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ABOUT THE COVER

The shown engineering flight animation was one of the components of the Transportation Safety Board (TSB) of Canada investigation process in the development of the sequence of events leading to the unstable approach accident of the Boeing 737-210C operating as First Air Flight 6560 from Yellowknife, Northwest Territories, to Resolute Bay, Nunavut, on Aug. 20, 2011 (see page 22). TSB photo.
On behalf of all your elected ISASI officers and appointed chairmen of committees and working groups, I wish all Society members and supporters a healthy, prosperous, and happy new year.

I am sure that 2016 will bring collective and individual challenges as we go about our tasks of making the skies safer through analytic, thorough, and conclusive accident investigations aimed at determining cause and not blame. I am equally sure that we are up to the task of meeting such challenges.

In 2015, the Society enlarged its scope of activities to service the broader landscape of air safety. For example, we have achieved unprecedented involvement in International Civil Aviation Organization (ICAO) deliberations, seen greater attention to issues in both our working groups and committees, established two new working groups: Airports and Critical Incident Stress Management (CISM), published the ISASI Unmanned Aircraft System (UAS) Handbook and Accident/Incident Investigation Guidelines prepared by the UAS Working Group, achieved continuing growth of students selected to receive ISASI’s Kapustin memorial scholarships, celebrated the award of the first ISASI–Robertson Family Aviation Safety Fellowship endowed by ISASI’s Lederer Award recipient Dr. Harry Robertson, and saw continuing growth in safety conferences conducted by our ISASI societies.

In this regard, I attended the Middle East and North Africa Society (MENASASI) third annual seminar in November 2015. The seminar was held at the Intercontinental Hotel Festival City in Dubai, United Arab Emirates (UAE). The event, hosted by the general civil aviation authority, with sponsorship from Airbus, Etihad Airways, Emirates Airline, flydubai, and the Gulf Aviation Academy, attracted 120 attendees.

Speakers included Marcus Costa, chief of air accident investigation for ICAO, who updated the delegates on control of information initiatives at ICAO; Keith Conradi, chief inspector of the UK Air Accidents Investigation Branch, who discussed a series of North Sea helicopter accidents; Dr. Edna Naddaf, a corporate and aviation psychology consultancy, who gave an interesting presentation on the role of aviation psychology in building a culture of safety; and Capt. Ibrahim Koshy, director general of the Aviation Investigation Bureau of the Kingdom of Saudi Arabia, who spoke about developing investigative capabilities. Another 13 presentations covered biohazards, investigator safety, analysis, manufacturer support, challenges of sea search and recovery operations, and family assistance.

“Young Investigators Presentations” were given by Fatima Al Mansoori of Abu Dhabi University and Crystal Ioannou of the Emirates Aviation University. Al Mansoori gave a presentation titled “As-simulating Western-Based Crew Resource Management into a Middle Eastern Culture—A Personal Perspective,” and Ioannou gave her presentation on “The Good, the Bad, and the Ugly: The True Story Between SMS and Reality.”

Workshops on aviation insurance and human factors were held prior to the seminar. These were very informative and were attended by more than 80 delegates.

MENASASI is growing very rapidly in both individual and corporate membership. The next MENASASI seminar is scheduled to take place in November 2016 in Rabat, Morocco. The 2017 MENASASI seminar will be held in Saudi Arabia. The MENASASI group has committed and is currently planning to host the international ISASI conference to be held in fall 2018 in Dubai, UAE.

Since its founding in August 2013, MENASASI has exhibited phenomenal growth. This is recognition of ISASI’s international value and a tribute to MENASASI President Ismaeil Al Hosani and his colleagues at the Air Accident Investigation Sector of the UAE General Civil Aviation Authority.

I close this message with the knowledge that with your help our Society will move forward into 2016 in a positive and productive way.
INDEPENDENCE DOES NOT MEAN ISOLATION

By Rémi Jouty, Director, Bureau d’Enquêtes et d’Analyses pour la sécurité de l’aviation civile (BEA), France

(Remarks presented by Director Jouty in his keynote address to the delegates of the ISASI 46th annual international conference on air safety accident investigation on Aug. 26, 2015, held in Augsburg, Germany.—Editor)

With the theme of this year’s conference being “Independence Does Not Mean Isolation,” I will try to develop some thoughts on the words “independence” and “isolation” based on the BEA’s experience.

As to the question of isolation, recent months have shown that the BEA certainly does not work in isolation, if I judge this, for example, by the news media exposure we have been subject to recently!

Next, to discuss the need for independence, I think it is useful to ask, “Why should a safety investigation be independent?” Is there a difficulty or some issue in having an independent safety investigation? As we all know only too well, as per Annex 13, the sole objective of the safety investigation is accident prevention, and its purpose is not to apportion blame or liability. What could the obstacles to an independent investigation be? Could anybody want to oppose the goal of preventing future accidents? Who could want to influence our investigation activity? Why? How?

To address those questions, we need to consider the wider context in which a safety investigation takes place, which was called “the social context of an investigation” during one of the ISASI tutorials on Monday.

So what are the reactions after an accident?

The first question is obviously, for everyone, “What happened?” In these days of instant communication, social media, and wide access to various data, a large number of information, data, rumors, and statements circulate publicly very early. So here the difficulty is more to sort out the true information from unfounded affirmations, of validating data, of putting things into perspective, of developing meaningful data by gathering information that may not yet be available.

The next question is, “Whose fault is it, who is to blame?” I feel that this question is perceived as more and more important in our societies, which seems to be out of phase with our purpose of working solely for safety improvements, and with aviation promoting the concepts of just culture and protection of sensitive information. This question is asked by families of victims, and we obviously cannot blame them from asking this question. The question is also highlighted by the news media—which often tends to prefer the “simple answer” of saying who is to blame, rather than entering into complex technical explanations, which may be more relevant when dealing with improving safety. And, of course, lawyers and judicial authorities also ask this question, though in this they are simply doing their job.

The next reaction of “I want or I need to show that I care and that I am doing something about it” coming from political leaders seems to be an increasing trend. This has been noted during a tutorial on Monday and definitely has an influence on other actors and on the context in which we try to undertake the safety investigation.

Another reaction is, “I need to preserve my reputation and reassure my customers.” This reaction may come from the operator, manufacturer, and/or regulatory authority. Another motivation for this reaction could be the feeling of the need to avoid being blamed or found liable. A variant to this reaction is, “I need to preserve the reputation and honor of my members,” which may come from pilots’ unions.

And at the very end, there is the reaction of “I want to take this as an opportunity to improve safety.” This is obviously our domain, we safety investigators. It is also a domain in which regulators, manufacturers, airlines, and pilots will want to be involved as they deal with safeguarding or improving safety in the course of their daily business activity.

So considering all those reactions, where improvements in safety appear only at the end, we have to reconsider the question, “What is the purpose of a safety investigation?” Can it be, as [the International Civil Aviation Organization] ICAO says that its sole objective is to prevent accidents? Can we ignore other reactions and expectations? How can we handle these other groups with an interest in this accident and their typical reactions?

Let’s review our relationship with these various groups. Let’s start with manufacturers, airlines, regulators, and pilots’ groups. As I said before, they will be motivated by the need to preserve their reputation, to reassure their customers, to defend the honor of their members. Can we, or indeed should we, work and undertake our investigation without them? I believe not. Accident investigation is a technical activity and requires data, knowledge, and expertise from manufacturers, operators, pilots (although not necessarily pilots’ unions), and regulators. All of these organizations or groups of persons also have the goal of improving safety in their daily business.

Does this limit our independence? Maybe, and maybe not. But we cannot do without them, and we have to use this knowledge while taking care not to be biased or influenced in our analyses. Annex 13 provides a framework for that, which has proven to be effective over the years.

The next question is, “Whose fault is it? Who is to blame? Those asking these questions are families, the news media, and, obviously, lawyers and judicial authorities. As I said before, these questions seem to be of increasing importance. The way these questions are handled may be different in different countries, according to the laws and social traditions.

In France, some years ago, when things went wrong, the popular reaction was to cut off heads, preferably of somebody
important and visible like a king or somebody with the power to influence events. Things have changed a little bit, but it is still very much in our culture to want to designate somebody to be personally blamed and to be sentenced to jail. In other countries, expectations may take different forms, like public designation of an entity or a person to blame, or assigning punitive damages, or putting the emphasis on monetary compensation to be paid by those found responsible. However, I think that all over the world the “Whose fault is it?” reaction is there and has to be dealt with one way or another.

There is thus a wide variety of situations, and the international safety investigation system, defined by ICAO Annex 13 and by European Regulation 996/2010, has to accommodate these situations. To clarify, I will contrast various possible situations.

The first one, which I know best because it corresponds to my country, is where the judicial, criminal investigation is systematic in the case of a fatal aviation accident and takes place in parallel, but at the same time, as the safety investigation. This may be seen as an undesirable situation from the point of view of the safety investigation and just culture, but it may nevertheless have the positive effect of relieving some pressure on the safety investigation authority. When you get the question, “Whose fault is it?” you simply answer, “That’s part of the judicial procedure!” However, it creates other problems. The judicial investigation (or the investigating judge) is independent, and he may see the safety investigation as a threat to his independence. And, indeed, judicial and safety investigations have to agree on ways to share evidence, including sensitive data, which should, ideally, be dedicated to safety only. And both have to compromise their own independence to find ways to permit both investigations to progress at the same time from basically the same facts and data.

In some other countries, there is no judicial investigation, or the judicial investigation, usually more targeted at civil litigation, is less visible, or takes place only after the safety investigation. Nevertheless, the “Who is to blame” reaction is still there, from the first day after the accident, and the appetite for answers to the question is still very strong. In that situation, I feel it is difficult for the safety investigation to ignore the question. The safety investigation will then be expected to, at least implicitly, help answer to the question. In such a situation, can we still say that the sole objective of the safety investigation is improving safety? I noted with interest that in countries in which there is no criminal investigation, or where the judicial investigation is not “visible,” the safety investigation procedures sometimes bear some striking formal similarity to judicial procedures, as if it were trying to mimic judicial procedure in order to achieve a similar social objective.

Let’s now look at the reaction “I want to show that I care and that I am doing something about it,” which we seem to see more and more often these days. It makes sense for political leaders to show their compassion for victims after a disaster, and it has always been a reaction to be expected from them. However, nowadays we sometimes see them going a step further and being seen to be in control of the investigation, and communicating on technical details on what they believe could have happened, with sometimes inaccurate or nonvalidated information. This may easily cast some doubts on the reputation of independence of the safety investigation.

What can we do about this? From my perspective, it would appear to me that little can be done about this. Informing political leaders or their closest advisors of what a safety investigation is and why it is important to preserve its independence may be helpful. However, those involved may sometimes be inclined to protect their own interests in the short term, regardless of future consequences.

Another course of action that could be considered would be to delay communication on the safety investigation for a few days or weeks, as the period of time when political leaders are engaged in communicating on the event does not usually last long. I believe this is not usually an option, since nowadays a lot of information or rumors circulate very early, and there is a need for the safety investigation to put the facts straight right away to avoid false information and speculative scenarios being remembered as being what actually happened.

So in conclusion, I would say that our independence has limitations in several ways because a safety investigation takes place in a wider framework involving many other entities that are interested, for many different reasons, in the accident and from which either we cannot, or should not, be isolated.

As a footnote to the above, I found this sentence that could be interesting in this discussion on the independence of safety investigations: “Indépendance est un statut, l’impartialité est une vertu”—which I would translate as “independence is statutory, impartiality is a virtue.” This sentence is said to have been formulated by Robert Badinter, who was a French lawyer, minister of Justice, and then chairman of the Constitutional Court. He is famous for having fought that nasty habit the French had of cutting off heads when something went wrong: as minister of Justice he led the decision to abolish the death penalty in France. He pronounced this sentence when he was appointed chairman of the Constitutional Court, at a time when there was a debate on the degree of independence of this court, notably in relation to political leaders. This shows that this debate on the limits of independence is present even for the judicial authorities for whom one would see independence as being taken for granted and not subject to debate. I would like to take this sentence on board and conclude that what we should really aim at is impartiality. Some degree of independence is one means, clearly necessary to achieve impartiality; but as you have seen, I feel that perfection cannot be reached in this area.

Independence is not enough in itself to ensure impartiality. It also requires, perhaps more importantly, technical competence. This in turn requires having access to technical capabilities, whether in house or through other organizations, and here we touch on the idea of cooperation and mutual assistance, which Ulf Kramer, and then Johann Reuss, raised in an earlier session.

Thus, when we undertake an investigation impartially and on a sound technical basis, we need to ensure that the outcome of the investigation reaches its target, and for this we need credibility. Credibility will result from our past performance, notably in terms of technical value and good communication.
A New Tool for Analyzing The Potential Influence of Vestibular Illusions

Boeing saw the need for a valid, accessible tool that allows investigators to look at flight data and determine if spatial disorientation may have contributed to pilot control inputs.

By Randall J. Mumaw, Associate Technical Fellow, Human Factors, Boeing; Eric Groen, Senior Scientist, TNO; Lars FucKee, Lead Engineer, Boeing; Richard Anderson, Senior Accident Investigator, Boeing; Jelte Bos, Senior Scientist, TNO, and Professor, VU University; and Mark Houben, Research Scientist, TNO

(Adapted with permission from the authors’ technical paper entitled A New Tool for Analyzing the Potential Influence of Vestibular Illusions presented at ISASI 2015 held in Augsburg, Germany, Aug. 24–27, 2015, which carried the theme “Independence Does Not Mean Isolation.” The full presentation, including cited references to support the points made, can be found on the ISASI website at www.isasi.org under the tag “ISASI 2015 Technical Papers.”—Editor)

In January 2004, a B-737-300 crashed minutes after takeoff from Sharm el-Sheikh, Egypt. The departure was on a dark night, over the Red Sea, and there were few, if any, visible cultural landmarks that could be used to orient to the horizon. The captain (the pilot flying, PF) had initiated a long left climbing turn, but partway through that turn the airplane had actually made a slow transition from a left bank to a right bank (20 degrees and increasing slowly). The first officer (F/O) informed the captain that they were turning right in this exchange: F/O: Turning right, sir. Captain: What? F/O: Aircraft turning right. Captain: Turning right? How turning right?

At this point, the captain was making control inputs on the wheel to roll further to the right, and continued doing so. The airplane eventually rolled to about 110 degrees to the right before substantial control inputs in the opposite direction were made, which were made too late to avoid the crash into the Red Sea. During this event, the captain seemed unable to determine which way to roll the airplane to restore it to wings level—at one point trying to engage the autopilot to get assistance in recovering from the upset. The investigation reached the conclusion that the pilot was spatially disoriented. (Of course, virtually every accident is the result of a chain of events and failures, and, in Boeing’s analyses, no accident was judged to be caused solely by a pilot’s spatial disorientation.)

This event and the findings of the investigation were surprising for many safety experts studying commercial jet transports: spatial disorientation (SD) was not considered a significant hazard in airline operations. SD was known to be a risk in high-speed, highly maneuverable military jets. But in the relatively stable world of commercial jet transports, SD was not considered a threat. At this point, the findings from Flash Air seemed to be a “one off” event. Unfortunately, two more similar B-737 accidents happened.
in 2007 (Adam Air at Sulawesi, Indonesia; Kenya Airways in Douala, Cameroon). In each case, the PF made control inputs away from wings level, resulting in a loss of control (LOC) and fatal crash.

In 2008, Boeing took a closer look at the influence of SD in commercial transport accidents. We established a clear definition of SD for this context and searched for accidents and major incidents that fit that definition. In some cases, accident reports, especially reports from before 1990, did not provide sufficient detail to place the event conclusively in the SD category. However, this extensive search identified 16 SD-related accidents and one major incident in the period of 1991–2007; roughly one event per year (see Figure 1). Also, 2008 produced another B-737 accident (Aeroflot Nord at Perm, Russia) that had the same signature of the PF rolling away from wings level. Further, since 2008, other accidents and incidents around the world have been linked to SD—e.g., Afriqiyah A330 at Tripoli, Libya in May 2010, and the Scat CRJ200 near Almaty, Kazakhstan, in January 2013.

One important finding of this review of accidents and incidents was the identification of two very different SD phenomena that were contributing to these accidents:

- **Sub-threshold roll**—In these cases, the pilot had an understanding or expectation of the airplane's orientation; typically, it was wings level. Then, for various reasons, the airplane rolled away from that orientation at a rate less than 5 degrees per second. Roll rates this slow fall below the vestibular system's ability to detect, hence the name sub-threshold. Further, load factors during the roll were less than 1.2 g's, indicating both that pilots were not loading up the airplane during an intentional turn and that their somatosensory (or "seat-of-the-pants") input would not have been significantly different from level flight. Pilots were unaware of the change in orientation and then suddenly found their airplane banked at 35 degrees or beyond. In this situation, these pilots were apparently confused about which direction to roll back to wings level, and they rolled the airplane in the wrong direction. These inappropriate pilot inputs were key because the airplane was not initially in an unrecoverable attitude. Note that it is possible that a post-roll illusion could also have influenced the progressively inappropriate control inputs.

- **Somatogravic illusion**—This illusion is quite different from the first. Sub-threshold roll relies on the vestibular system failing to detect a change to the airplane. The somatogravic illusion, on the other hand, is the result of a misinterpretation of a very noticeable sensation related to linear acceleration. This illusion typically occurs on a go-around when the airplane transitions from a slowing down to a rapid acceleration and pitch up. The vestibular system cannot distinguish between an inertial acceleration and a component of gravity, and the rapid acceleration can be misinterpreted as a further pitching-up moment. Again, poor-visibility conditions contribute by removing valid visual inputs. As the airplane begins the go-around, the pilot perceives that the airplane is pitching-up considerably and starts to push the nose downward to compensate. This can result in an actual nose-down attitude and descent into the ground.

**Commercial Aviation Safety Team**

These insights from the 2008 work led Boeing to engage the larger aviation safety community. In 2009, we approached the Commercial Aviation Safety Team (CAST) to share our findings on SD events. CAST takes the role of bringing together government and industry to analyze safety issues, generate potential solutions, assess the feasibility of those solutions, and adopt the solutions that are both effective and feasible. These solutions become the official CAST safety enhancements, which are then implemented by CAST members.

CAST agreed to study this issue beginning in 2010 and combined it with

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*Figure 1. Identified SD events.*
another group of LOC events tied to energy state. The larger theme for CAST was the pilot’s loss of awareness regarding airplane state: loss of attitude awareness (SD) and loss of energy state awareness. More generally, it was called airplane state awareness. The group given this charge included members from Boeing, Airbus, Embraer, Bombardier, Honeywell, Rockwell Collins, MITRE, Airlines for America, the Regional Airline Association, the National Air Carrier Association, the FAA, NASA, and pilots’ unions (ALPA and the APA).

This group conducted a detailed analysis of the following SD-related events, which was meant to be a representative set, not an exhaustive set of SD-related events:

- Gulf Air, Airbus A320, Aug. 23, 2000, Bahrain.
- Aeroflot-Nord, B-737-500, July 14, 2008, Perm, Russia.

The CAST analysis identified a number of other issues that contributed to many of these events. The most relevant of these for the SD events were:

- Lack of external visual references—In these SD-related events, due to darkness or IMC, flightcrew members had no clear view of the horizon through the flight deck windows and, therefore, lacked normal orientation and self-motion cues, such as perspective, depression angle, optical flow, and motion parallax. A visible horizon can establish “visual dominance,” a well-known perceptual phenomenon in which the visual input can overcome a vestibular illusion.
- Crew distraction—While some form of distraction occurs on virtually all flights, it is successfully managed by flight crews in the vast majority of cases. Flight crews are trained to eliminate and/or manage distractions. In the events we analyzed, the basic task of aviating was neglected, attention was not given to critical alerts or displays, or decision-making was hindered. A major component of this failure of attention was channelized attention, a phenomenon in which a pilot becomes completely focused on some task or issue and is unable to shift attention to other important tasks— in this case, aviating.
- Crew resource management—CRM is a broad term and covers many aspects of crew performance. Most relevant here was the inability of the flightcrew member who was NOT disoriented to intervene or take control from the PF. An authority gradient was at play in several of these events, as well as poor understanding or execution of managing an incapacitated pilot (i.e., the disoriented pilot). The one event that was not an accident was a case in which the pilot monitoring (PM) grabbed the wheel and column and fought hard (against the PF) to bring the airplane out of the dive (at about 320 feet above ground level).

The CAST work led to a number of proposed safety enhancements tied to changes to airplane design, operational procedures, and pilot training. It also called out specific needs in the areas of aviation safety R&D and safety data management [CAST’s final report on this analysis of airplanes state awareness events can be found at www.skybrary.aero/index.php/Commercial_Aviation_Safety_Team_(CAST)_Reports].

For the SD events, the safety enhancements ideally address both the PF’s inappropriate control inputs and the PM’s reluctance or inability to intervene when the PF is incapacitated by SD. One specific safety enhancement that Boeing is pursuing is a roll arrow that provides alerting and roll guidance to the pilot when bank angle exceeds 45 degrees. We believe this enhancement addresses both guidance for control inputs and more effective intervention.

**Accident investigation and analysis**

While the CAST work identified a broad set of safety enhancements, it failed to touch on accident investigation. In large part, the investigation agencies that try to make sense of pilot actions have no capability to assess the potential for SD. A few of the events mentioned above were subjected to this type of analysis because the investigating agency hired outside experts to apply their perceptual models to the flight data. Other investigation reports have only speculated about the possible influence of SD on the pilot’s actions and have provided no analysis. Boeing saw the need for a valid, accessible tool that allows investigators to look at flight data and determine if SD may have contribut-
ed to pilot control inputs. We turned to a group with expertise in modeling perceptual systems and illusions: the Netherlands Organization for Applied Scientific Research, or TNO. [TNO is the acronym for the Dutch version of this long title.]

TNO, with a long tradition in vestibular research, developed a general perception model to predict and analyze human motion perception in environments such as airplanes, cars, ships, and also moving-base simulators. Its state-of-the-art model consists of mathematical representations of the sensory systems involved in motion perception (i.e., visual and vestibular system) as well as their neural interaction. The model takes in time histories of self-motion and -orientation and predicts how they are being perceived. With respect to spatial orientation in aviation, the dominant issue is the perceived self-orientation relative to gravity. Essentially, the model takes the pilot’s point of view—i.e., the orientation of perceived gravity with respect to the self. Moreover, it is essential to understand that the human sensors are not perfect, and the central nervous system (CNS) does not reckon all laws of physics, such as Newton’s second law, and the differential relationship between position, velocity, and acceleration. This allows for perceptual ambiguities that basically determine spatial disorientation. The TNO model has been successfully applied to predict motion sickness incidence and to evaluate motion cueing in flight simulators.

We used the TNO perception model as the starting point for the collaborative development of a standalone software tool to support the analysis of SD events from flight data. The basic idea is that comparison between recordings of aircraft motion and attitude (model input), and the way this is being perceived according to the model (model output), should help identify the phases of flight that are prone to induce spatial disorientation. In its current state, the interpretation of the model output in terms of SD requires a subject-matter expert. The objective of the project was to make the model applicable and accessible for accident investigators by 1) implementing a module that automatically recognizes SD events in the data, also referred to as detection and identification, and 2) adding a user friendly interface.

**Basic perception model**

The perception model consists of the relevant sensory transfer functions and the visual-vestibular interactions that play a role in human spatial orientation (see Figure 2). In this model, the organs of balance within our inner ears sensing physical motions are divided into otoliths (OTO) and semicircular canals (SCC). The otoliths typically respond to specific force (f) and code for linear acceleration, and the semicircular canals respond to angular accelerations of the head, and their output codes for angular velocity (ω). Within the visual system, the optic flow (FLW) in the retinal image typically carries information on head velocity. In addition, horizontal and vertical elements in the retinal image provide a visual frame (F), and together with polarity (P) cues about what is “up” and what is “down” these determine the visual orientation of the head with respect to Earth (p).

Still, these vestibular and visual cues do not fully account for human orientation. Human subjects typically underestimate their self-tilt, a phenomenon called the A- or Aubert effect. To explain this bias toward the longitudinal body axis, which is considered a somatosensory phenomenon, Mittelstaedt in his 1983 writing *A New Solution to the Problem of the Subjective Vertical* assumed a body-fixed “idiotropic vector” (IV and i), which is added vectorially to the vestibular vertical.

The neural integration of these sensory signals has been implemented as follows. As stated, the otoliths respond to specific force (f), i.e., the vector sum of the free-fall acceleration determined by gravity (g), and inertial accelerations determined by linear motion (a), hence $f = g + a$. Although of different origin, accelerations due to gravity and inertia are inherently indistinguishable (Einstein’s equivalence principle). According to R. Mayne’s *A Systems Concept of the Vestibular Organs* (1974), our brain seems capable of making the distinction by a neural process that behaves like a low-pass filter (LP). Assuming that the brain “knows” that gravity is constant, and accelerations due to head motion are relatively variable, a low-pass filter adequately separates both components from the otolith output (f). Additional information on angular motion of
the head, coming from the semicircular canals and visual flow, is included in the model, not only to estimate subjective rotation (SR), but also to apply the required rotations (R and R⁻¹) for estimating the specific force components relative to Earth. This is required because the specific force is sensed in a head-fixed frame of reference, while gravity is constant in an Earth-fixed frame of reference. Using a weighted vector addition, the resulting internal estimate of gravity (g) is combined with the visual and idiotropic vectors to determine the subjective vertical, or SV.

In order to make the model applicable as a standalone tool for the detection of SD illusions from flight data, three enhancements were needed: 1) a “detection and identification module” to automatically recognize SD; 2) visualization of the model output; and 3) a user interface to allow interaction with the input and output. These enhancements are discussed in the next sections.

**SD categories**

Based on the results of the aforementioned Boeing study, the current project focused on automatic detection of vestibular illusions, in particular sub-threshold roll motion and the somatogravic illusion. More complicated vestibular illusions (e.g., the Coriolis illusion), as well as visual illusions tied to motion and orientation (e.g., “black hole,” vection illusion), fell outside the scope of this project, as these require information that is not available from the flight data recorder, such as the pilot’s head movements (Coriolis) and visual inputs.

Sub-threshold roll motion is related to the functioning of the semicircular canals and falls in the category of “somatogyral illusions.” This involves misperceptions of angular motion in general, not only undetected motions that remain below the perceptual threshold, but also false (after-) sensations of motion when the real (aircraft) motion has stopped. Examples of the latter are the “post-roll illusion” and the “graveyard spin.” Figure 3, page 9, shows the response of the semicircular canals to a step input of roll motion that is sustained for several seconds before it abruptly ends again. Since the semicircular canals behave like a high-pass filter, they only respond to changes in angular motion and not to constant rates. Hence, as the figure illustrates, the pilot accurately perceives the onset of roll motion, but this sensation gradually fades as the motion continues at a constant rate. Eventually, the sensation may become sub-threshold even though the aircraft is still turning at a rate that is above the perceptual threshold. When the turn is stopped, however, an after-sensation appears in the opposite direction of the original aircraft motion. This illusory after-sensation may prompt the pilot to make inappropriate control inputs. In the case of roll motion, it has been shown that the post-roll effect induces pilots to overshoot the bank angle. Hence, this vestibular effect also contributes to the crew’s confusion about the direction in which an aircraft is banking.

The “somatogravic illusion” is related to the functioning of the otoliths and the perceptual ambiguity of the specific force. The illusion has been studied during sustained centrifugation, where the constant tilt of the specific force is gradually being perceived as “vertical.” For example, a subject who is seated upright and facing the center of the centrifuge soon feels him- or herself tilted backwards, similar to the effect that a pilot may experience during a go-around maneuver. Figure 4, page 9, illustrates the model output in such a (simplified) situation.

**SD detection and identification**

The SD detection and identification module includes logic that discriminates between the various SD illusions (see Figure 5). The module first computes the mismatch between the perceived attitude (the subjective vertical) and the true orientation of the aircraft relative to Earth, as well as the mismatch between the perceived (subjective rotation) and angular rates. When one of these mismatches exceeds a critical value, another logic is
applied to identify whether a misperception of attitude results from the somatogravic illusion or from a cumulative effect of misperceived angular motion. Further, computations are being made to differentiate whether a somatogyrical illusion occurs during aircraft motion (when the perceived angular rate drops below a threshold value) or after aircraft motion (the post-roll effect, when the after-sensation exceeds the same threshold value). Looking at Figure 3, page 9, this means that although the perceived angular rate starts fading quite soon during the roll motion, it is only identified as SD when it drops below the threshold. Similarly, at the stop of the airplane roll, the illusory after-effect is only designated a post-roll illusion as long as the model-output exceeds the threshold. In addition, aircraft motions that do not exceed the threshold value at all are being identified as sub-threshold motion. The critical values used for identification are based on TNO research as well as the open literature and can be adjusted to optimize the model’s signal-to-noise ratio.

The TNO software tool

The software application takes in time histories of flight data (e.g., from a flight data recorder) selected in the ”Input and Settings” tab (see Figure 6) that also allows the user to set critical values. The model then computes the perceived motion, and labels the SD categories, that are shown on the ”Results” tab together. The model output can be saved to file on the ”Outputs” tab. Figure 6 shows a screenshot of the ”Results” tab of the graphical user interface (GUI). The plots on the left part of the window show time histories of rotation and attitude in three cardinal directions (x-axis = roll, or surge; y-axis = pitch, or sway; z-axis = yaw, or heave). The solid lines reflect actual aircraft motion (model input), and the dotted lines reflect the perceived motion (model output). The area between aircraft and perceived motion is shaded to indicate the mismatch that is input into the SD detection. The upper right part of the window shows the criteria settings. The bottom tracks show various SD labels that have been identified by the model: ”attitude” (mismatch in perceived attitude), ”grav” (somatogravic illusion), ”gyral” (somatogyrical illusion), ”sub” (sub-threshold angular motion). The bottom right of the window contains an animation of aircraft attitude (solid aircraft icon) and perceived attitude (transparent aircraft icon); the view can be toggled between aft and side view. When there is a misperception of attitude, these two deviate. The animation can be controlled with play, pause, and stop buttons. The vertical black line in the time series at the left part of the GUI shows the current time of the animation.

The example in Figure 6 corresponds to a coordinated turn to the right at 30 degree angle of bank. Around $t=7$ s, the perceived roll rate (dotted line in the upper time history) starts to wane due to the dynamics of the semicircular canals. This results in a mismatch between actual and perceived bank angle (more specifically, an underestimation of bank angle), as indicated by the ”attitude” track at the bottom. Between $t=8.5$ s and $10$ s, the label ”gyral” is also activated, indicating that the perceived roll rate has dropped below the threshold (3 degrees per second) while the aircraft is still rolling at a rate above this threshold (hence, the somatogyrical illusion). Being a coordinated turn, the aircraft’s specific force banks with the airplane up to about 30 degrees, and hence remains aligned with the body axis throughout the maneuver (solid line in the bottom time history). The model output (dotted line) in the same plot shows that the pilot briefly perceives banking to the right, but then the low-pass filter that distinguishes between inertial and gravitational acceleration causes the specific force to be perceived as vertical. Eventually this results in the feeling of ”level flight” while in reality the aircraft is banked relative to the Earth. Finally, after 10 seconds, the sub-threshold label is activated because the actual roll rate has dropped below the perception threshold.

Figure 7 shows another screenshot produced from data of a takeoff flown in a flight simulator. Due to the forward acceleration of the aircraft (solid line in upper plot), a false perception of pitching up arises (dotted line in bottom plot) while the aircraft stays level (i.e., zero pitch). From about $t=13$ s, the mismatch between perceived and actual pitch is large enough (criterion set at 8 degrees) to be identified as the somatogravic illusion, as well as misperceived attitude. These two examples show that both the somatogyrical and the somatogravic illusions can lead to misperceived attitude. In the case of the somatogyrical illusion, this is due to the time integral of misperceived angular motion.

A case study

This analysis, driven by the TNO model, shows that the vestibular system can often be fooled by airplane flight, and we know that virtually every pilot has experienced at least momentary confusion about orientation. However, we also know that pilots are rarely so disoriented that they make inappropriate flight control inputs because, typically, the visual infor-
The role of this tool in accident investigation is to help us understand why inappropriate control inputs—rolling away from wings level or pushing the nose down at a low altitude—were made. Figure 8 shows a brief illustration (part of a larger case study) using data from a B-737-300 accident highlighting this capability. The airplane took off on a dark night over water, so there were few visible cultural landmarks to support orientation. The PF had initiated a long left-climbing turn, but partway through that turn the airplane made a slow transition from a left bank to a right bank. This period of transition from about 20 degrees left bank to 20 degrees right bank took about 70 seconds, and the airplane was pitching up and slowing down 15–20 knots during this period.

The model analysis indicates that, during this period, there was no vestibular feedback on the airplane’s orientation and motion, which, without strong visual input on orientation, would have led to the PF’s confusion about the airplane’s orientation. The SD track “sub” shows that the transition from banked left to banked right was almost completely sub-threshold, meaning that the pilots did not feel the airplane’s roll motion. Second, similar to the example in Figure 7, page 11, the specific force vector during this coordinated flight remained aligned with the airplane’s z-axis, which from a vestibular perspective is undistinguishable from wings level. Hence, there was no meaningful vestibular information about the airplane’s change in attitude, which explains the SD track “attitude” in Figure 8.

Looking in more detail at the figure, the sub-track is interrupted at places where the model output for roll rate temporarily exceeded the threshold (refer to Figures 3 and 4, page 9, to see how the internal threshold determines whether the model output activates an SD label). The interruptions of the attitude track correspond to periods where the mismatch in perceived attitude was smaller than the criterion of 8 degrees. Note that according to the shaded area in the bottom time history, there was little or no vestibular feedback about the change in heading (perceived yaw angle remained around 0 degrees), but since heading does not affect the orientation relative to gravity, it is not included in the determination of SD.

During this 70-second period, also, the PF became confused and distracted by some unexpected behavior from the autoflight system. This distraction probably reduced his awareness of his slow, perhaps inadvertent, control inputs to roll right. When the PF was told that he was turning right, he became confused about his orientation and how to return to wings level. Subsequent roll inputs were strongly to the right, leading to a loss of control and fatal crash.

This short illustration of the model’s analysis capability shows how it can be combined with the cockpit voice recorder, flight data recorder, and environmental data inputs to create a more complete picture of the pilot’s understanding of the state of the airplane. This data integration and analysis is at the heart of accident investigation and allows us to explain flight control inputs more completely.

**Conclusions**

Any accident investigation that implicates human performance issues (“pilot error”) needs to consider performance in context, and, in some cases, that context should include the sensory systems’ inputs to the pilot’s overall situation awareness. The long history of aviation safety has shown that SD occurs and can have fatal consequences. The TNO tool offers a method to more completely examine that context. It shows what the pilot’s vestibular system was telling the pilot about his or her orientation and motion. Certainly, this input is only part of the whole picture; but when there is a degraded visual environment, we have seen that the vestibular inputs can drive the pilot’s actions into a larger upset and loss of control. In some cases, the reality generated by these false perceptions can be strong and enduring and, unless there is a rapid and forceful response from the PM, can lead to a crash.

These SD events will probably continue to occur in the short term. The recommendations from CAST advocate for changes to airplane design, operations, and flight crew training to address some of the factors that contribute to turning SD into accidents. We hope that, eventually, these changes will significantly reduce the risk of SD turning into a LOC event. In the meantime, the tool developed by Boeing and TNO can become an essential element of the accident/incident investigation process.
Investigating the Voyager Pitch-Down Incident

The Voyager investigation is a case study of civil/military cooperation demonstrating that independence most certainly does not mean isolation.

By Col. Crispin Orr, Head of the UK Military Air Accident Investigation Branch

On Feb. 9, 2014, a Royal Air Force (RAF) Airbus A330 Voyager aircraft, ZZ333 (see Figure 1), with 189 passengers and 9 crewmembers on board, was flying on its first-ever nonstop routing to Afghanistan. At 1549 UTC (night time) the aircraft was in cruise at FL330 over Turkey with Autopilot 1 engaged. The captain was alone on the flight deck as the copilot had left his seat for a break and was in the forward galley. Suddenly and without warning, the aircraft pitched down violently, throwing unrestrained passengers and crew to the ceiling. The captain attempted to take control by pulling back on his side-stick controller and pressing the autopilot (AP) disconnect button, but these actions were ineffective. The aircraft lost 4,400 feet in 27 seconds, registering a maximum rate of descent of 15,800 feet/minute and reaching Mach 0.9 as the crew wrestled with what they thought to be an autopilot malfunction. Fortunately, the aircraft was brought back under control and diverted successfully to Incirlik Airbase in Southern Turkey. Twenty-five passengers and 7 crewmembers reported minor injuries; however, the consequences, had the incident occurred closer to the ground, could have been catastrophic.

This adapted article will outline the investigation undertaken by the UK’s Military Air Accident Investigation Branch (MilAAIB) in support of a service inquiry to establish the cause of the incident and make recommendations to prevent a recurrence. It is a case study of civil/military cooperation demonstrating that independence most certainly does not mean isolation.

The MilAAIB was established in 2011 following Charles Haddon-Cave Queen’s Counsel independent review of the broader issues surrounding the loss of the RAF Nimrod aircraft XV230 in Afghanistan in 2006. Among his many criticism of the Ministry of Defense’s (MOD) airworthiness regime, he made a number of specific recommendations with respect to accident investigation. Consequently, the MilAAIB was established as a professional and joint military air accident investigation branch, completely independent of the Army, the Royal Navy, and the Royal Air Force. The branch was established at Farnborough alongside the civilian Air Accident Investigation Branch (AAIB) to ensure maximum benefit from their corporate knowledge and experience gained from 100 years of investigations since Capt. George Cockburn of the Royal Flying Corps was appointed as the very first inspector of air accidents. Operating
under a charter from the State for Defense secretary and reporting directly to the director general of the Defense Safety Authority (DG DSA), the MilAAIB is as independent as it can be, while also employing military experts who can deploy at a moment’s notice to accidents worldwide, including to operational theatres.

**Initial investigation**

When notification came in of the Voyager incident, the MilAAIB was ideally placed to coordinate any response with the AAIB. The Voyager is an Airbus A330 aircraft modified to provide a multi-role tanker transport capability to the RAF. The aircraft are owned and operated by Air Tanker Ltd, a joint venture made up of Cobham, Airbus, Rolls-Royce, Thales, and Babcock, but the majority of deployable personnel (aircrew and engineers) are military. Each aircraft must be able to switch between the civil aircraft register and the military aircraft register depending on how it is being used. On February 9, ZZ333 was operating as a military aircraft, so the lead for any investigation fell to the MilAAIB. However, we were delighted to be able to include an AAIB investigator with extensive experience of the A330 in the team of three who deployed.

Their immediate task was to secure the vulnerable and perishable evidence and provide an initial assessment of the situation. The quick access data PCMI card, the digital flight data recorder (DFDR), and cockpit voice recorder (CVR) were returned to the UK for download and analysis, concurrent with initial technical investigation and interviews in Turkey. Incredibly, there was very little damage to the aircraft, and it soon became apparent that the crew’s diagnosis of an autopilot fault was not supported by the physical and data evidence, which indicated that the event was triggered by a full-scale deflection of the captain’s side-stick controller (see Figure 2), at which point the autopilot had disengaged. Following the MilAAIB’s initial report on February 12, the DG DSA elected to convene a full service inquiry.

**What caused the pitch down?**

The initial focus for the inquiry was to determine what caused the pitch-down event, as this was still unknown and there were a wide range of possibilities. There was some urgency to this as Air Officer Commanding 2 Group, the operational duty holder, had elected to “pause” Voyager flying, and there was considerable public interest given the huge number of A330 aircraft flying worldwide. From the outset, we had full engagement and support from the operator (Air Tanker) and the OEMs (Airbus and Rolls-Royce), with these companies providing valuable assistance to the investigation in Turkey and back in the UK. The AAIB kindly downloaded the DFDR and CVR data for us, and the DFDR data were sent to Toulouse, France, for detailed examination by Airbus flight control specialists. In parallel, the side-stick unit (SSU), which had passed all functional checks, was returned to the UK for a more detailed forensic technical examination.

The breakthrough came a few days later when one of the MilAAIB investigators was listening (for the 100th time) to the CVR and detected a distinct noise on the cockpit area microphone channel, 1 minute and 44 seconds before the pitch-down event. This corresponded with a very small forward displacement of the captain’s side-stick that was too small to cause the autopilot to disengage and so did not result in any disturbance to the aircraft. The noise reoccurred just before the pitch-down event, and spectral analysis confirmed that the sound exactly matched the electric motor used to move the captain’s seat forward.

This temporal and directional correlation between seat and side-stick movement was compelling, and the investigation sought to establish how they could be connected. The small initial displacement of the side-stick and the subsequent linear ramp to full-scale deflection in the fore-aft axis without any lateral input could not be recreated by human pilot input, so the panel’s focus turned to the possibility of an object connecting the seat to the side-stick. All official items and personal effects that had been on the flight deck at the time were examined, with particular interest in the captain’s camera, which had been seen in the vicinity of the captain’s side-stick shortly
before the event.

Twenty-eight photographs had been taken of the cockpit in the eight minutes prior to the incident, with the last photo taken 1 minute and 35 seconds before the initial side-stick displacement. Analysis of the CVR revealed that four seconds after the last photo was taken, the purser had come onto the flight deck and had a short conversation with the captain before returning to the cabin. On close examination, the camera was found to have a large dent on its right-hand side. This was mapped forensically using surface profilometry and found to be a perfect match with the hand grip flange at the base of the side-stick. Furthermore, chemical analysis indicated that trace amounts of material in the indentation matched the material type of the side-stick.

Using the Voyager simulator, the team placed a copy of the camera between the armrest, which had been adjusted to the captain’s preferred setting, and the side-stick. When the seat was motored forward, the camera pushed the side-stick fully forward and became geometrically locked in place (see Figure 3). The hand control base plate was perfectly aligned with the position of the dent in the captain’s camera. The reconstruction took only a few seconds to set up and could be repeated time and again.

The investigation continued to examine all other possible explanations for the pitch-down event, but with the likelihood of a technical cause diminishing and Airbus coming under increasing pressure from worldwide customers to clarify the situation, urgent safety advice was issued to the RAF and to Airbus on February 28, confirming that human factors was the probable cause of the Voyager pitch-down event and highlighting the magnitude of the risk presented by foreign objects in the immediate vicinity of the side-stick. This was followed by an interim report that was published on the Gov.uk website a couple of weeks later.

Once all other possibilities had been eliminated, the panel concluded that the cause of the pitch-down event was an inadvertent physical input to the captain’s side-stick by means of a physical obstruction (a camera) that jammed between the left armrest and the side-stick unit when the captain’s seat was moved forward.

**How was the aircraft recovered?**

Having established the potential for the camera to geometrically lock in place, the investigation sought to establish how the aircraft was recovered. When the aircraft pitched down, the captain’s instinctive reaction was to pull back on the side-stick. This can be seen clearly from the DFDR traces, albeit the side-stick remained substantially blocked in the forward position. Convinced it was an autopilot malfunction, the pilot repeatedly pressed the AP disconnect button on the side-stick (although the autopilot had in fact, already disconnected).

The copilot, who had hauled himself back into the cockpit, also pulled back on his side-stick. Reacting to the captain’s shouts that he couldn’t get the autopilot out, the copilot pressed his AP Disconnect button repeatedly. The button has a dual function, and when the autopilot is disconnected, as it was in this case, the button switches the priority stick input to the Flight Control System (FCS) between the LHS captain’s side-stick and the RHS copilot side-stick. Had control been formally handed to the copilot, the captain’s inputs would have been locked out and the problem neutralized. But in the confusion of the event, on a darkened flight deck, in a negative “g” bunt, the crew became fixated on trying to get the autopilot out and control priority kept switching back to the fully deflected left stick.

Fortunately, the A330 fly-by-wire FCS incorporates overspeed and pitch-down self-protection features to prevent exceedance of flight envelope limitations. Three seconds after the initiation of the pitch down, the FCS acted to limit the pitch attitude to 15 degrees nose down, and 10 seconds later the high-speed protection feature activated to reduce the engine thrust to idle and pitch the aircraft up at approximately 1.75 g’s (see Figure 4, page 16). The aircraft flew itself out of the dive.

Thirty-three seconds after the pitch down, the obstruction was cleared, the captain’s side-stick sprung back to the neutral position, and the crew regained full control of the aircraft. The investigation considered whether the obstruction was cleared by a movement of the side-stick, the seat, the armrest, the camera, or a combination of these. Extensive simulator tests were conducted, and the evidence strongly suggested that the camera was physically manipulated from behind the side-stick, but the crew was unable to clarify this.

It is noteworthy that during the pitch down, the captain, in his desperation to regain control, considered switching off the Air Data and Inertial Reference Units (ADIRU) in order to place the aircraft...
into “direct law” control mode. Had he done this, the aircraft’s pitch and overspeed self-protection features would have been disabled, and the aircraft would almost certainly have exceeded its certified flight envelop limits by a considerable margin, potentially leading to significant damage to the aircraft.

Human factors analysis
Having established “what” happened during the incident, deeper analysis was undertaken with the assistance of the human factors experts from the RAF Centre of Aviation Medicine to probe “why” it had happened to enable formulation of recommendations to prevent recurrence. The pertinent sequence of events was that the camera was taken onto the flight deck, the camera was used, the camera was placed behind the side-stick, and the seat was then moved without any appreciation of the potential outcome.

Carriage of the camera was not prohibited by any rules or regulations, and the investigation found its presence was consistent with normalized behavior regarding loose articles on RAF air transport aircraft. This behavior had itself been the subject of a safety investigation at RAF Brize Norton, following concern at the number of loose articles found by maintenance personnel on the flight deck of C130 aircraft. The Voyager crew was required to take a large number of items with them, including two sets of body armor, combat survival waistscoats, crew weapons, aircraft documentation, two route bags, and worldwide navigation charts—and there was little dedicated storage for these items. With the acceptance of a large number of official items on the flight deck, the carriage of a small number of personal effects was not considered unreasonable.

Equally, there was no specific rule that prohibited use of the camera during flight. The captain was a photography enthusiast and had often taken pictures on the flight deck. However, the Voyager Operations Manual did state that “flight crew must refrain from nonrelevant duties while the other pilot is away from the active ATC frequency,” and this procedural defense was breached by the pilot taking 28 photos when alone on the flight deck. It was a very quiet period of the flight, and it was assessed that low pilot workload and boredom, compounded by the presence of only a single person on the flight deck for an extended period of time, all made the use of the camera more likely and therefore was a contributory factor.

The placing of the camera behind the side-stick created a hazard that was unrecognized and subsequently led directly to the pitch down. The distraction of the captain by the purser entering the flight deck may have contributed to this. The minimum distance between the armrest and the side-stick was 50 millimeters; but as this incident proved, the two could be coupled by a foreign object placed in the space between. Although there had been no recorded incidents of this happening in 190 million flying hours of Airbus aircraft, inadvertent disconnection of the autopilot by knocking the side-stick had occurred 26 times on the Voyager in the previous two years—none of which had been reported.

The Airbus Flight Crew Training Manual advocated a clean cockpit: “objects not stored in their dedicated area in the cockpit may fall and cause hazards such as damage the equipment or accidentally operate controls or pushbuttons.” And MAA Regulatory Article 2309 directs “that the aircraft commander should ensure that all loose articles and stores are properly stowed such that there is no possibility of fouling the flying controls.” However, the risk regarding flight deck control interference on the Voyager had not been specifically identified and was therefore not being actively managed by the duty holder.
The final link in the chain was the movement of the seat, which is a routine occurrence in flight on the A330. The investigation considered that the time delay between the captain putting the camera down when the purser entered the flight deck, and his separate action to adjust his seat position 104 seconds later using a switch in a different area of the flight deck, meant that the resultant change in aircraft attitude would have been extremely unexpected. It is not surprising that the captain did not see the connection between these events at the time.

**Recommendations to enhance safety**

This incident was an extraordinary and possibly unprecedented event. However unlikely an exact recurrence may seem, the consequences of flight control interference can be catastrophic. The service inquiry illuminated a number of underlying issues that warranted attention and made 24 recommendations to enhance flight safety. Some of these issues are not unique to the Voyager (or indeed to military aviation in the UK), and the following recommendations may be of interest:

- Implement a comprehensive strategy to effect a positive change in the safety culture with respect to loose articles on the flight deck.
- Take steps to minimize what is carried on the flight deck and maximize the use of designated stowage areas.
- Review the rules governing minimum crewmembers at their station.
- Take measures to further strengthen the reporting culture.
- Ensure that the critical importance of a clear handover of control in side-stick equipped aircraft is emphasized throughout training.
- Examine ways of managing low in-flight pilot workload.
- If possible, implement measures that could help prevent the placing of loose articles in close proximity to the side-stick.

**Concluding remarks**

- **The incident**—This incident was a very serious near miss and serves as a timely reminder that one simple and unthinking act such as placing a loose article close to the aircraft controls could develop quickly into a catastrophic event. On this occasion, the A330 automatic self-protection features likely prevented a disaster of significant scale. Fortunately, there was no accident, but the occurrence was nonetheless investigated to the same degree by the MilAAIB and others in support of a full service inquiry.

- **No-blame safety investigation focused on identifying carefully targeted recommendations to enhance safety**—The investigation was a no-blame safety investigation, so while others outside our community may focus on the rights or wrongs of the crew’s actions on the day, we were able to probe the underlying human factors and organizational issues and illuminate wider cultural concerns that need to be addressed to prevent other loose-article-related events. The recommendations made have been carefully targeted at those senior post holders in defense who have the means to effect the changes required. Their implementation will be tracked to completion and may only be closed by DG DSA.

- **Thorough and expert team effort**—The inquiry was undertaken impartially by a panel and a professional investigation branch that were completely independent of the operator, the regulator, the manufacturer, et al. However, a thorough and evidence-based investigation could not have been completed effectively without the full cooperation of Air Tanker Ltd and the MOD Project Team, the full support of the civil AAIB and the Airbus Investigation Team, the technical assistance of Rolls-Royce, the forensic laboratory capabilities of the Materials Integrity Group, the 1710 Naval Air Squadron, the data-fusion capabilities of QinetiQ, the evaluation skills of test pilots from the Air Warfare Centre and Airbus, and the human factors expertise residing in the RAFCAM. Working together as a team, we were able to resolve the apparent conflict between the crew’s perception of what happened and the evidence from the DFDR and understand what was initially a perplexing mystery.

- **Independence**—It is my contention that independence is very important, especially in the leadership of a major investigation. The investigation must be protected from improper interference, and investigators must have the freedom of maneuver to conduct the investigation without fear or favor. But it is our experience that this does not mean and cannot mean isolation. We in the MilAAIB recognize that we are dependent on other agencies. Some are independent, and some are not, but we highly value their necessary expert contribution regardless. Hence, we go to some lengths to develop our support network, and ISASI seminars are a marvelous opportunity to further cultivate that!

- **Transparency**—We also recognize, that despite being a military unit engaged on very sensitive work, there is a balance to be struck between protecting sensitive information and sharing information that can enhance safety. In this we draw a distinction between protecting the inputs to an investigation (confidential witness testimony, for example) and providing maximum transparency of the process and the outputs. Following the Voyager pitch-down incident, there was legitimate concern from Airbus operators worldwide until the probable cause was established and communicated. It was therefore beholden on us to promulgate that safety advice to stakeholders as soon as we had something tangible to release. At the end of an investigation, we always publish the final report on the Internet. But with the Voyager, in a first for us, we also published an interim report on the Internet as soon as the probable cause was established and while the investigation was still ongoing. This public release was hugely effective in defusing public concern and is a practice that we have now adopted as an SOP. We think this transparency of process and output help to demonstrate our independence without in any way compromising it. We steadfastly defend that independence, but we also strongly support the view that independence does not mean isolation.
Investigating Human Fatigue

The key to any robust investigation is to ask the right questions and gather as much data as possible to ensure important fatigue-related factors are not being missed.

The 24/7 nature of aviation means that fatigue will always be a consideration in accident investigations. Fatigue is a condition characterized by increased discomfort with lessened capacity for work, reduced efficiency of accomplishment, and loss of power or capacity to respond to stimulation, and is accompanied by a feeling of weariness and tiredness (FAA pilot safety brochure Fatigue in Aviation. Publication # OK-07-193). A group of international human performance experts conceded “fatigue...is the largest identifiable and preventable cause of accidents in transport operations.”

The adverse effects of fatigue on human performance have been demonstrated in scientific research and accident and incident investigations. These effects include slowed response time, reduced vigilance, and poor decision-making. No one is immune, and fatigued aviation personnel put themselves and others at risk. However, the ability to collect and analyze data to conclusively identify fatigue as a causal/contributing factor in accidents is challenging, as fatigue can be subtle and there is no “blood test” to provide a positive-negative indicator. Investigators must not only determine if persons involved were experiencing fatigue at the time of the accident, but also whether their actions were consistent with the known fatigue-related performance decrements.

Over the last decade, tools and techniques for investigating fatigue have evolved, and the number of potential data sources useful to evaluate fatigue in an operator have increased. Here we will highlight the “nuts and bolts” of fatigue investigation in the context of two accident investigations in which the U.S. National Transportation Safety Board (NTSB), an independent agency, collaborated with the operators, the Federal Aviation Administration (FAA), and the Bureau d’Enquêtes et d’Analyses pour la Sécurité de l’Aviation Civile (BEA) in accordance with the provisions of Annex 13 to the Convention on International Civil Aviation. Specifically, UPS Flight 1354, an Airbus A300 that crashed on approach to Birmingham–Shuttlesworth International Airport in Birmingham, Alabama, and a Eurocopter AS350-B2 helicopter operated by Sundance Helicopters on a sightseeing trip that crashed near Las Vegas, Nevada.

What do we look for?

Before delving into the case studies, it is important to understand what investigators look for to determine whether fatigue played a role in an accident. There are five factors that can lead to a fatigued state that are considered in each accident investigation: 1) circadian factors; 2) time since awakening; 3) quantity of sleep; 4) quality of sleep; and 5) sleep disorders.

Circadian factors are those factors affecting an individual’s normal circadian rhythm, such as a schedule inversion/rotation or crossing multiple time zones. Humans naturally follow a diurnal schedule, and the primary circadian trough is about midnight to 0600, with the window of circadian low generally occurring between 0300 and 0500. However, shift work and long-distance flights across multiple time zones can disrupt this sequence. While research suggests that it is possible to shift one’s circadian clock about 1 hour per day, the ideal conditions required are difficult to obtain and the shift is often less. Further, personal obligations often result in the shift worker reverting to a diurnal schedule when off duty, thus negating any circadian shift that may have occurred.

Time since awakening refers to the number of hours the individual has been awake since a last major sleep opportunity of three hours or more. According to the National Sleep Foundation’s “How much sleep do we really need?” on average, individuals need seven to nine hours of sleep per night to feel rested upon awakening, resulting in 15–17 hours of wakefulness each day. Research quantifying performance impairment associated with sustained wakefulness found that performance remains relatively stable throughout the time that coincides with a normal waking day, but that prolonged wakefulness of 17 hours can result in measurable performance impairment (comparable to having a blood alco-
By Katherine Wilson, Ph.D., Human Performance and Survival Factors Division, U.S. National Transportation Safety Board (NTSB)

Quantity of sleep is the number of hours slept during each major sleep period in the days preceding an accident. A minimum of three nights’ sleep activity should be documented, but data should be collected for as far back as is considered to be reliable from the source. An individual’s normal sleep patterns should also be documented to determine the number of hours needed to be wake rested. Knowing the “normal” amount of sleep is very important to investigators, as it allows a comparison to be made between the number of hours slept and the individual’s normal sleep requirements to quantify acute and chronic sleep debt. Just two hours of sleep loss can result in reduced performance and alertness.

Quality of sleep, or how well the individual slept, can further help investigators understand an individual’s fatigued state. It should be determined whether the individual’s sleep was fragmented (e.g., multiple sleep periods in a given 24 hours) and/or disturbed (e.g., awakenings during a sleep period). Factors that can influence quality of sleep include environmental reasons such as noise, light, and phone calls and medical reasons such as heartburn or headache and internal reasons such as life stressors.

Sleep disorders and medical factors, including physical and mental disorders, and medications can impair sleep and lead to a fatigued state. Physical and mental disorders can include pain, urinary frequency, neurological disease (e.g., Parkinson’s disease, dementia), cough/shortness of breath, and psychiatric disease. Medications for conditions such as depression, hypertension, osteoporosis, and seizures (among others) can also interfere with an individual’s sleep. Finally, sleep disorders, including sleep apnea, restless leg syndrome, and narcolepsy, can result in a restless night’s sleep and a fatigued state. The most common sleep disorder, sleep apnea, affects 10–20 percent of the adult population.

The data needed to examine these factors should be collected from as many sources as possible. Key evidence sources include, but are not limited to, interviews with the individual operator or those who have knowledge about the individual, work schedules/logbooks, cellular telephone records, audio/video/data recordings, other time-stamped records (e.g., hotel records, company badge access), and medical records. However, there are challenges to collecting such data such as operator available capability, memory limitations, perishable evidence, time-stamp irregularities (time zone differences, noncalibrated clocks), and legal hurdles that must be considered.

Once the data are collected, they must be organized and analyzed to determine whether the operator was fatigued at the time of the accident. If it is determined that the operator was fatigued, it then must be determined whether the actions taken by the operator that led to the accident are consistent with the known performance decrements of fatigue. If the operator’s actions are consistent with being fatigued, fatigue likely caused or contributed to the accident. While fatigue is the focus of this discussion, other factors may also be causal or contributory to the accident sequence, such as workload, training inadequacies, or previous operator performance deficiencies, to name a few, that should be considered.

In the following two case studies, fatigue was determined to have a role in the accident.

A tale of two accidents. What role did fatigue play?

UPS Flight 1354—On Aug. 14, 2013, about 0447 Central Daylight Time (CDT), UPS Flight 1354, an Airbus A300-600, crashed short of Runway 18 during a localizer nonprecision approach to Runway 18 at Birmingham–Shuttlesworth International Airport (BHM) in Birmingham, Alabama, fatally injuring the captain and first officer (see Figure 1). At the time of the accident, dark night visual meteorological conditions prevailed at the airport; however, variable instrument meteorological conditions with a variable ceiling were present on the approach north of the runway. The flight had departed from Louisville International Airport–Standiford Field (SDF) in Louisville, Kentucky, about 44 minutes before the accident.

As the pilot flying (PF), the captain was responsible for monitoring the airplane systems and flight path, and as the pilot monitoring (PM), the first officer was responsible for monitoring and cross-checking the PF. The takeoff, climb, and cruise phases of the flight were normal, and the crew completed all required checklists. The flight was cleared direct to BHM, which the crew entered into the flight management computer (FMC). While
established at their cruising altitude, the first officer tuned in the ATIS and reported to the captain that Runway 18 was in use at BHM. Shortly thereafter, the captain briefed and set up the approach per UPS procedure using the profile approach briefing guide. When descending to 3,000 feet, BHM approach control directed the flight crew to turn 10 degrees right to join the localizer. Both crewmembers recognized that the localizer was captured. However, about this time, the first officer failed to “clean up” the approach in the FMC, which required her to remove the direct to BHM so that only the localizer approach to Runway 18 was available. Because she did not complete this step, a route discontinuity was present in the FMC. The flight crew failed to recognize the route discontinuity in the FMC for the remainder of the flight, which did not allow the FMC to capture the computer-generated flight path, also known as the profile, for vertical guidance to the runway. When the automation did not capture the profile, the captain reverted to vertical speed mode to descend toward the runway; however, he did not communicate this to the first officer.

About one minute before the airplane impacted trees, the first officer stated, “Let’s see you’re in…vertical speed…okay” to which the captain stated, “...yeah I’m gonna do vertical speed. Yeah he kept us high.” The airplane was descending at 1,000 feet per minute (fpm), which was increased to 1,500 fpm shortly thereafter, but again was not verbalized by the captain.

About 30 seconds before impact, the first officer made the appropriate 1,000 foot callout, and the captain responded, “Alright ah DA [decision altitude] is twelve ah hundred.” Neither crewmember recognized that the flight was descending at 1,500 fpm, which exceeded the stabilized approach criteria below 1,000 feet of a maximum of 1,000 fpm descent. At this point, a go-around should have been executed. The first officer confirmed the DA, and the captain stated, “two miles,” which coincided with the distance to the runway when the DA should be crossed. About this same time, the first officer should have made the approaching minimums and five seconds later the minimums callout; neither callout was made and the flight crew did not recognize that the flight descended below minimums. About eight seconds before impact with trees, the crew received a sink rate alert, and four seconds before impact stated they had the airport in sight. The first point of impact with trees was about 6,387 feet north of the Runway 18 threshold.

Postaccident examination found no evidence of any structural, engine, or system failure or anomaly occurring prior to impact, and the airplane met all FAA regulations and the manufacturer’s recommended maintenance program.

Therefore, the investigation focused on the flight crew. A review of company records revealed that the flight crew had adequate experience and was properly trained for the flight. While the investigation also focused on the flight crew’s workload and expectation of weather conditions, the information presented here will focus on flight crew fatigue.

Data were used to determine whether the flight crew fatigue was causal or contributing to the accident. Data were gathered through interviews, company records, hotel records, cellular telephone records, and information retrieved from six personal electronic devices found in the crewmembers’ personal possessions. The captain had been off duty for seven days prior to returning for duty the day before the accident. There was nothing from the previous day’s schedule that was unusually demanding, and it did not result in an extended duty day or reduced rest period the day before the accident. In addition, he took steps to be fit for duty and to mitigate the effects of fatigue when flying during the overnight hours by napping prior to returning to duty and securing a sleep room at the UPS facility during his two duty periods before the accident. Although he had an adequate sleep opportunity the day before the accident, daytime sleep can be less restorative than nocturnal sleep. He had also previously reported to colleagues that he had a difficult time adjusting when returning to night flying.

The first officer had a 62-hour scheduled layover prior to returning for duty the day before the accident. During the period, the first officer visited a friend in a nearby city and reverted to a diurnal schedule. On the subsequent nights leading up to the accident flight, a review of data from the first officer’s mobile devices revealed that she did not have ample sleep opportunity to obtain adequate rest prior to resuming duty and returned to duty with an estimated three-hour sleep debt. The first officer was aware of her fatigued state as evident in text messages retrieved from her cellular phone at the end of this duty period; she was estimated to have a nine-hour sleep debt. During her 14-hour-and-30-minute layover the day before the accident, she had less than a five-hour-and-30 minute sleep opportu-
nity due to electronic device usage and unknown activities outside of her hotel room.

At the time of the accident, the flight crew had been on duty about eight hours and 30 minutes. The captain had been awake about 14 hours, and the first officer had been awake for more than 18 hours. Although the duty day was not unusually long, the first officer, particularly, had been awake for an extended period of time. In addition, the accident occurred about 0447, and the flight crew was awake in opposition to their normal circadian rhythm. Neither flightcrew member had a known sleep disorder or reported difficulty sleeping to their family during their off-duty periods.

The investigation determined that the errors made by the flight crew during the approach (e.g., failing to clean up the FMC, missing callouts, continuation of an unstabilized approach) were consistent with the known effects of fatigue. Therefore, the NTSB cited the crewmembers’ fatigue due to operating during the window of circadian low [circadian factors], and the first officer’s ineffective off-duty time management and acute sleep loss [quantity of sleep and time since awakening] as contributing to the continuation of an unstabilized approach. As a result of this investigation, the NTSB made one safety recommendation to the FAA and two companion recommendations to UPS and the Independent Pilots Association related to fatigue. [See the full report at http://www.ntsb.gov/investigations/AccidentReports/Reports/AAR1402.pdf.]

Sundance Helicopters sightseeing trip—
On Dec. 7, 2011, a Sundance Helicopters sightseeing tour Eurocopter AS350-B2 helicopter crashed near Las Vegas, Nevada, about 1630 Pacific Standard Time, fatally injuring all aboard (see Figure 2). The helicopter was operating as a “twilight tour” sightseeing trip. Dusk light and visual meteorological conditions prevailed at the time of the accident. The helicopter had departed from Las Vegas McCarran International Airport (LAS) in Las Vegas, Nevada, about nine minutes before the crash.

Maintenance was performed and completed on the accident helicopter the day before the accident, including a 100-hour inspection. The 100-hour inspection was to be completed every 100 flight hours and included a combination of visual, condition, and measurement checks throughout the helicopter. These checks were specified in the 100-hour checklist contained in the Eurocopter Aircraft Maintenance Manual. In addition, maintenance performed included the replacement of the tail rotor servo, the engine, and the main rotor fore/aft servo with a new (zero hour) unit. Following the maintenance, a quality control (QC) inspector inspected the work and completed a ground run and checks.

On the morning of the accident, a check pilot performed a before first flight (BFF) check (an external inspection of the helicopter), where he found the hydraulic belt loose, conducted a post-maintenance flight check, and then flew a tour flight in the accident helicopter. The accident pilot flew the accident helicopter on one tour flight before the accident flight.

Examination of the wreckage found that the flight control input rod was not connected to one of the three hydraulic servos that provides input to the main rotor. Missing from the wreckage were the bolt, washer, self-locking nut, and split/cotter pin that normally secure the input rod to the main rotor/af servo. Postcrash examination of likely scenarios for why the helicopter experienced a loss of control in flight determined that the disengagement of the fore/aft servo bolt was most likely. Further testing of the most likely explanation for how the bolt disengaged during flight determined that the hardware was improperly secured during the previous day’s maintenance. Specifically, the split/cotter pin was not installed or not installed correctly, allowing the self-locking nut to separate from the bolt, and then the bolt to work its way out of the joint due to normal inflight vibratory forces. At this time, the input rod would have separated from the linkage and the helicopter would have become uncontrollable.

The investigation focused on the mechanic and inspector who replaced then inspected, respectively, the fore/aft servo the day before the accident. It was the mechanic’s responsibility to connect the input rod to the servocontrol distributor by 1) installing the pin, washer, and nut, 2) torquing the nut, and 3) securing the nut with the split/cotter pin (see Figure 3). If the nut meets the torqueing requirements for Eurocopter, it can be reused, otherwise it must be replaced with a new nut. During postaccident interviews, the mechanic indicated that the nut was airworthy and could be reused. After reassembly, he said he torqued and safe tied everything, including securing the input rod connection with a split pin.

The inspector reported that he inspected the fore/aft servo input rod, hardware, and split pin and marked them with a torque pen and that he inspected the hydraulic lines that connect to the manifold; he did not find any problems during the inspections. The inspector also performed ground run and checks with the mechanic’s assistance. The checks took about 40–45 minutes to complete and were completed about 1800 the day before the accident.

Despite the statements made by the mechanic and inspector, the evidence indicates that the split/cotter pin was not present or not installed improperly; however, neither the mechanic nor the inspector recognized this. There were no significant issues in either of their performance histories, time pressure, or environmental issues to explain the performance lapses. Although the investigation also focused on the maintenance work cards, the information presented in this example will focus on the role of fatigue on the performance of these individuals. Data sources included interviews.

Figure 3. A properly installed nut and split/cotter pin of the fore/aft servo input rod connection.
Both the mechanic and inspector were contacted on December 5 to report for work the next day (December 6), although they were both previously scheduled off duty. The mechanic reported that his normal bedtime was about 0200, and he would wake up between 1000 and 1200. On December 5, he went to bed about 2200, but had difficulty falling asleep until about 0000 and received about five hours of sleep. The QC inspector reported that his normal bedtime was about 2200 or 2300, and he would wake up about 0730 or 0800. On the night of December 5, he went to bed about 2100 and awoke at 0400. When he conducted the inspection on December 6, he had been awake more than 14 hours.

Both the mechanic's and inspector's work shift normally began at 1200, but on December 6 they reported for duty about six hours earlier (see Table 1). Research shows that adjusting to an early-morning shift (phase advance) can be more difficult than adjusting from a day shift to a night shift (phase delay). In addition, the mechanic began his duty day with a three-hour sleep debt. The investigation also found that maintenance personnel did not receive human factors training, which should have included causes of fatigue, its effects, and effective countermeasures.

### Table 1. The mechanic’s and inspector’s shift information

<table>
<thead>
<tr>
<th>Personnel</th>
<th>Normal Shift</th>
<th>Shift Originally Scheduled for December 6</th>
<th>Actual December 6 Shift</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanic</td>
<td>1200 to 2300</td>
<td>Off duty</td>
<td>0550 to 1846</td>
</tr>
<tr>
<td>Inspector</td>
<td>1200 to 2300</td>
<td>Off duty</td>
<td>0531 to 1855</td>
</tr>
</tbody>
</table>

### Conclusion

Continuous operations in aviation mean that fatigue will always be a concern, especially when there is an accident. As investigators, we must thoroughly gather and examine the data to determine what role, if any, fatigue played in an accident by considering the five factors that can lead to a fatigued state (circadian factors, time since awakening, quantity of sleep, quality of sleep, and sleep disorders). We have highlighted two NTSB investigations in which fatigue was determined to be a contributing factor in the accident and resulted in five safety recommendations to improve flight crew and maintenance operations as well as training for fatigue.

However, these accidents had vastly different circumstances, and the conclusions were made using different sources of data. The UPS investigation harvested considerable amounts of time-stamped data such as cellular telephone and hotel and company records to determine the flight crew's sleep opportunities, which was supplemented by family and colleague interviews. The Sundance investigation, on the other hand, relied primarily on interviews with the involved individuals and some company records. There is no right or wrong way to gather and analyze fatigue-related data. Technology is becoming more commonplace, and thus the use of electronically based data to make these determinations will only continue. If organized and analyzed correctly, the data can provide additional detail and confidence to investigators about whether fatigue was a factor in an investigation. But in the end, the key to any robust investigation is to ask the right questions and gather as much data as possible to ensure important fatigue-related factors are not being missed.

Disclaimer: The views expressed in this paper are not those of the NTSB and are not necessarily endorsed by the safety board.
Unstable Approaches: A Global Problem

By David Ross (MO5600), Senior Regional Operations Investigator, Transportation Safety Board of Canada

The Transportation Safety Board of Canada, or TSB, is an independent agency dedicated to advancing transportation safety. The TSB conducts independent investigations of selected transportation occurrences to determine causes and contributing factors, and then reports publicly on what has been learned.

To instill confidence in the public regarding the investigation process, it is essential that an investigating agency be independent and free from any conflicts of interest when conducting an investigation. As such, the TSB is an independent agency, separate from other Canadian government agencies and departments. TSB final reports and safety communications are not subject to government revision or approval. Our independence enables us to be fully objective in making findings as to causes and contributing factors, and in making transportation safety recommendations.

However, while the TSB is independent of other organizations, we recognize that collaboration is essential to the effective conduct of an investigation. This collaborative approach is enabled through International Civil Aviation Organization (ICAO) Annex 13, as well as the TSB legislation, regulations, investigation policies, and procedures.

So how do we conduct an independent investigation when we are collaborating with others? The collaboration is initially focused on data collection under the direction and control of the TSB. The TSB then conducts its analysis of the data independently of any other organization. This independent analysis, in the form of a confidential draft report, is then provided to designated reviewers who are asked to review and make representations on the report. In this second collaborative phase, the TSB considers the representations only for their contribution to the accuracy and soundness of the report and for their contribution to the advancement of transportation safety. The findings in the final report released to the public are those of the TSB.

The accident

On Aug. 20, 2011, a Boeing 737-210C was operating as First Air Flight 6560 from Yellowknife, Nunavut (see Figure 1). During the instrument landing system approach to Runway 35 True at Resolute Bay, the aircraft progressively diverged to the right of course. The crew initiated a go-around after a ground proximity warning system “sink rate” alert occurred, but there was insufficient altitude and time to execute the maneuvers and avoid collision with terrain. The aircraft struck a hill about one nautical mile east of the runway and was destroyed by impact forces and a post-crash fire (see Figure 2). Eight passengers and all four crewmembers died in the crash, and the three surviving passengers were seriously injured. The accident occurred during daylight in instrument meteorological conditions.

TSB response

In August 2011, the TSB was conducting an exercise field investigation to test equipment and procedures. The scenario was a simulated mid-air collision at Resolute Bay with a large-scale multi-department government response to a major air disaster. The TSB exercise team was on a Royal Canadian Air Force (RCAF) C-17 that landed at Resolute Bay about one hour after the accident. The TSB team immediately shifted from exercise to investigation mode and began collecting information. The TSB deployed additional investigators to Resolute Bay and Yellowknife. The cockpit voice recorder (CVR) and flight data recorder (FDR) were recovered and transported to the TSB laboratory in Ottawa, Canada, where another team was formed.

ICAO Annex 13 notification provided an accredited representative from the U.S. National Transportation Safety Board (NTSB) with technical advisors from Boeing, Pratt & Whitney, and the Federal Aviation Administration. Other organizations participating in the investigation were First Air, Transport Canada (TC), the Air Line Pilots Association, and the RCAF.

As mentioned previously, the initial portion of the investigation focused on data collection both at the crash site and elsewhere. All of the organizations mentioned above participated in this collaborative phase, with TSB investigators leading functional groups.

Sequence of events

An important part of the TSB investigation process is the development of a sequence of events, and the identification and analysis of safety-significant events. Information for the sequence of events of this accident came primarily from the FDR, the CVR, and a military air traffic control radar system that was operating at Resolute Bay. The sequence of events was depicted in several ways as follows: a plan view of the flight path (see Figure 3, page 24), an event sequence in the TSB safety analysis software module (see Figure 4, page 25), a word processor table (see Figure 5, page 25), FDR data plots, and an engineering flight animation (see Figure 6, page 26). While the sequence of events was developed in collaboration with other organizations, analysis of the events was done independently by TSB.
Figure 3. Sequence of events, plan view.
Many events during the arrival of First Air Flight 6560 warranted further investigation and are described in the investigation report; however, this presentation will focus on only selected events as they relate to crew resource management, or CRM, and the continuation of an unstable approach. There were also many events that were not recorded that warranted further investigation, especially autopilot and flight director mode changes that should have occurred during the approach.

### Autopilot and flight director mode changes

The FDR showed that the autopilot was engaged throughout the arrival of Flight 6560. The captain would have needed to make both autopilot and flight director mode selections (see Figure 7, page 26) as the flight approached from the southwest toward the localizer. However, only the autopilot engagement status was included in the limited number of parameters on the FDR. Additionally, the operator’s standard operating procedures at the time did not require crew callouts of mode selections or changes, and none were recorded on the CVR. The challenge to the investigation was to understand and explain how the pilots likely operated these systems and what information they had available during the approach.

Autopilot and flight director mode changes

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During the on-site work at Resolute Bay, the NTSB accredited representative suggested that the use of a flight simulator could be beneficial to the investigation. The TSB accepted this idea, and a simulator project team headed by the author was formed.

In addition to TSB investigators, the simulator team included representatives from the NTSB, Boeing, the FAA, and First Air. The team had broad expertise and included investigators, engineers, pilots, and human performance experts. Following several months of extensive planning, the team convened in Vancouver, British Columbia, Canada, in March 2012, and conducted about 10 hours of simulator work over two days (see Figure 8, page 27). A key factor in the successful completion of this project was the collaboration of multiple organizations, each with its own expertise.

The simulator project produced two key pieces of information. First, that a pilot applying sufficient force on the control wheel could cause the autopilot to shift modes without inducing any roll. Second, that use of the VOR/LOC mode resulted in either interception of or convergence with the localizer in every case. Both of these ultimately played a role in the analysis and findings.

Follow-on meetings of the simulator team led to examination of decades-old engineering documents to establish the conditions and limitations for autopilot and flight director localizer capture.

During the analysis phase, TSB investigators examined dozens of segments of the flight to make conclusions as to the likely autopilot and flight director system states and mode changes.

This portion of the investigation produced two findings as to causes and contributing factors. First, that as the aircraft rolled out of the turn onto final approach, the captain likely made a control wheel roll input that caused the autopilot to change to a mode wherein the aircraft rolled to and maintained wings level, and that the crew did not detect the mode change. Second, that the flight directors likely subsequently changed modes, resulting in a change of pilot roll guidance.

### CRM

CRM was identified as a potential safety issue within the first week of the investigation when the initial CVR transcript became available. The CVR recording was essential to the analysis of the role CRM played in this accident, and the TSB final investigation report made extensive use of those extracts of the CVR recording related to causes and contributing factors or the identification of safety deficiencies.

Data collection for this portion of the investigation involved gathering and reviewing hundreds of documents, conducting interviews with the peers of the occurrence pilots, observing the
operator’s CRM training delivery, and carefully examining the operator’s flight operations policies and procedures. TSB investigators repeatedly reviewed and analyzed the CVR recordings. As important as what was said was how it was said, and the current operational cockpit context in which it was said. As with the autopilot and flight director analysis, investigators examined dozens of segments of the flight to understand why the pilots did and said what they did.

The analysis of CRM on Flight 6560 focused on several of the mandatory CRM training topics required by the Canadian Commercial Air Services Standards. Two of these were workload management and communications.

Ineffective workload management resulted in the Flight 6560 pilots becoming task-saturated and shedding tasks during the final two minutes of the flight. A prime example of this was an 80-second discussion on final approach about the flight’s divergence from the localizer (see Figure 9, page 28). During this period, the crew became immersed in the navigational issue and did not action the remaining landing checklist items to finish configuring the aircraft for the approach. Once final configuration changes did occur, they were hurried and neither pilot made all of the specified callouts.

Analysis of the sequence of events identified many instances of ineffective communication between the pilots. Communication difficulties were exacerbated by standard operating procedures that did not specify standard phraseology to operationalize company operating policies for stable approaches. One example of this was the first officer’s statement that they were at three miles and not configured. The investigation concluded that it is almost certain that the intended message was that the approach was unstable and a go-around was required. However, the captain’s interpretation of this statement was that they needed to finish configuring the aircraft for landing.

This critical miscommunication occurred while each crewmember likely had a different mental model of the current situation and the aircraft flight path. The
investigation concluded that the captain’s mental model was likely that the autopilot would re-intercept the localizer from the right and a landing would follow. However, the first officer’s mental model was likely that Flight 6560 was full deflection from the localizer, was still diverging to the right of course on an unstable approach, and a go-around was necessary. The final report included a finding as to causes and contributing factors that the crew did not maintain a shared situational awareness and that, as the approach continued, the pilots did not effectively communicate their respective perception, understanding, and future projection of the aircraft state.

This portion of the investigation led to several findings as to causes and contributing factors. Key among them was an overarching finding that the crew’s CRM was ineffective, and another finding that adaptations to standard operating procedures by the crew contributed to their ineffective CRM.

The investigation also examined one of First Air’s Boeing 737 bases to determine whether any of the standard operating procedure adaptations identified in Flight 6560 existed elsewhere in the company. The final report included a finding as to causes and contributing factors that other B-737 pilots did employ adaptations and that the operator’s supervisory activities did not detect the adaptations.

Investigators also studied the company’s CRM training program. The initial CRM course used presentations prepared by the TC in the mid-1990s, and five of the required subjects were not presented during the one-day course observed by TSB investigators. The recurrent CRM course was more up-to-date, including elements of more recent generations of CRM training but consisted of only two hours of training. The investigation made a finding as to causes and contributing factors that the company’s initial and recurrent CRM training did not provide the crew of Flight 6560 with sufficient practical strategies to enable effective CRM.

The Canadian CRM training standard was also scrutinized. This standard was brought into force in 1996 in response to TSB Recommendation A95-11, which called for CRM and decision-making training to be mandatory for all operators and aircrew involved in commercial aviation. However, the standard has remained unchanged in the intervening years, while CRM best practices and training methods have evolved through several updated generations. The TSB final report for the Resolute Bay investigation included a finding that current TC CRM training standards and guidance material have not been updated to reflect advances in CRM training, and there is no requirement for accreditation of CRM facilitators/instructors in Canada. This situation increases the risk that flight crews will not receive effective CRM training.

The TSB issued a recommendation (A09-02) in 2009 that the TC require commercial air operators to provide contemporary CRM training for air taxi and commuter pilots. The TC accepted the recommendation. Over the past five years, the TC has worked toward updating the CRM training standard and expanding CRM training into all sectors of commercial flight operations.

The TSB reassesses all recommendations annually to determine what progress has occurred. During the 2014 reassessment, the TSB rated TC’s progress on this recommendation as satisfactory intent, but expressed concern about the slow pace of action to address this recommendation, especially when no information was provided about when the new standard was expected to come into force.

When the Resolute Bay investigation report was released, the TSB issued another board concern that, without a comprehensive and integrated approach to CRM by the TC and aviation operators, flight crews may not routinely practice effective CRM.

Unstable approaches

As was the case with CRM, within the first week after the accident the investigation had identified an unstable approach as a potential safety issue. The company had in place both a no-fault go-around policy and a stable approach policy with detailed criteria that became applicable during an approach in IMC at 1,000 feet above aerodrome elevation. Initial plots of the Flight 6560 FDR data showed that the indicated airspeed recorded at this point in the approach was 176 knots, 44 knots greater than Vref. This was well in
excess of the company specified limit of $V_{ref} + 20$ knots. Once the FDR data was integrated with the CVR and radar flight path, four additional unstable parameters were identified.

Two key questions the investigation looked into are as follows. First, why was an unstable approach continued despite policies in place to prevent this? Second, did continuing an unstable approach introduce unacceptable risk?

The investigation revealed that the company’s stable approach policy had not yet been translated into procedural guidance in the aircraft operating manuals for the company’s various fleets. Consequently, when Flight 6560 entered the stable approach zone, the first officer needed to improvise because he did not have any standard phraseology to communicate clearly to the captain that the approach was unstable and they needed to go-around. As discussed above, the first officer’s attempt to communicate this was misunderstood by the captain, who commenced the final landing configuration changes rather than initiating a go-around.

Part of the TSB risk-analysis process is to identify similar occurrences. Investigators reviewed investigation reports from Canada and other countries and identified many occurrences that had an unstable approach as a contributing factor. These occurrences demonstrate that the severity can range from no injuries or damage to multiple fatalities and aircraft destruction. They also demonstrate that, despite a significant industry effort to put in place defenses to mitigate the risks associated with unstable approaches and their consequences, the current defenses are not always robust enough to prevent catastrophic outcomes.

Line-Oriented Safety Audits (LOSA) and flight data monitoring programs (FDM) are two means for airlines to identify risks present in their operations, including unstable approaches. However, LOSA is voluntary, and First Air has not participated in the program. At the time of the accident, First Air was putting in place a FDM monitoring program but had not yet achieved results because of data collection and quality problems.

LOSA observations of more than 20,000 flights show that 4% of those flights had an unstable approach (see Figure 10), and that 97% of the unstable approaches continued to a landing (see Figure 11). On only 3% of unstable approaches did the crews execute a go-around.

In 2013, a worldwide fleet of western-built jet aircraft weighing greater than 60,000 pounds made 25.2 million departures. Assuming the LOSA unstable approach information is representative of this fleet, that means that in 2013 almost 1 million of those flights ended with an unstable approach to a landing. This does not include smaller jet aircraft and a large fleet of turboprop aircraft also used by airlines.

In its final report on this investigation, the TSB urged the Canadian aviation
industry to take three steps to reduce this risk to the system.

- First, for operators to have practical and explicit policies, criteria, and standard operating procedures for stabilized approaches that are enshrined in the company operating culture.
- Second, for companies to have contemporary initial and recurrent CRM training programs delivered by qualified trainers, and to monitor and reinforce effective CRM skills in day-to-day flight operations.
- Third, to monitor standard operating procedure compliance through programs such as FDM and LOSA.

In Canada, the TC requires airline operators to have safety management systems (SMS), CVRs, and FDRs. However, these air carriers are not required to have an FDM program. Even so, many of these operators routinely download their flight data to conduct FDM of normal operations. Air carriers with an FDM program have used flight data to identify and mitigate many problems, including unstable approaches.

In its final report, the TSB concluded that, unless further action is taken to reduce the incidence of unstable approaches that continue to a landing, the risk of approach and landing accidents will persist. Therefore, the TSB issued Recommendation A14-01 that the TC require Canadian airline operators to monitor and reduce the incidence of unstable approaches that continue to a landing.

The TC agreed with the intent of the recommendation, and, on June 27, 2014, issued a civil aviation safety alert requesting Canadian airline operators to use their existing SMS processes to address and mitigate hazards and risks associated with unstable approaches. This safety alert also indicated that, beginning in 2015–2016, the TC will, within the context of normal surveillance activities, assess the effectiveness of the various measures undertaken by airlines in reducing the number of unstable approaches that continue to a landing, including how airlines track, analyze, and implement corrective measures.

In conclusion, the TSB can emphatically state that “independence does not mean isolation.” Teamwork is essential in every investigation, and investigators should be encouraged to surround themselves with experts and to collaborate with them.

4% unstable approaches

96% stable approaches

Figure 10: Unstable approaches.

3% of unstable approaches end in a go-around

Continue to Landing
Go Around

97% of unstable approaches continue to a landing

Figure 11. Unstable approaches continued to a landing.
CORRECTION

In the Change Point Analysis Applied to SMS article by Paulo Razaboni in the October–December 2015 issue of the Forum, the wrong chart was displayed as Figure 9 on page 30. Below is the correct chart and its description.

Figure 9. Using the above data set, the algorithm reveals three changes, the latest one in Jul/2013 (96% confidence), earlier ones in Oct/2011 and in Jul/2012. Short-term behavior is stable, and long-term presents a downtrend. Distribution is not normal considering the whole set. Some level of seasonality may be assigned, as the sinusoidal curve roughly fits the data, the worst month identified as August (42% above the average).

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( Chan_wing_keong@mot.gov.sg)
Australian, Richard Sellers
( richard.sellers@defence.gov.au)
Canadian, Barbara Dunn (avsafe@shaw.ca)
European, Keith Conradi
( k conradi@aaib.gov.uk)
Korean, Dr. Tachwan Cho (contact: Dr. Jenny Yoo—dgjennyyoo@naver.com)
Latin American, Guillermo J. Palacia (Mexico)
Middle East North Africa, Ismaeil Mohammed Abdul (contact: Mohammed Aziz—mohammed@azz.com)
New Zealand, Alister Buckingham
( alister.buckingham@ca.govt.nz)
Pakistan, Wg. Cdr. (Ret.) Naseem Syed Ahmed
( naseem640@hotmail.com)
Russian, Vsvolod E. Overharov
( orap@mak.ru)
United States, Toby Carroll
( toby.carroll@sbcglobal.net)

UNITED STATES REGIONAL CHAPTER PRESIDENTS
Alaska, Craig Bledsoe
( craig_bledsoe@ak-prepared.com)
Arizona, Bill Waldock (wwaldock@msn.com)
Dallas-Ft. Worth, Tim Logan
( tim.logan@wnco.com)
Great Lakes, Matthew Kenner
( mtkenner@esi-il.com)
Mid-Atlantic, Ron Schleeke
( ronschleeke@aol.com)
Northeast, Luke Schiada (lschiada@aol.com)
Northern California, Kevin Darcy
( kevin.darcy@rtiforensics.com)
Pacific Northwest, Kevin Darcy
( kevin.darcy@rtiforensics.com)
January-March 2016 ISASI Forum
Embry-Riddle Aeronautical University

A pioneer in aviation education since 1926, Embry-Riddle Aeronautical University continues to be the most highly regarded institution dedicated to the field. It is the nation’s largest, oldest, and most comprehensive aeronautical university, with a curriculum at the forefront of the industry’s developments and demands for the future.

Embry-Riddle sets the standards for aviation education, is involved with the formulation of national and international policy related to aviation, and remains the nexus of aviation education. Every student in an aviation curriculum benefits from hands-on learning in new, expertly maintained aircraft, labs that replicate the nation’s airspace, state-of-the-art maintenance and avionics repair facilities, and unrivaled aviation simulation centers.

However, Embry-Riddle is so much more.

For ever-inquisitive minds, analytical thinkers, and problem solvers, Embry-Riddle offers applied research degree programs to challenge and excite. These programs are deeply rooted in research; and while some areas may be focused on aviation and aerospace, the fundamentals can be applied to any other industry.

For instance, the Applied Aviation Sciences Department operates the Aerospace Forensics Lab, a critical teaching tool for the aerospace and occupational safety degree program. Current artifacts include several fixed-wing aircraft and a helicopter that have all been involved in actual crashes. This lab allows students to view and touch the wreckage while practicing the science of aircraft accident investigation.

Potential research topics include experiential learning techniques, forensic imaging, metallurgical failure analyses, software uses for accident scene diagrams, powerplant system analysis, flight instrument impact capture marks, and the pedagogy of wreckage layouts to maximize student learning. This approach can lead students to careers in accident investigation; aircraft manufacturing; airport safety; environmental, health, and safety; ergonomics/human factors; OSHA compliance management; and risk management.

Embry-Riddle’s storied history in flight education has positioned it to become a pioneering institution for the study of space-related endeavors. The university now offers degree programs that include astronomy and astrophysics, space physics, and commercial space operations—the only degree of its kind in the world. Students benefit from building relationships with faculty and industrial professionals and from alliances with organizations and companies, including NASA, United Space Alliance, SpaceX, The Boeing Company, Honeywell, and Virgin Galactic.

Embry-Riddle’s beautiful residential campuses in Daytona Beach, Fla., and Prescott, Ariz., offer students the choice of a spectacular beach setting or an amazing mountain community. Embry-Riddle Online and the Worldwide Campus operate a globally recognized learning system that leverages online and face-to-face instruction and a network of educational facilities designed to support student advancement in the U.S. and abroad.

Students come from all 50 states and 125 countries around the world, and there is one trait they all share—a determination to succeed. The bonds they develop in classrooms and residence halls last a lifetime. The university’s Alumni Association, with 120,000 members, works to connect alumni with one another and with hundreds of employers around the globe.

This iconic institution celebrates its 90th anniversary in 2016. Whether a student is interested in applied science, aviation, business, computers and technology, engineering, security, intelligence and safety, communications, or space, Embry-Riddle will continue to set the standards for aviation and aerospace education—and so much more. ♦

For more information, visit www.embryriddle.edu.