], here we look only at the aspects that lead to the encounter itself.

Approaching an area of convective weather, the pilots manually adjusted the gain on the radar to make any weather returns more prominent. There is no indication that they also adjusted the radar tilt setting. Turning away from an area that displayed once the gain was increased, the aircraft flew into an area of HAIC. This encounter resulted in the loss of all three airspeeds and a series of following events. It is important to note that had the flight not encountered HAIC the accident would not have occurred.

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[2] For a deeper understanding of the factors that lead to the accident after the encounter with HAIC the reader is referred to Rapoport and Malmquist (2017).

3.1.2 Hawaiian 35

On December 18, 2022, a Hawaiian Airlines Airbus A330 encountered severe convective turbulence. The crew stated that they were in clear skies with the onboard weather radar showing no returns. The crew stated that a "cloud shot up vertically (like a smoke plume) in front of the airplane in a matter of seconds…" There was not enough time to avoid the weather and a number of people were injured [5].

3.1.3 ExpressJet 4538

The weather radar has several features, such as range, tilt (manual control of the antenna angle), and gain (how much of the energy leaving the antenna is focused in a particular direction), which must be used correctly during operation. If these tools are improperly managed, weather targets can be missed or underestimated [6]

There were no reported problems with the on-board weather radar system. If the flight crew were operating the unit within its limitations, thunderstorms should have been displayed to them at some point [6].

3.1.4 Delta 1889

On August 7, 2015, at 2002 mountain daylight time, the crew of a Delta Airlines Airbus A-320 operating as flight 1889 between Boston and Salt Lake City declared an emergency and diverted to Denver after penetrating a thunderstorm and incurring hail damage to the cockpit windows and airframe (figure 1). The flight was being operated by an experienced professional crew, actively monitored by a certified dispatcher, and receiving air traffic services from a controller with NEXRAD precipitation data superimposed on his radar traffic display. The control facility involved also had an NWS meteorologist on duty with full access to multiple sources of weather information. Nonetheless, an air carrier aircraft with 124 people aboard experienced a hazardous encounter with convective weather [7].

3.1.5 NTSB Paper: Preventing Turbulence-Related Injuries

In 2021 NTSB published a research report [8] on Preventing Turbulence-Related Injuries in Air Carrier Operations. Although the report including a number of factors and mitigations, pertinent to this paper and presentation, the following paragraphs are beneficial:

> Regarding use of weather radar, pilots reported that use of weather radar was covered in training but that it was mostly learned on the job during initial operating experience and that weather radar training quality depended on the trainer (P. 30).
>
> The captain described the turbulence as "very violent and very quick" and stated that, at the time of the turbulence encounter, the airborne weather radar only displayed indications of light rain. However, the aircraft had entered or was very near an area characterized by hail activity according to the Cooperative Institute for Mesoscale Meteorological Studies' severe hail index, as shown in figure (p. 48).

These aspects provide a basis for understanding why pilots might be flying into convective weather.

3.2 Terminal Environment Weather

The following accidents were used for examining the terminal environment.

3.2.1 Delta 191

As the exceptionally experienced crew of Delta 191, a Lockheed L1011, descended into the Dallas-Fort Worth (DFW) area, thunderstorms were developing. As the flight turned to final they saw that there was weather in the area. It is not known what the radar might have been indicating, but presumably the crew was using the standard manufacturer guidance of tilting the radar just high enough to eliminate ground returns. There was some rain on final, but the aircraft landing in front of them had no problems. A Learjet landed just ahead of them and only encountered rain. Delta 191 encountered a severe microburst and crashed [9].

3.2.2 USAir 1016

On July 2, 1994, a USAir Douglas DC-9 crashed after encountering a microburst on approach to the Charlotte/Douglas International Airport in Charlotte, North Carolina [10]. The accident had similarities to several other accidents that had occurred previously.

As USAir 1016 maneuvered for the airport the storm did not raise any particular concerns, with the crew having visual contact with the airport (p.4). There was what was considered a small weather cell in the vicinity of the approach end of the runway (p. 21), and as the flight turned towards the airport they could still see the runway with just a thin veil of rain between them and the airport (p. 5). Further bolstering the crew's confidence that it was safe to continue, the air traffic controller informed them that a Fokker FK-28 (a smaller aircraft) that had landed 4 minutes earlier reported a "smooth ride all the way down final", as did another flight ahead of them (p. 4).

The pilots were aware that a storm was growing over the approach end of the runway, and discussed a plan of action should they need to abort the approach (p. 4). Despite this, the flight encountered a microburst at 1842 local time and crashed during an attempted go-around (p. 6).

4.0 CAST Methodology

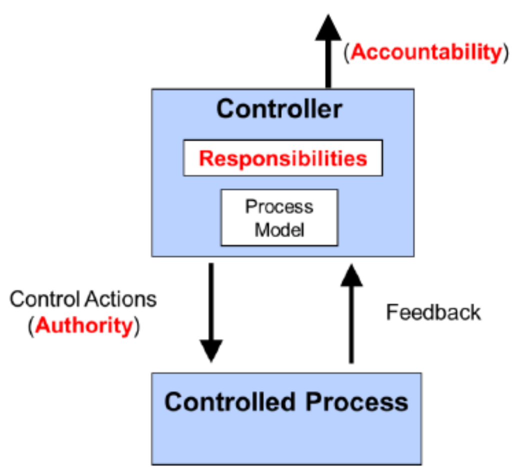
Aviation has an excellent safety record and learning from past events has led to many controls being introduced into the system. The goal of the CAST analysis is to determine why the controls (as a whole) were ineffective in preventing the current loss. To accomplish this goal, a model is first created of the current controls and overall control structure. This model then becomes the focus of the analysis.

The control structure uses the basic engineering concept of feedback control. Figure 1 shows a simple feedback control loop. The usual requirements for effective management—assignment of responsibility, authority, and accountability—are mapped onto this control loop. The controller has responsibilities assigned to it with respect to enforcing the system safety constraints. It satisfies these responsibilities by issuing control actions on the process it is controlling (representing its authority). The controller can determine what type of control actions are required to satisfy its responsibilities for preventing hazards given the current state of the controlled process, as identified through feedback from the controlled process.

As an example, The FAA has responsibilities related to overseeing the safety of flight in the U.S. They have various types of control actions to carry out their responsibilities, such as airworthiness circulars and directives, FAA regulations, handbooks and manuals, Notices to Airmen (NOTAMs), policy and guidance, etc. Feedback comes in the form of reporting systems, accident and incident analyses, audits and inspections, etc. to determine the current state of safety of the air transportation system. Ultimately, they are accountable to the U.S. Dept. of Transportation, Congress, and the executive branch.

Figure 1

Simple Control Loop



Leveson, Simple Control Loop, Figure , 2012

Feedback information is incorporated into the controller's model of the controlled process, called the *process model* or, if the controller is a human, it may be called the *mental model*. Accidents often result when the controller's process model becomes inconsistent with the actual state of the process and the controller provides unsafe control as a result. For example, the air traffic controller thinks that two aircraft are not on a collision course and does not change the course of one or both. Other examples are that the manager of an airline believes the pilots have adequate training and expertise to perform a particular maneuver safely when they do not or a pilot thinks that de-icing has been accomplished when it has not.

There are four general types of unsafe control actions:

- A provided control action leads to a hazard: e.g., a pilot turns to a heading when there is a convective weather in front of them.
- Not providing a necessary control action leads to a hazard: e.g., a pilot does not turn away from a heading with convective weather in front of them.
- A control action provided with wrong timing (early, late) or control actions in the wrong order leads to a hazard: a pilot starts a turn too early or too late resulting in flying into convective weather.
- A continuous control action provided for too long or too short a time leads to a hazard: e.g., the pilot is told to continue to climb to 30,000 feet (to avoid weather) but instead levels off at 25,000 feet.

These four types of unsafe control actions, along with the hierarchical safety control structure, can be used after an accident to generate the causal scenarios that led to the loss or to identify future potential accident scenarios so they can be eliminated or mitigated in the system design.

Problems can occur not just because of inconsistency between the controller's process model and the state of the controlled process but also when different controllers, all involved in the same general task—particularly under safety-critical or emergency conditions—are operating with different mental models of either (a) what the system is currently doing, or (b) what should be done to control it. Process models are kept up to date, as stated, through feedback or from information received externally. A common factor in accidents is that appropriate feedback or other information about the state of the controlled process is incorrect, missing, or delayed, for example in several of the thunderstorm encounters the pilots did not see any weather returns on their onboard weather radar. The use of the process model concept is a much better way to understand why humans or software may have done the wrong thing and how to prevent such events in the future than simply saying the human or software or organization "failed," which only attaches a pejorative word without providing any insight about *why* the person or software did something dangerous.

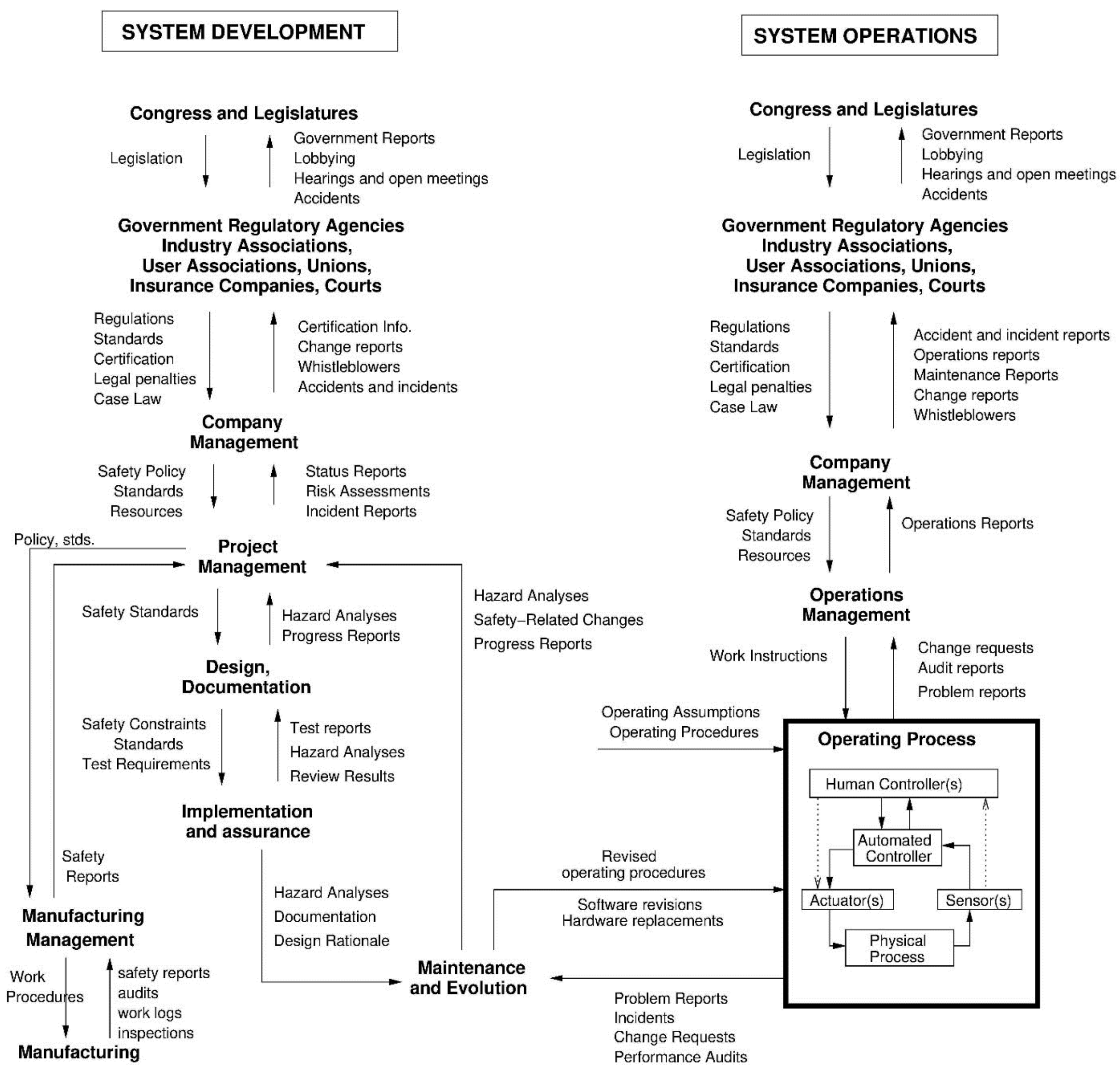
The basic control loop shown in Figure 1 is combined with others to create the more complex control structure in real safety control systems. Figure 2 shows a generic example of a safety control structure. The controls related to development are shown on the left and those relating to operations on the right. The downward arrows represent control actions while the upward arrows show feedback. Each level of the control structure controls the components at the level below.

There is usually interaction between parallel control structures. Manufacturers must communicate to their customers the assumptions about the operational environment in which the original safety analysis was based, e.g., maintenance quality and procedures, as well as information about safe operating procedures. The operational environment, in turn, provides feedback to the manufacturer about the performance of the system during operations. Each component in the hierarchical safety control structure has responsibilities for enforcing the safety constraints appropriate for that component. Taken together, the entire control structure should prevent or mitigate hazardous system behavior.

Note that the use of the term “control” does not imply a rigid command and control structure. Behavior is controlled not only by engineered systems and direct management intervention, but also indirectly by policies, procedures, shared value systems, and other aspects of the organizational culture. All behavior is influenced and at least partially “controlled” by the social

Figure 2

Example Control Structure



Leveson. A generic example safety control structure. Figure 2, 2012

and organizational context in which the behavior occurs. Engineering (i.e., designing) this context can be an effective way to create and change a safety culture, i.e., the subset of organizational culture that reflects the general attitude about and approaches to safety by the participants in the organization or industry [11]. Examples of control in this context can be the type of control that ATC exercises over aircraft. It is not a direct control, but rather can be seen to be a constraint on the behavior of the aircraft, just preventing airplanes from getting to close to each other. Another example is the way that ICAO provides some controls to each of the signatory state's regulator agencies.

4.1 CAST for Convective Weather

There are four steps for the CAST process:

1. Describe proximate events. This is done to provide a basic understanding of what occurred. The basic proximate events were described previously.
2. Create a control structure. This enables us to visualize the controls that are in place in prevent an accident.
3. Analysis of the components of the control structure.
4. Examine factors spanning components. These include:
    a. Industry and organizational safety culture
    b. Safety information system
    c. Dynamics and changes over time
    d. Communication among controllers

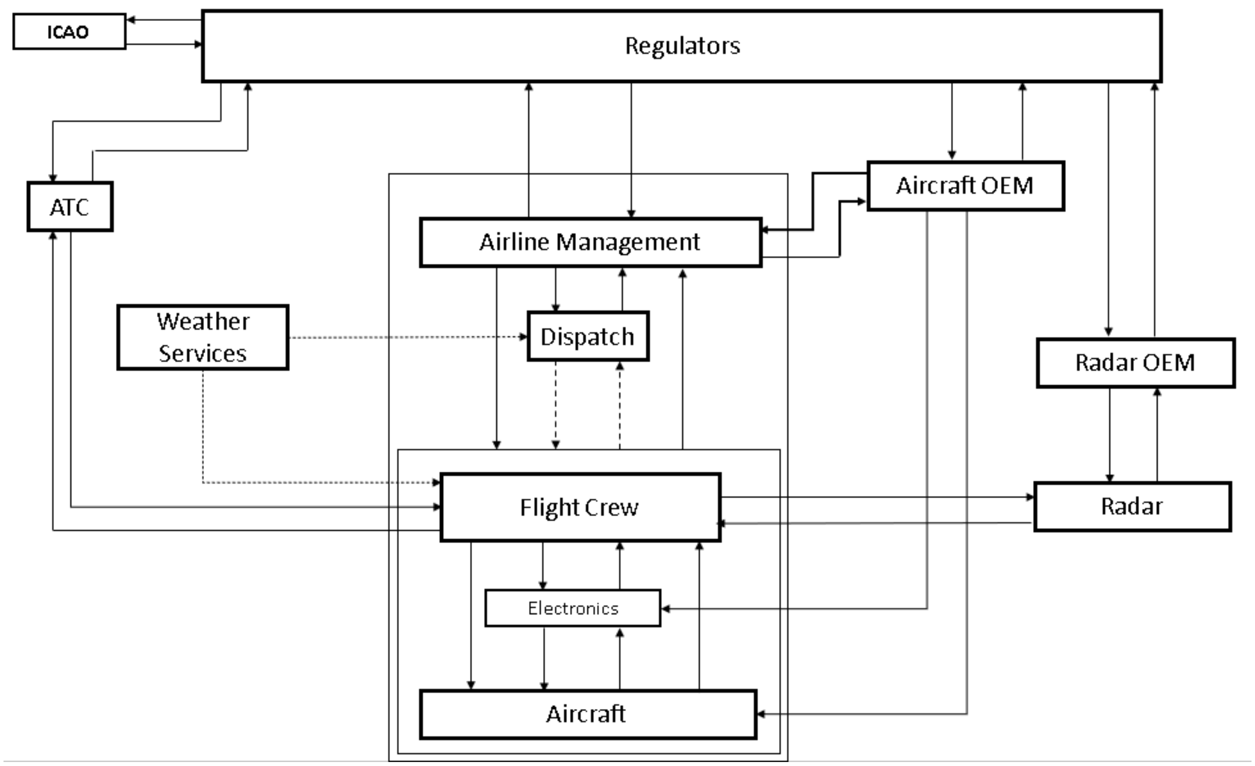
A control structure for the specific hazard of convective weather is depicted in Figure 3. This control structure is generic in that it could be applied to any airline in any region of the world. Starting from the bottom is the aircraft itself. As with any part of the control structure it is possible to define the aircraft in more detail as necessary for the analysis, such as flight controls themselves. Above the flight controls are any electronic controls, such as autopilot or flight control computers. Above that would be the flight crew, which can be further divided to show the relationships between the pilots themselves. Moving further, there is dispatch, the airline management (which can be further detailed as needed to look at the management structure for training, policies and procedures). The original equipment manufacturer (OEM) is modeled, as having control over the aircraft design itself and associated the procedures (which are provided to the airline for training),

Pilots and dispatch are provided weather information but do not usually provide direct feedback to the weather services. The pilots do control and get feedback from the onboard weather radar. Higher up on the control structure we have regulators, who provide oversight and are supposed to control the behavior of the entities under their jurisdiction.

When analyzing the convective weather encounters we use the control structure as a guide to understand why a particular control was not effective in preventing the accident or incident. This provides a way to capture both the control and feedback aspects. In this way the event is not analyzed as a linear sequence, but rather holistically. Starting at the bottom, each component is analyzed to see if it performed any unsafe control action. If it did, the analysis considers the context in which it occurred and then identifies recommendations.

Figure 3

Convective Weather Control Structure



S. Malmquist, Weather Event Control Structure, Figure 3, June 20, 2023

5.0 Investigating the context

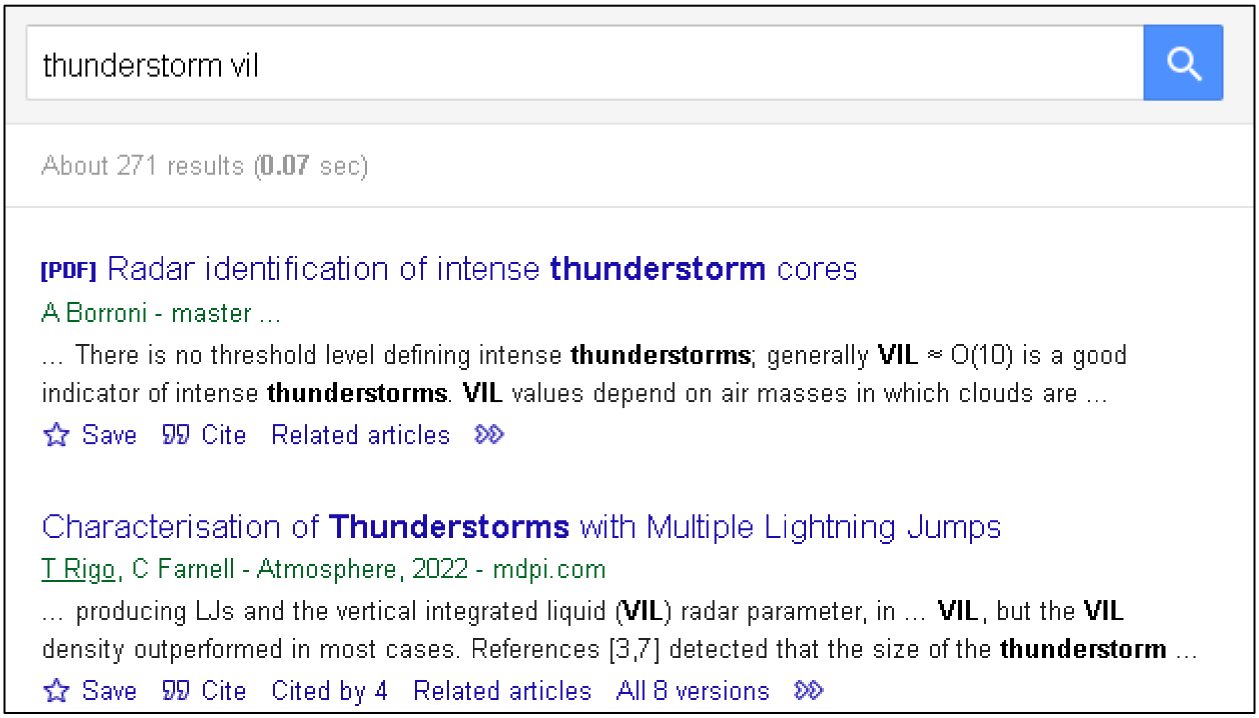
The following section includes information that was found through the CAST process, so ordinarily would not be presented until the appropriate point in that taxonomy. It is presented here to provide context and continuity for the reader.

5.1 The Nature of Convective Storms

Pilot education on meteorology has changed little since the 1960s, and perhaps even before. The emphasis has been on teaching basic principles, which have not changed significantly over the years. This is despite recent advances in understanding of weather, particularly convective weather, which has not been included in training even as knowledge has improved. For convective weather, the topic of this paper and presentation, the science has rapidly moved beyond the material contained in both civilian and military aviation meteorology training materials. The understanding of how thunderstorms portray on radar and the regions of storms containing vertical integrated liquid (VIL) is a topic of particular value to aviation, yet discussion on these topics is scant in most aviation training materials – even most weather radar guidance materials from the manufacturers tread lightly on the topic. Despite this, more is learned every day. A search on scholar.google.com using the terms “thunderstorm VIL” yielded 271 results just since 2022 (see Figure 4).

Figure 4

Scholar.Google.Com search for “Thunderstorm VIL”



SMalmquist. Google search. Figure 4. Search conducted on June 19 2023.

5.2 Enroute differences

Weather radar detects precipitation, and the wave length for airborne radar was chosen to be able to detect rain drops in particular. It is very good for rain, and much less able to detect frozen precipitation. The radar has controls for the antennae tilt, range and the gain. The tilt allows the radar to scan at different angles and is generally limited to a positive and negative 15 degrees from the aircraft axis. The gain controls how much noise is displayed. If the gain is very low then only the strongest of the radar weather returns are displayed. If it is very high then the screen will depict most of what the radar is returning. This latter may seem ideal, but too much gain is analogous to a lot of static on a radio. The signal we are looking for (in the case of a radio, the voice), may not be discernable from the static.

Guidance for manual operation in cruise flight typically consists of reducing the tilt until ground return appears at the outer edge of the screen. Above 35,000 feet the curvature of the earth results in a tilt setting considered too low, so the guidance varies from about a 1 degree downward tilt for longer ranges to up to 7 degrees for targets closer in. In all of this, the beam is being pointed to around 25,000 feet, which is where water will typically be present in North

American thunderstorms. Although this is typical for North American storms, not all North American storms are typical. There is considerable variation depending on the part of the continent, the season, and terrain. To compensate for this a pilot needs to understand more than just the basic weather theory, but also a more nuanced understanding of the radar system itself.

The strategy outlined above, although reasonable for North America most of the time, is not well suited to storms in other regions [12,13]. Rockwell-Collins, highlighted this issue for the design of algorithms in their latest generation of onboard radars stating in a white paper [12]:

> With the introduction of tools such as the TRMM (Tropical Rainforest Measuring Mission) and Cloud. Sat satellites, climatologists, such as Dr. Ed Zipser of the University of Utah, have made major discoveries that are directly applicable to in-flight weather radar. For instance, two key findings that are directly applicable to aviation safety are that 1) worldwide convective activity varies significantly depending on its geographic location and that, 2) rainfall rates (the traditional measure for weather radars) do not necessarily equate with actual thunderstorm threats…
>
> …The Rockwell Collins radar team converted a Boeing Business Jet (BBJ) into a flying weather radar laboratory and conducted worldwide research to correlate Dr. Zipser's findings with the airborne radar environment….

A key aspect is that it was found that oceanic storms will often "rain out" at lower altitudes and the precipitation at the higher levels with then be frozen and difficult to detect utilizing traditional radar techniques (p. 10). Liu and Zipser [14] found that:

> Radar reflectivity below the freezing level usually decreases toward the surface over land, but increases toward the surface over the ocean. Increasing reflectivity toward the surface is hypothesized to occur mainly when raindrops grow while falling through low clouds, which is favored by high humidity at low levels, and by updraft speeds lower than the fall speed of raindrops, both more likely over oceans. Other things being equal, proxy evidence is presented that the more intense the convection, the more likely reflectivity is to decrease toward the surface, and that this is at least as important as low-level relative humidity.

Despite the more recent findings the guidance for pilots on the use of inflight radar has not been revised to reflect the better understanding. There is no general requirement to revise the guidance by regulators once a system is certified [15]. In the case of Air France 447, the flight crew was apparently following the guidance they were taught and was present in their manuals. Unfortunately, the guidance was not adequate to allow them to steer clear of the storms. While they did make a turn to avoid what they showed on the radar, they still encountered HAIC in the tops of the storm, which ultimately led to the loss of the aircraft [4].

Radar controls can be either manual or automatic, depending on the particular installation. There are variations in the algorithms for automatic control between manufacturers. Some essentially mimic the guidance above (while automatically eliminating ground return displays), others use the software to display a constant altitude, with weather below 25,000 feet displaying as *off-path* weather, and still other manufacturers vary the strategy depending on geographic location and time of day. Pilot understanding of the automation logic and an in depth understanding of the nature of convective weather in different regions, climates, seasons and terrain, is critical for maximum effectiveness. Outside of North America this can be even more critical.

The lack of a deeper understanding of these factors likely explains the majority of the encounters in the cruise environment.

5.3 Terminal Environment

The scenarios for the windshear encounters are quite similar in all of the cases. A combination of a lack of clear radar indications of a threat coupled with other aircraft passing through the areas without a problem are typical. USAir 1016 is a good case study. A clue to how the threat was hidden can be found in the reports from the ground based doppler weather surveillance radar, WSR-88D, observations. As the storm was growing the reflectivity was much lower at the lower altitudes than it was at higher ones (p. 28-29). This is indicative of rain being held aloft. It is important to understand how the guidance provided to pilots may result in pilots missing cues of an impending microburst.

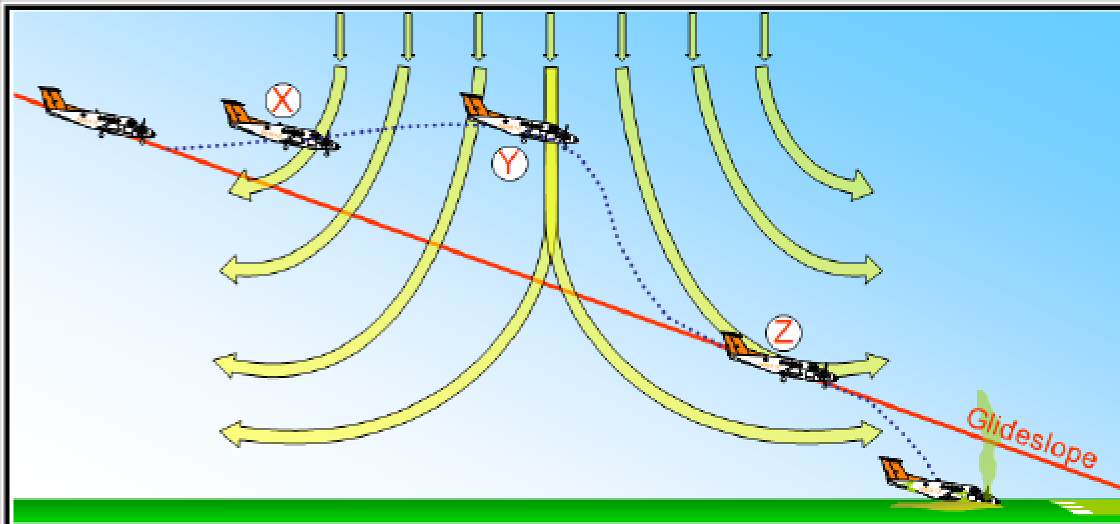
The majority of guidance provided to pilots on microbursts centers around the identification of developed microbursts, as described in the FAA's Pilot Windshear Guide [16]. Figure 5 is typical for most manuals and guidance displaying the effect of entering the headwind portion, the downdraft and finally tailwind sections. The typical guidance to avoid windshear is enumerated in the Flight Safety Foundation's ALAR Briefing [17] which contains valuable guidance based on ICAO (International Civil Aviation Organization) and FAA guidance, and includes recommendations such as reviewing weather reports, utilizing weather radar, observing conditions, paying attention to windshear alerts, looking for VIRGA and dust clouds, etc. Missing, however, is guidance on how one might utilize the weather radar itself as an aid. The FAA Pilot's Windshear Guide [16] contains similar guidance, while guidance on the use of onboard radar generally originates from the radar manufacturers, and this guidance is often incorporated in airline flight manuals and other material. For takeoff and landing the guidance has traditionally been to adjust the tilt setting to reduce ground clutter, typically 3-5 degrees up [18].

5.3.1 The Nature of a Microburst

Dr. Fujita's preliminary wor[19] on studying microbursts provides some illuminating insights as to the formation of microburst through reviewing vertical radar slices to evaluate the known microbursts. This work has been elaborated upon and, as will be discussed next, provides some tools that pilots can use in the absence of an installed microburst detection system (it is important to note that a microburst detection system is different than a windshear detection system, the latter identifying developed microburst/downburst and the former an impending microburst/downburst). Interestingly, although containing no detailed discussion, the FAA AC-00-6B [20] does show an accurate pictorial (Figure 6).

Figure 5

Typical portrayal of a microburst encounter

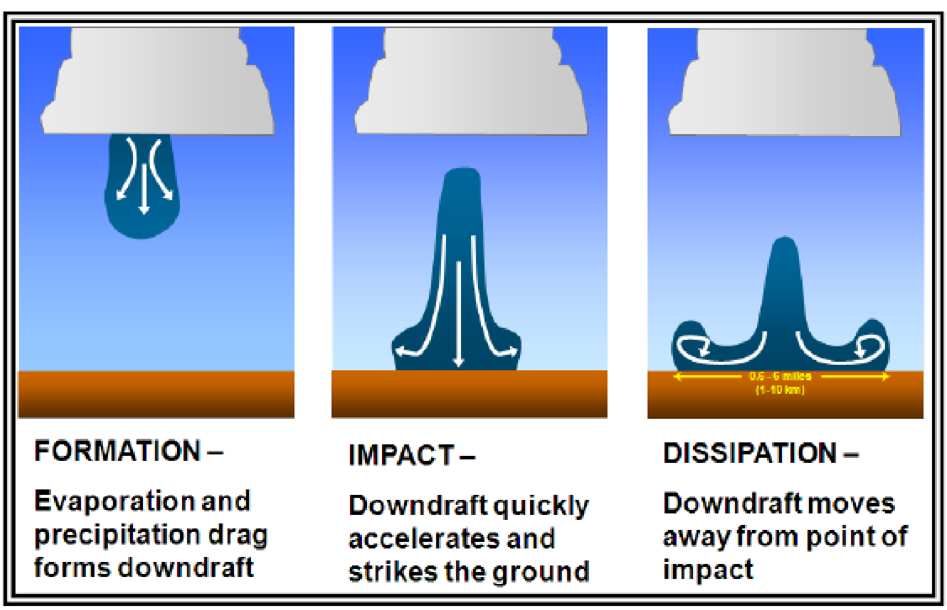


At point X, the aircraft enters the microburst zone where a headwind causes it to balloon above the normal glideslope. At the center of the microburst, point Y, there is a downdraft which causes the aircraft to sink. At point Z, the aircraft enters the most lethal zone where a sudden tailwind causes the aircraft to lose airspeed.

FAA, Microburst, Figure 5, 2016, p. 19-7

Figure 6

Microburst sequence



FAA, Microburst, Figure 6, 2000

5.3.2 Pilot Technique in the Terminal Environment

As outlined by Rhoda and Pawlak [21], pilots are flying through convective storms in the terminal environment much more often than many realize. Ground based detection systems provide limited warning of hazards associated with thunderstorms such as wind shear, but aircraft operating outside the immediate area of an equipped airport receive no protection from these airport-centric systems, and, of course, many secondary, general aviation and non U.S. international airports have no wind shear detection capability at all. Microburst detection systems provide more protection, but these are installed at only the larger airports. This leaves pilots trying to avoid convective weather dependent on air traffic control to the extent radar weather advisories are provided (and in international locations that service is generally not available), airline dispatchers, and, most often, their own onboard systems and weather knowledge.

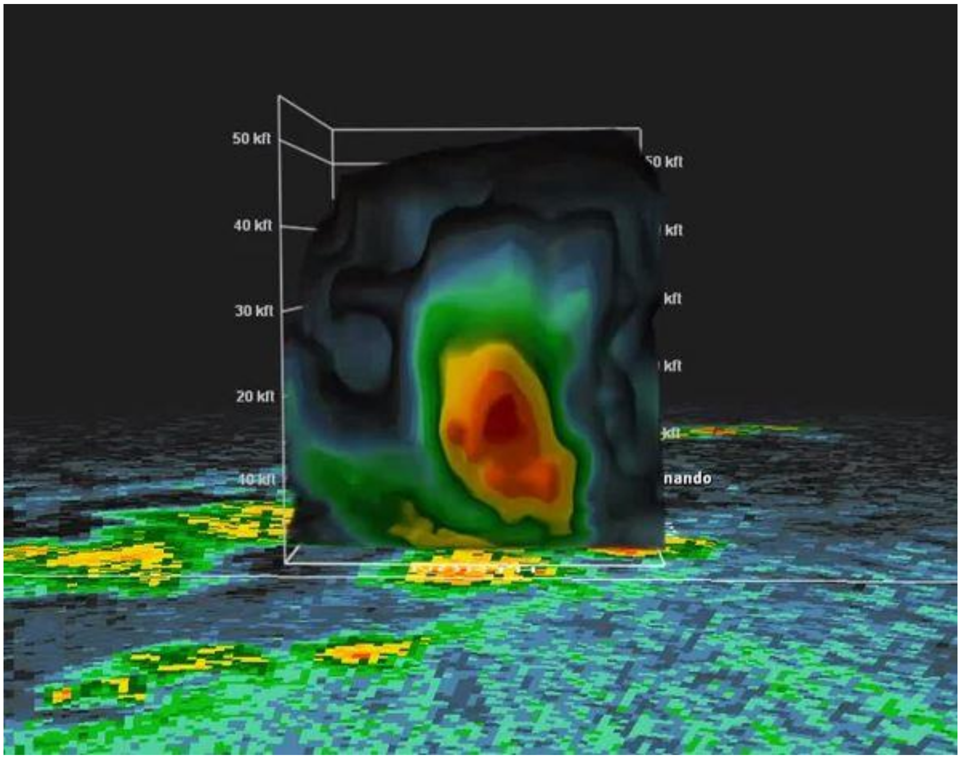
Radar operational techniques that are suitable for enroute cruise flight are not useful in terminal operations. In the enroute case, the assumption is that the aircraft will be above most of the weather and should therefore be looking down to detect hazards. Unfortunately, such a setting is impractical for the terminal environment as it may detect returns associated with low altitude precipitation and does not allow pilots to differentiate between low altitude stratus rain (associated with a stable environment) versus precipitation with extensive vertical development (i.e. a thunderstorm in a convective environment.)

When flying at low altitude in the vicinity of thunderstorms, it is prudent to tilt the radar up to look for concentrations of wet precipitation that may soon become part of a convective downburst [22]. An illustration of this can be seen in figures 7 and 8. Figure 7 is a snapshot of an impending downburst over Memphis in 2012. Figure 8 is a profile of a microburst-producing storm over Alabama [23]. As can be seen in the images, the “wet core” of these storms is elevated to around the 20,000-foot level with relatively light amounts of precipitation at the lower altitudes.

As outlined in Wolfson [23], the classic formation of a microburst occurs when the updrafts of a building thunderstorm are holding large volumes of water aloft. That water eventually becomes so heavy that it overcomes the updrafts and falls rapidly to the ground. It stands to reason that a radar beam directed at the lower portions would fail to capture the dangerous amounts of water held aloft at the incipient phase of an impending microburst. Note that Figure 8 depicts the water dropping from above but the article from which the image was obtained does not elaborate on the implications this might have for how a pilot might operate onboard radar.

Figure 7

Downburst over Memphis



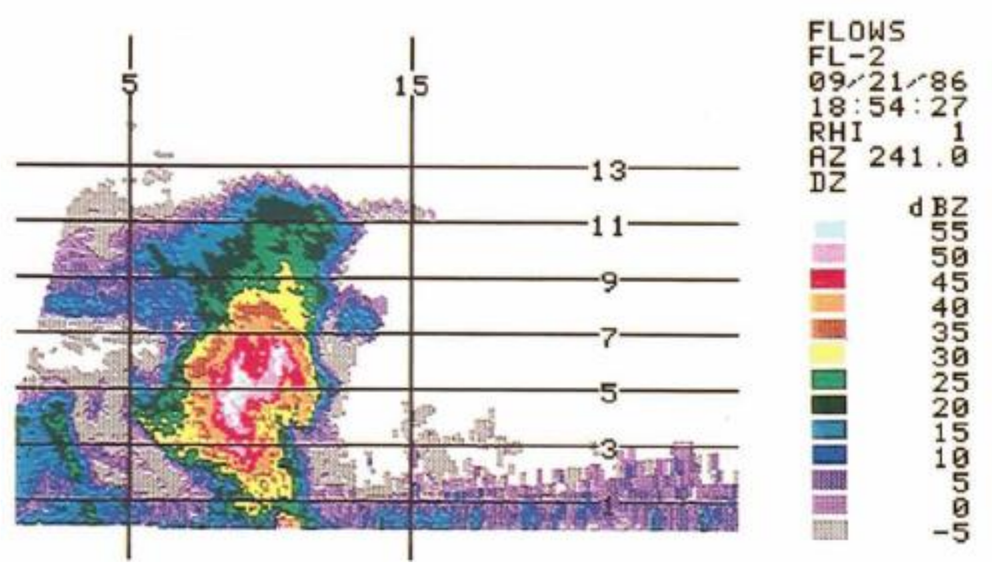
MEM CWSU, Downburst over Memphis, Figure 7, 2012

The conditions that USAir 1016 encountered could have been predicted. The Vertically Integrated Liquid water (VIL) from the ATC WSR-88D radar was captured [10] displaying the intensity of the precipitation and several heights, measured in dbz. At 1823z the base of the storm indicated 5-15 dbz, the mid 25-30. At 1829z the base reflectivity had increased to 40dbz , the mid levels increased to 50 dbz. Echo tops showed 25-30k (p. 28). By 1835z the base reflectivity had increased to 50dbz and at 1841z it was still 50dbz at the base but the area at higher elevations was smaller and significantly lower than previous scan (P.29). Further, as stated in the report, ATC controllers are “absolutely not” taught to interpret information from ASR-9 radar, and their interpretations are very subjective, where one controller may regard VIP level 2 as pertinent and another only report level 5. It also might not be reported at all (p. 93).

The combination of a lack of knowledge (not the fault of the flight crew, but a general industry concern) and lack of ground-based warning systems that adequately provide ample warning, and/or better onboard radar systems led this crew to their accident.

Figure 8

Actual Microburst



Wolfson, Microburst, Figure 8, 1988, p. 58: Heights are shown in kilometers.

6.0 System Theoretic Analysis using CAST

When analyzing these events using system theory there is never a time we would say that a person "failed" to do something. Terms such as "error" or "loss of situational awareness" also have no place in the analysis or findings. If someone did not do what we thought they *should have done* we first consider that this might be due to our own hindsight bias. We then investigate why it *made sense* for that person – the flight crew, the air traffic controller, meteorologist or even the designer of the weather detection system – to have made the choices they made. Only through this understanding is it truly possible to identify mitigations that will be effective in the future. Following is an abbreviated summary of the findings from the CAST analysis.

The analysis itself starts at the bottom of the control structure, with the aircraft. We will assume here that the aircraft and its systems worked as designed, with no failures. We will assume the same for any electronic control systems (fly-by-wire and autopilots).

6.1 Aircraft (including flight control system and components)

Failures and contributing interactions: None.

Context: The aircraft flies into convective weather because the pilots directed it that way, so here is becomes important to analyze the pilots.

Recommendations: None

6.2 Flight crew

Responsibility: Maintain aircraft flight clear of convective weather.

Unsafe Control Actions: Maintained course or turned to a heading where convective weather was present.

Contextual Factors: Pilot training and radar indications result in pilots thinking that the threat is less than it is.

Recommendations: Pilots need to individually obtain more knowledge and training. See recommendations below.

6.3 First Officer

Responsibility: Provide control so pilot in command stays clear of weather. If PF, remain clear of weather. If PM, provide control to PF/Captain.

Unsafe Control Action: Did not ensure that the flight maintained path clear of weather, either as PF or as the control to the PM/Captain.

Contextual Factors: First officer is in subordinate position and also does not usually have the level of experience necessary to provide good alternative actions.

Recommendation: See recommendations below.

6.4 Captain

Responsibility: Keep aircraft clear of convective weather.

Unsafe Control Action: Did not ensure that aircraft remained clear of weather.

Contextual Factors: Pilots not trained to fully understand the risks or to interpret weather.

Recommendations: More individual training if companies are not providing it. See below for more information.

Here the Pilot Monitoring does act as a control to ensure that the Pilot Flying does not do something unsafe, but this is more complex as, in terms of weather decision making, the captain will be the one making a decision with the first officer needing to act as a control – yet the first officer can be overruled by the captain, so this can be problematic. Several accidents have resulted from this scenario, such as American 1420 at Little Rock in 1999 [24]. It should be noted that this issue is predicted when analyzed with system theory, so we do not have to wait for an accident to identify recommendations and solutions.

The pilot decisions are based on a combination of training, experience and information. The quality of that information is dependent also on training and experience as well as the available technology. Controllers above the pilot include dispatchers and ATC, both of whom make judgments also based on training, experience and information. It is the job of the airline and regulators to ensure that the training, policies and procedures are providing the support necessary.

When we analyze the pilots it becomes immediately clear that most pilots did not receive meteorology training that is more than rudimentary. The airline training is minimal and mostly limited to basic airborne weather radar controls. Interpretation is left to learn through experience. This can lead to incorrect mental models. Pilots may believe that having the radar tilted at 3 degrees up in the terminal environment is adequate, but they are only viewing low altitude rain at that setting. Similarly, the lack of understanding of where to point the radar beam enroute can lead to pilots either over scanning the area that might indicate the most threat or misinterpreting the results. This is directly due to the lack of more than rudimentary training at the airline level.

Newer radars contain automated settings, but these settings are also limited to the scenarios that were part of the requirements. One manufacturer, for example, considers any weather in cruise below 25,000 feet to be "off path" and depicts it accordingly. Although that model is fairly good for flying in the United States, it is not quite adequate for many other parts of the world. Regardless of the architecture used, pilots that rely on the automated system to depict what they need to know are demonstrating the same sort of automation dependence that we hear so much about in airplane handling.

6.5 Dispatcher

Responsibilities: Provide flight planning and weather information to avoid areas of convective weather.

Unsafe Control Action: Provide routing that is not clear of convective weather areas.

Context: Dispatchers can be somewhat automation dependent in that the computer will issue a "legal" flight plan, even if it might encounter areas that could be hazardous. The assumption is that the pilots will avoid the weather. The system is also somewhat reliant on the fact that historically, most of the time, aircraft do avoid the more dangerous areas. In addition, dispatchers receive only minimal training on the weather products and their meteorology training is similar to the pilots.

Recommendations: Provide additional training to dispatchers. Add more dispatchers so each dispatcher is less reliant on automated products.

6.6 Air Traffic Control

Responsibilities: Primary responsibility is separating aircraft. In the U.S., ATC also will advise aircraft of convective weather, workload permitting.

Unsafe Control Action: Not providing aircraft with vectors clear of known weather.

Context: ATC provides weather information on a workload basis and controllers receive only minimal training on meteorology. In addition, they often are not fully aware of the advantages and limitations of ATC radar.

Very similar limitations occur with both dispatchers and air traffic controllers. In the U.S. air traffic controllers do provide some assistance for weather avoidance (this is not something that I have witnessed in any other part of the world). Although the approach controllers are limited to more basic radar, the enroute controllers in the U.S. have the ability to select altitude ranges to display weather. These ranges are surface to 60,000 feet, 24,000 feet to 60,000 feet and 33,000 feet to 60,000 feet. ATC normally selects the range based on the altitudes they are assigned to work at that time, however, they can change the selection at any time. It might be beneficial for controllers to provide information that they see at the various settings to the pilots as that can give a greater understanding to the pilots of the vertical makeup of the storms. An additional benefit is that ATC radar does not attenuate, so is better able to depict the extent of the weather area.

Recommendations: Provide ATC with more comprehensive weather training.

6.7 Airlines

Responsibility: Provide pilots with adequate training and aircraft with adequate equipment to avoid encounters with convective weather.

Unsafe Control Action: Not providing adequate training for pilots.

Context: Most airline training is conducted such that it meets the minimum requirements set forth by the regulation. The industry has long relied on pilots learning how to avoid weather through experience. Although the airlines do update to the latest models of weather radar, they are often not aware of the limitations of the newer automated systems.

Recommendations: Provide more training to pilots on meteorology, weather radar and limitations of weather radar.

Several of the newer radar systems have a mode to depict the storms in a vertical profile. This is a particularly useful feature that can greatly aid in pilot decision making. Still, pilots must understand that some storms do not portray in the "classic" manner, as previously described. An oceanic storm may appear to be below the aircraft due to the precipitation being frozen at the higher levels. Still, no onboard radar that I am aware of is depicting an incipient microburst, as previously described. The model of storms that is being used for building the automated radar system requirements is not adequate.

For the terminal environment, pilots need to be trained to be looking for the threat of water being held aloft in these storms. Manual tilting the radar beam upwards provides some relief, although the antennae tilt limitations result in only being able to detect water 15,000 feet above them at the 10-mile range and just 7,500 feet above them at the 5-mile range. Some installations are further limited, ironically, when in the windshear detection mode when vertical scan is reduced to allow for a higher scan rate. Current windshear detection (predictive windshear) algorithms are only able to detect a microburst *after* it has occurred. Hardly predictive, and not the scenario that generally results in an accident. A developed microburst is fairly obvious and can be easy to avoid in most cases. A dry microburst less so, but still there are many available clues. Manufacturers should implement algorithms for onboard systems that mimic those developed by the MIT Lincoln Laboratory [25], looking at the potential of water suspended aloft. These could be stored in the computer buffer for aircraft in the approach environment, further enhancing the capabilities.

6.8 Radar manufacturers

Responsibility: Provide weather radar that accurately depicts the convective weather for the theaters in which the particular airline will operate.

Unsafe Control Action:

1. Providing automated weather radar that may not be modeled for the particular region of the world the airline is flying to. Does not provide such information to customers.
2. Not including algorithms that will detect potential for incipient microbursts in the terminal environment.

Context: Radar manufacturers are in the business of selling radar systems so will provide information on capabilities but less so on limitations of systems.

Recommendations: Manufactures should provide information on their system limitations.

6.9 Regulators

Responsibility: Provide oversight to the airlines and manufacturers. Provide training and equipment to U.S. ATC, and oversight of ATC in general.

Unsafe Control Action: Provides limited oversight that only meets the minimum regulatory requirements.

Context: Limited funding results in the regulatory agencies being limited in their ability to provide the oversight needed.

Recommendations: Provide more oversight and training. Expand installations of the microburst detection systems.

6.10 Factors Spanning Components

Examining the factors spanning components begins with analysis of the industry and organizational safety culture.

6.10.1 Industry and Organizational Safety Culture

A key component that is evident here is that the industry has been somewhat complacent regarding meteorology and radar training. Airlines appear to assume that certain types of knowledge are already present when they hire a pilot. Aerodynamics, meteorology and how to operate weather radar all fall into that group. Unfortunately, this assumption is no more valid than assuming a pilot will have knowledge about the systems on a particular type aircraft based on their general system knowledge obtained previously.

6.10.2 Safety Information Systems

Safety information systems are part of the safety controls that enable safety critical information to be shared easily and rapidly. Although information on events is generally available, the associated lessons and training from those is not. Safety information should be improved.

6.10.3 Dynamics and Changes over Time

Dynamics and changes over time include several factors. The first is the increasing prevalence of convective weather due to climate change. The second is the advent of newer automated radar systems that change how weather is depicted, often without sharing the underlying assumptions. Finally, the airline industry is seeing many new pilots who have not had the same level of experience, so what pilots could learn from each other through flying with more experienced pilots is no longer available. This requires more in-depth and focused training.

6.10.4 Communication among Controllers

Communication among controllers here would refer to the communication between the manufacturers of radar systems with the airlines and regulators, as well as the communication between ATC and pilots. ATC and airlines should work together more to ensure that each understands the capabilities and limitations of the other.

Conclusion

The CAST analysis makes it clear that the answer to all of the issues is more training coupled with improved technology. This must come from the higher levels of the control structure. Airlines could implement the training themselves, but likely need the lead of regulators to set the standards for which they need to train. Similarly, regulators would be the ideal source for new onboard weather radar requirements. Such guidance need not be statutory but could, instead, but in adopting standards and guidance materials that point the way forward.

This paper provided a demonstration of the findings from using the Causal Analysis with System Theory (CAST) method derived from System Theoretic Accident Models and Processes (STAMP) to examine several accidents and incidents involving convective weather encounters involving transport aircraft. The results included a discussion of new and recent research into the nature of convective weather that can result in radar signatures that may not present in the manner that pilots have been taught to expect. These were examined for convective storms over various regions of the world and concluded with a discussion about some techniques that might identify these threats.

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