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# Developing Temporal Markers to Profile Operational Errors

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16. Abstract <p>A commonly held view is that system and human vulnerabilities, whether they emerge at a common moment or over a situation, can form links in a chain of events resulting in an air traffic operational error (OE). However, this truism has not led to the development of better techniques for profiling this progression. If we generally accept that OEs evolve over time, then OEs have temporal characteristics. By better understanding these temporal characteristics, we will better understand how vulnerabilities become links in a chain so that resources can be allocated effectively to develop mitigation strategies. Two activities were conducted to develop the temporal markers (TMs) framework. First, air traffic subject matter experts identified objective (or calculable) points that can be identified a traffic situation. These points could differ at the point in time they occur, but they would occur in some form in most, if not all, OEs. A list of TMs was generated and tested using archival en route OEs. Using the framework is straightforward. This preliminary evidence suggests that temporal profiling could help to discover trends across OEs that are not currently being systematically examined. A larger set of OEs could be tested with this method to accomplish this. Ultimately, the technique should be used for all OEs in the national airspace so that a TM database could be developed for OE trend analysis.</p>					
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# DEVELOPING TEMPORAL MARKERS TO PROFILE OPERATIONAL ERRORS

## INTRODUCTION

Researchers and operational personnel alike generally accept the view that air traffic operational errors<sup>1</sup> (OEs), like many types of events in complex systems, evolve over time (e.g., Dekker, 2002; Dörner, 1996; Harry and Schroeder, 2000; Klein, Orasanu, Calderwood, and Zsombok, 1993; Perrow, 1999; Petersen, 1996; Phimister, Bier, and Kunreuther, 2004; Reason, 1997; Sagan, 1993; Salas and Klein, 2001). If we generally accept that OEs evolve over time, then we can expect OEs to have temporal characteristics. However, the truism that events in complex systems have a temporal component has not yet led to development of better techniques for profiling the temporal progression of evolving events such as OEs. This project was conducted to begin to fill this gap. Temporal information may give OE analysts another means to identify and evaluate a variety of potential OE reduction strategies.

A commonly held view is that system and human vulnerabilities can converge at one moment or may be distributed over the course of an evolving situation. In either case, they can contribute to, or cumulate in, unsuccessful outcomes. Many researchers have devoted attention to identifying and analyzing these precursor and error-producing human and system conditions (e.g., Bier, 1998; Krause, S. S., 2003; Petersen, 1996; Phimister, Bier, and Kunreuther, 2004; Rasmussen, 1980; Reason, 1990, 1997). On the other hand, the study of temporal characteristics in this context has received little attention and is generally conducted relative to its perception and related subjective experiences (e.g., Block, 1990; Gibbon and Allan, 1984).

Although many types of data are currently reported after an OE, by identifying the temporal characteristics of OEs, we should be able to understand OEs from a different perspective. Presently, over 200 elements of information are recorded as part of the Federal Aviation Administration's (FAA's) OE reporting process. In addition to a description of when and where the event occurred,

these encompass characteristics of the controllers and supervisors involved, training, past performance of personnel (i.e., involvement in previous incidents), equipment and aircraft. Items also cover data posting (e.g., computer entries and flight progress strips), controller's use of radar displays to maintain knowledge of the traffic situation, communications, coordination, transfer of position responsibilities (i.e., position relief briefings), and in air traffic control towers, the observation of aircraft.

A chronology (timeline) of the OE is routinely developed by quality assurance personnel at air traffic facilities during the FAA's OE reporting process as part of the Final Operational Error or Deviation Report (Form 7210-3; FAA, 2002). Directions for completing the Final OE/D Report are:

Explain, in chronological order, each factor relevant to the incident. Tell a detailed story, describing the pertinent actions of all those involved (e.g., controllers by position, supervisors, aircraft, etc.). It should be apparent what actions (or lack of) contributed to or caused the incident. Include any explanations necessary from previous blocks. (pg. 7)

Two examples of timelines from our archive are shown below, although the amount of content and format of timelines included in the Final Report varies widely across facilities.

### Example 1:

1356:24	DAL1906 checked on frequency at FL330.
1358:42	R63 cleared DAL1906, due to ZID Letter of Agreement, direct Pocket City, then MOSEY5 arrival to CVG. R63 cleared DAL1906 to turn left heading 3-5-0, when able direct Pocket City.
1358:52	DAL1906 acknowledged the heading of 3-5-0 direct Pocket City and MOSEY.
1401:16	AAL2736 advised R63 that his TCAS had activated advising him to climb due to traffic at his altitude.

### Example 2:

1931:35	When DAL0025 reported on frequency climbing to 17,000 feet, Specialist "A" cleared the aircraft to climb and maintain FL220 and to proceed direct Birmingham (BHM).
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<sup>1</sup> An operational error is defined as an occurrence attributable to an element of the air traffic system in which (1) less than the applicable separation minima results between two or more aircraft, or between an aircraft and terrain or obstacles (e.g., operations below minimum vectoring altitude (MVA); equipment / personnel on runways), as required by FAA Order 7110.65 or other national directive; or (2) an aircraft lands or departs on a runway closed to aircraft operations after receiving air traffic authorization, or (3) an aircraft lands or departs on a runway closed to aircraft operations, at an uncontrolled airport and it was determined that a NOTAM regarding the runway closure was not issued to the pilot as required (FAA Order 7210.56, 2002).

- 1932:14 When DAL1347 reported on frequency, Specialist “A” cleared the aircraft to climb and maintain 17,000 feet.
- 1933:12 Separation was lost.
- 1933:20 Specialist “A” cleared DAL1347 to level off at present altitude. DAL1347 did not respond until the third call at which time the aircraft was already level at 17,000 feet.
- 1933:37 Specialist “A” instructed DAL0025 to expedite climb to FL220.
- 1933:47 Specialist “A” cleared DAL 1347 to descend and maintain 16,000 feet.

Various stakeholder groups have long monitored incoming OE reports so that strategies could be developed to reverse human performance errors, such as readback/hearback errors, lack of positive control and misapplication of procedures. Several analyses incorporated a temporal dimension. For example, air traffic operations tracked the number of OEs relative to the controller’s time on position and number of aircraft being handled by the controller (Pounds and Ferrante, 2005). Researchers examined whether information about the stabilization of controllers’ scanning patterns during the first 10-20 minutes on position could be used to inform our understanding of how controllers establish situation awareness during that time (Smolensky, 1993). Although much attention has been devoted to understanding the transfer of position responsibilities and despite an ongoing interest in time as a factor in relation to various air traffic operations, there is currently no way to identify and analyze information about how an OE evolves temporally.

One means for understanding the evolution of an OE might be to look for events that could be identified temporally, which all OEs have in common or which could potentially occur in every OE. We called these events *temporal markers* (TMs). These points may differ in when they occur during the OE timeline, but they occur in some form in most, if not all, OEs. TMs could also be used to compute time intervals. We called these time intervals calculated between two TMs the Temporal Marker Time Spans (TMTs).

This idea led us to first identify an exhaustive list of TMs. The list was then organized into a framework and tested using a convenience sample of OEs to see whether using TMs would yield new information about OEs. This report details how this was accomplished, the resulting framework of TMs, examples of new information and examples of difficult questions that could be answered by this type of analysis.

## Step 1 – Identifying the TM Framework

### Method

In Step 1, we first had to define (operationalize) what we meant by *temporal markers* and determine whether any events in OEs matching the definition could be identified using available materials generated from previous OE investigations. In Step 2, we used the list of temporal markers identified in Step 1 to analyze a convenience sample of OEs. A short summary completes each section, although the principal discussion of the results is reserved for the conclusion of the paper.

We defined a *temporal marker* (TM) as an objective (or calculable) point in time that can be identified during the unfolding of the OE. Temporal markers must be identifiable (or calculated) from data sources available in the AT facility. The range of possible TMs was bounded only by “the context of an operational error.” These event points could occur at different times during an OE, but they would occur in some form in most, if not all, OEs.

### Participants

Three retired FAA air traffic control specialists (ATCSs) with experience in OE investigations were recruited as ATC subject matter experts (SMEs) to assist in the development of a comprehensive list of TMs. Their collective experience included 87 years of facility management and operational supervision in en route and terminal operations.

### Materials

A convenience sample of six OEs from one Air Route Traffic Control Center (ARTCC) was used for Step 1. These were selected because both the Final OE/D Report (FAA Form 7210-3) and the Systematic Air Traffic Operation Research Initiative (SATORI) re-creation for each were available from an existing archive. SATORI (Rodgers and Duke, 1993) was developed, tested and fielded to all en route facilities and regional quality assurance offices with the goal of gaining “a better understanding of the interaction between the various elements of displayed information, verbal interactions and the control actions taken by air traffic control specialists” (pg. 1). Information about the SATORI system’s capabilities first appeared in ATCA’s Journal of Air Traffic Control (Rogers and Duke, 1993). SATORI is still currently in operational use and enables its users to re-create segments of operational traffic in a format similar to what was displayed to the ATCS, for example, showing relative location and separation, speeds and headings of aircraft. Among other things, SATORI can display full and limited data blocks, beacon targets and conflict alerts. Video and audio are synchronized and the air traffic situation can be displayed in four dimensions. At en route facilities, SATORI systems enable the

facility quality assurance staff to re-create OE situations for the controllers involved.

The SMEs were provided with our definition of a *temporal marker* and a list of some TM examples, such as the time when the aircraft entered the controller's assigned airspace, the time when the aircraft checked on the controller's frequency and the time when the controller issued the first control instruction to the pilot.

#### Procedure

The SMEs convened as a group on several occasions to create an exhaustive list of TMs. An iterative process was used to develop, test and modify the list. At the first meeting, the principal investigator for the project discussed the project goals with the SMEs. The SMEs then observed SATORI re-creations and reviewed the final reports from three OEs to familiarize themselves with the materials for the project. They were then asked to generate a list of events that, from their experience, were common to all OEs. From these, the SMEs then drafted their first TM list using the TM definition.

At the second meeting, the list was reviewed, discussed and edited. Once this draft list was judged by the SMEs to be complete, it was tested using the three remaining OEs. To test the list, the SMEs first viewed the SATORI playbacks for the three OEs and noted any TMs on the list that needed to be modified or any that needed to be added to or deleted from the list. The group convened a third time to review and finalize the list.

#### Results

The list of TMs that the SMEs developed and concurred with included identifiable, objective event points that occur during the evolution of an OE, reflecting several types of activities and demonstrating what kinds of information can be extracted from data available at facilities. TMs enable OEs to be described in more detail than is generally the case.

Table 1 shows the final list organized as a general framework. Columns in the table represent the numbering system (TM #), TM definitions<sup>2</sup>, sources where a time stamp for the TM can be found (Data Source) and one or more columns for the aircraft of interest (A/C #). Column headings in Table 1 show how the analyst would set up the framework to examine TMs in an OE with two aircraft in conflict and another aircraft of interest. Each column is discussed below as it would be used by an analyst.

<sup>2</sup> Throughout the framework, controllers are described as appropriate according to their relationship with each other or with the aircraft, i.e., receiving, relieving, transferring. This helps the analyst to remember relative relationships in the OE.

#### Aircraft Numbering Methodology

The analyst first numbers each aircraft to permit TMs to be identified for each aircraft as needed. Aircraft are designated systematically as A/C1, A/C2, A/C3 and so on. The number assigned to the aircraft is based on the sequence of its entry into the controller's airspace where the OE occurred.—whether by (a) coordination accomplished between controllers using the land line, (b) using automated handoff and acceptance, or (c) pilot initiated contact with ATC. The first aircraft discussed (or flashed) between the handoff and receiving controllers, or that contacted the controller directly (e.g., for VFR service in the airspace), is labeled as A/C1. The second aircraft discussed (or flashed) between the handoff and receiving controllers, or that contacted the controller directly, is labeled as A/C2 and so on. All aircraft of interest as elements of the OE situation are assigned a number using this method. In addition to an aircraft that was being transferred between handoff and receiving controllers, an aircraft might also have contacted the controller directly, for example, for VFR service through the airspace, to request flight following, or to request an IFR clearance after departing an uncontrolled airport where the center provides departure services.

An example of how aircraft are numbered is as follows. Consider a situation in which an aircraft (Cessna1234) departed an uncontrolled airport. This airport did not have an affiliated Terminal Radar Approach Control (TRACON) facility so ATC services for pilots arriving and departing this airport were provided by the center controller working the center's Alpha sector.

- The pilot of Cessna1234 contacted the Alpha sector controller at 0800 and requested IFR clearance through Alpha sector.
- Alpha sector controller issued the pilot of Cessna1234 the appropriate clearances.
- The Alpha sector controller also verbally accepted a handoff of another aircraft (MEL0098) from an adjoining sector controller at 0805.
- Another aircraft (HRZ990) was flashed to the Alpha sector controller, who then clicked on the flashing datablock and accepted the handoff of HRZ990 at 0806.
- The pilot of HRZ990 requested to remain in level flight at 35,000 feet (to transition Alpha sector).
- Cessna1234 and MEL0098 lost separation at 0811.
- To reestablish separation between Cessna1234 and MEL0098, the Alpha sector controller instructed MEL0098 to climb to 35,000 feet.
- At 0812, separation was lost between HRZ990 and MEL0098.

**Table 1.** Framework of temporal markers for an OE situation having three aircraft of interest, including clarification for some temporal markers (in italics).

TM # <sup>a</sup>	Temporal Markers for Center and Terminal (Radar)	Data Source <sup>b</sup>	A/C 1	A/C 2	A/C 3
1	Time position relief briefing completed.	4			
2	Time relieving controller assumed position.	5,4			
3	Time controller being relieved left position.	8			
* TM#1: <i>The time when completion is acknowledged by the receiving controller.</i>					
* TM#3: <i>Position is considered “left” at the time the relieved controller unplugged from the position.</i>					
4_1a	Time of 1st Inter/Intra facility coordination initiated on the involved A/C.	6,4			
4_1b	Time of 1st Inter/Intra facility coordination completed on the involved A/C.	6,4			
* TM#4a and 4b: <i>land line coordination.</i>					
5a	Time radar identification initiated by transferring controller (Handoff, Point out)*.	6,1,4			
5b	Time radar identification completed by receiving controller (Handoff, Point out)*.	6,1,4			
* TM# 5a and 5b: <i>These two TMs may be the same controller if initial identification is being established.</i>					
* TM# 5a and 5b: <i>If no landline coordination takes place, this would be the first coordination for the aircraft completed electronically.</i>					
6	Time A/C checked in on receiving controller's frequency.	4			
7	Time two-way communications established between pilot and receiving controller.	4			
8	Time A/C entered receiving controller's airspace.	1,6			
9_1a	Time of 1st ATC instruction by receiving controller.	4			
* TM# 9_1a: <i>may occur at the same time as TM#7.</i>					
9_1b	Time pilot verbally responded to 1st ATC instruction from receiving controller.	4			
10	Time of first point where positive separation between A/C was not ensured.	1,2,6,9			
*TM#10 is the first time when the aircraft were set on conflicting headings. The “first point” was defined irrespective of the location of the aircraft —					
1. <i>the aircraft could be in the previous sector, e.g., if separation was not guaranteed before the aircraft was “shipped” to the next controller.</i>					
2. <i>the aircraft could be in the receiving controller’s sector after the controller takes the handoff of the aircraft.</i>					
This can occur as a result of either (for example) –					
1. <i>controller action or inaction to ensure separation</i>					
2. <i>pilot actions or inactions (e.g., on wrong frequency in new sector)</i>					
11a	Time of last ATC instruction by receiving controller prior to loss of separation.	4			
11b	Time pilot acknowledged last ATC control instruction by receiving controller prior to loss of separation.	4			
12	Time conflict alert activated.	6,1			
13_1a	Time of controller's 1st instruction to avoid separation error.	4			



**Table 1** (continued).

13_1b	Time pilot verbally responded to controller's 1st instruction to avoid separation error.	4			
14	Time separation lost.	7,2,1			
15_1a	Time of controller's 1st attempt to reestablish separation.	4			
15_1b	Time pilot verbally responded to controller's 1st attempt to reestablish separation.	4			
16	Time separation reestablished.	2,1			

a. Left column shows sequencing codes. Shading indicates element groups.

b. Data source codes are listed with the relevant TM. Data sources are listed in Table 2.

**Table 2.** Sources of data to find times to complete the Temporal Markers in Table 1.

<u>Code</u>	<u>Data Source</u>
1	SATORI or RAPTOR
2	NTAP (National Track Analysis Program)
3	CDRs (Continuous Data Recording)
4	Audio tapes
5	SISO (sign in-sign off /out records)
6	DART (Data Analysis Reduction Tool)
7	OEDP (Operations Error Detection Program, also known as the “snitch patch”)
8	Personnel interviews
9	Flight progress strips

To maintain sequence information, Cessna1234 would be designated as A/C1 and MEL0098 would be designated as A/C2. In cases where a third aircraft (e.g., HRZ990) influenced the events leading to an OE, it would be designated as A/C3, and TMs would be identified for it also if, for example, the analyst wanted to specify its role in the event. In this example, A/C3 lost separation with A/C2 subsequent to when separation was lost between A/C1 and A/C2 (e.g., the controller created a second OE while reestablishing separation after the first OE).

In another case, perhaps A/C3 required special handling or multiple communications with the Alpha sector controller prior to when separation was lost between A/C1 and A/C2. Examining TMs for an A/C3 or A/C4 would shed light on situations where other aircraft were involved but did not lose separation or were suspected of being a contributing factor to the OE. This method of examining traffic events could be used with as many aircraft as the situation warranted.

No explicit rules were developed during this project about what circumstances dictate that the analyst should use more than two aircraft. A useful guide for this decision would be to include other aircraft when the information would contribute to a better understanding of the OE.

Columns as many A/C as needed would be used by the analyst, and times corresponding to each TM for the A/C would be entered in the appropriate column. Using this method, the framework permits more than two aircraft to be tracked if the analyst determines that information about the third aircraft is needed to better understand how the OE developed.

#### Temporal Markers for Center and Terminal (Radar)

This column of the framework describes each TM identified by our SMEs. Several of the TMs are annotated for clarification. Each annotation is shown in *italics* beneath the TM to which it refers.

#### Data Source

The SMEs also identified the source(s) of the data needed to identify each TM and these are listed in the adjacent **Data Source** column. These codes represent the sources where one would find the information to identify when that particular TM occurred. The data sources corresponding to the codes are listed in Table 2. Only one TM requires that the data be obtained from facility personnel (TM #3: “Time controller being relieved left position.”). The rest are obtained using data from

automation and tools used in en route facilities, such as the National Track Analysis Program (NTAP), flight progress strips and audio tapes.

TM #

The left-hand column in Table 1 lists the alphanumeric code assigned to each type of TM. Because the primary goal of this project was to identify temporal characteristics in an OE as it evolved over time, we first assigned each type of TM a sequencing code. (The obvious choice for a numbering method was to use the common method of assigning the first TM as #1, the second TM as #2 and so on.) This is the first character of the TM# code and indicates the relative order for that type of TM within the general sequence of TMs that make up the framework.

Thus, it was reasonable to assign the first TM of the framework to the first moment when a controller assumed position responsibility. However, transfer of position is a complex, multi-step procedure and encompasses several sub-tasks, so these steps were designated as TM#1, TM#2 and TM#3 as follows.

- TM#1: Time verbal position relief briefing completed.

The time when the verbal briefing was completed was defined as the moment when the receiving controller acknowledged that it was completed (FAA, 2004). By that time, the relieving controller has asked any questions necessary to ensure a complete understanding of the operational situation and these have been completely answered by the controller being relieved.

- TM#2: Time relieving controller assumed position.

The time when the relieving controller takes responsibility for the position was defined as (a) when the relieving controller makes a statement or otherwise indicates to the controller being relieved that position responsibility has been assumed and (b) the controller being relieved releases the position (FAA, 2004).

- TM#3: Time controller being relieved left position.

The time when the controller left position was defined as the time when the controller unplugged his/her headset from the position. Generally, the time at which the controller is relieved of position responsibility is formally defined as the time when the controller being relieved (a) signs off the position in accordance with existing directives or (b) otherwise indicates that the relief process is complete (FAA, 2004). In some situations, the controller being relieved may remain for a brief period and continue to observe and assist with traffic demands. During certain times, such as those of high workload or complex traffic situations, the controller being relieved sometimes stays at the position to assist the relieving controller after the

transfer of position responsibility has been accomplished. This overlap can be mandated, encouraged, or dispensed with, depending upon the facility or circumstances. Therefore, for our definition of TM#3, we considered the relieved controller to have left the position when he/she unplugged his/her headset from the position.

One number is not sufficient to distinguish all of the types of TMs which were identified. Some TMs tend to occur together and certain types of TMs tend to be repeated throughout the course of an OE. Thus, additional codes were needed for each TM and so two additional codes were systematically assigned following an underscore after the TM sequence number. We put an underscore after the first number to distinguish it from the next characters in the TM# string if that character was also a number.

The numbers and letters after the underscore indicate which TMs in an OE are repeated and which are related. Repeated instances of a TM are signified by adding a number series (i.e., “1,” “2,” “3,” and so on) after the underscore to indicate the TM’s sequence relative to that type. Thus the “1” after the underscore represents the first specific instance of that TM type. A “2” in that position after the underscore represents the second instance of that TM type.

The second character after the underscore is a letter. Letters were used to signify one element of a TM pair when two TM types are sequential, related activities. The letters “a” and “b” are used to indicate that two TMs tend to occur coupled, such as when an activity is initiated (i.e., “a”); its completion is also included (i.e., “b”). That is, if one occurs the other will also usually occur as shown in the example below.

TM #	Temporal Markers for Center and Terminal (Radar)
4_1a	Time of 1st Inter/Intra facility coordination initiated on the involved A/C.
4_1b	Time of 1st Inter/Intra facility coordination completed on the involved A/C.

The shaded rows in Table 1 highlight the TMs that typically occur together, either as groups of TM sequences (i.e., TM#1, TM#2, TM#3) or as pairs, shown by the “a” and “b” (e.g., TM#4\_1a, TM#4\_1b). Using TM# as an example, the “4” indicates that this TM is fourth in the TM framework’s sequence. The “1” following the underscore indicates that this is the first occurrence of this pair. The “a” and “b” indicate that this is a pair of TMs that can be expected to occur together. These are collectively interpreted as the first occurrence of the TM#4 pair. This coding scheme is useful when some types of TMs can clearly be grouped (e.g., the position relief) or

separated into specific elements (e.g., a controller-pilot communication exchange). For example, a clearance issued by the receiving controller to the pilot can be divided into two elements: the controller's communication and the pilot's response. Coding for this event is shown by TM#9, which indicates that this TM pair is the 9<sup>th</sup> type of TM in the framework, the first occurrence of this type (controller-pilot communication). The "a-b" designation distinguishes (a) the controller's instruction to the pilot from (b) the pilot's response to the controller.

1. Time of 1st ATC instruction by receiving controller (TM 9\_1a).
2. Time pilot verbally responded to 1st ATC instruction from receiving controller (TM 9\_1b).

As described above, some TMs may occur once for an OE (e.g., TM#1-3; the relieving controller took position responsibility after a briefing from the controller being relieved). Other types can be repeated (e.g., Time of 1<sup>st</sup> / 2<sup>nd</sup> / 3<sup>rd</sup> / etc. controller-pilot communications) and, thus, instances of a type may be repeated during the course of an OE's evolution. All TMs that are relative to aircraft can apply to each aircraft of interest. Therefore, no character was included in the temporal marker code to specify individual aircraft. The aircraft columns in the framework are used to distinguish TMs for the separate aircraft.

Although listing every communication with the involved aircraft might at first seem unwieldy or unnecessary, the cost-benefit tradeoff favors including them. The current requirement (FAA, 2002) for examining the unfolding of an OE is to examine the interval beginning five minutes prior to the involved aircrafts' initial contact with the controller having the OE (in our example, the Alpha sector controller) and concluding five minutes after separation is lost between the two aircraft in the OE. Gathering the data and transcribing the voice tapes to obtain a timeline of the event is work intensive for the facility staff. One benefit from including all communications with the aircraft in the TM framework is that the TM structure, by providing a standardized format for the timeline (which must be transcribed anyway), would provide elaborative information about exchanges and activities between the controller and the aircraft involved with the OE beyond that which is currently available. This would be valuable both for analysis of the individual OE case and when summarized at facility- or system-wide levels.

## Discussion

### Using TMs

Once the TMs in the template are populated with data from the OE, sets of TMs can be extracted from the framework to examine specific types of situations and activities. For example, our SMEs pointed out that there is a point in every OE when separation is not ensured for two aircraft, and if nothing interceded to change their trajectories, they would eventually lose separation. These two concepts need to be clearly distinguished: (1) when separation is not ensured versus (2) when separation is lost. They might seem similar in meaning but, in reality, they can differ markedly. The first, "when separation is not ensured," means that the aircraft are on courses that will lead to an eventual loss of separation if nothing else happens in the meantime, such as another action by a controller or a pilot. Two aircraft can be assigned headings and/or altitudes that will eventually result in an OE several minutes (or miles) before the OE. Thus, events might be set in motion, and an OE could essentially begin to develop in another sector prior to the one where it finally takes place. On the other hand, "loss of separation" means that the aircraft were already too close at the time and were in a conflict situation where less than minimum separation between them existed. Thus, "separation is not ensured" can be thought of as the projection of the current traffic situation into the future, whereas "loss of separation" is the outcome.

Analysts might want to look upstream from when the OE occurred to see whether earlier actions could be taken to avoid the OE. Because TMs can be uniquely assigned to each aircraft and because TMs are independent of the controller's airspace boundaries, this TM could occur before one or both aircraft are in the receiving controller's airspace (where the OE occurred), even though they may have already been handed off to the receiving controller (who "got the deal") with a TM sequence as follows.

1. TM#10: Time of first point where positive separation between A/C (e.g., A/C1 and A/C2) was not ensured.
2. TM#12: Time conflict alert activated.
3. TM#14: Time separation lost.
4. TM#16: Time separation reestablished.

Depending upon when TM#10 occurred, different strategies for mitigating future OEs of the same type are revealed. For example, controllers are expected to demonstrate good control judgment and to maintain awareness and separation of traffic. The controller using good

control judgment would not place aircraft in hand-off status in conflict or in a situation leading to possible loss of separation and would ensure that separation standards are maintained at all times. This includes ensuring that aircraft entering and departing his/her sector airspace are not in conflict or about to lose separation. The controller would also use procedures that do not place workload and stress on other controllers or facilities. Consider the different mitigating strategies suggested by two situations.

#### Variation A – TM#10 occurred prior to the handoff

The controller is required to “transfer control of an aircraft only after eliminating any potential conflict with other aircraft for which you have separation responsibility” (FAA Order 7110.65, 2004, Para 2-1-15), “[e]nsure that, prior to transferring communications: potential violations of adjacent airspace and potential conflicts between aircraft in their own area of jurisdiction are resolved” (FAA, 2004, Para 5-4-5) and “[r]estrictions issued to ensure separation are passed to the receiving controller” (FAA, 2004, Para 5-4-5).

However, this only implies that potential conflicts between aircraft in the receiving area of jurisdiction are resolved prior to transferring communications. In other words, the transferring controller should not have aircraft established on a conflicting course when transferring them to the receiving controller. If a controller were to transfer aircraft to another sector controller without ensuring that their separation would still be established for the receiving controller, the aircraft would be *on a conflicting course* but not *in conflict* when handed off. One might say, in other words, that an OE would be a “set up” for the receiving controller, who would receive a “dirty” traffic situation. In these cases, the receiving controller inherits a potential OE situation that was set-up by the previous controller and ultimately may “get a deal” unless he/she realizes after taking the handoff that the aircraft are on a conflicting course and takes steps to ensure their separation. Mitigation, in these cases, could target the procedures, controller performance and other factors related to the controller who handed off the aircraft, rather than (or in addition to) those of the controller in whose airspace the OE occurred.

#### Variation B – TM#10 occurred after the handoff

After receiving aircraft, the controller is required to maintain appropriate separation standards between them (FAA, 2004). When a controller accepts the handoff of aircraft that have separation ensured, the traffic situation is handed off “clean,” and the receiving controller must maintain separation standards between them. If the aircraft are then set on a conflicting course (either by the controller’s action or inaction) and lose separation, then

the receiving controller still “has the deal.” However, in this case, the aircraft were not on a conflicting course or in conflict when handed off but they lost separation while in the receiving controller’s airspace. In other words, the situation was handed off “clean,” but the receiving controller made it “dirty.”

To better understand OEs, analysts would like to know more about how events unfold, e.g., how often do certain types of events happen and does one type make an OE more likely to occur than another? This temporal knowledge could then be combined with other information (such as aircraft types, weather, procedures) to identify strategies to improve the system.

#### Summary of Step 1

The TM framework developed in Step 1 provides a method to structure an OE. By using objective temporal information to populate the framework, the result then can be used in different ways, depending upon the issue of interest. For example, in a case analysis of a single OE the framework could be used to clarify temporal relationships between a number of aircraft and the controller. Further, the organizing structure of the TM framework permits analysts to compare TMs across many OEs to identify possible systemic concerns.

In addition to identifying temporal markers, the sequenced nature of the framework could also be used to calculate intervals between TMs (a Temporal Marker Time Span; TMTS) for other patterns of interest, such as the TMTS between first point where positive separation was not ensured and time that separation was lost. With this in mind, the framework was tested to determine whether calculating these intervals would yield additional information.

### Step 2 – Testing the TM Profile

#### Method

##### Participants

The three SMEs from Study 1 also participated in this activity.

##### Materials

A convenience sample of 29 OEs was used, which did not include the 6 OEs used in Study 1. All of the OEs came from one ARTCC. These were selected because both the final report (FAA Form 7210-3) and the SATORI re-creation were available for each in an existing archive. A voice transcript was developed for each OE from its SATORI re-creation so that the SMEs could use a hard copy of the voice recording. We provided each SME with copies of the TM framework, the final OE reports and the voice transcripts of each OE.

**Table 3.** TMTS from (TM#2) the time the relieving controller assumed position to —

	Average	Median	Min	Max
a) (TM#9_1a) Time of 1st ATC instruction by receiving controller to A/C1.	0:23:51	0:20:44	0:00:38	1:17:25
b) (TM#10) Time of first point where positive separation between A/C was not ensured.	0:25:23	0:21:14	0:00:38	1:17:25
c) (TM#11a) Time of the last instruction by receiving controller to A/C1 prior to loss of separation.	0:26:59	0:21:41	0:00:38	1:27:30
d) (TM#14) Time separation lost.	0:28:30	0:22:38	0:01:38	1:27:32

### Procedure

The SMEs were instructed to fill out the TM framework for each OE using available information. The SMEs denoted aircraft identified from the OE materials as A/C1, A/C2, etc. according to the procedure described previously. The SMEs' task was to identify from the available materials the specific times for each TM for the aircraft that lost separation. If the TM was the type that recurred (time of 1st ATC instruction by receiving controller to A/C1, A/C2, etc.), then they identified the times for each recurrence by using the notation method developed in Step 1 of the project to expand the TM framework (i.e., TM#9\_1a, TM#9\_2a, TM#9\_3a and so on) to indicate temporal sequence.

The SMEs worked independently to complete the TM framework for each OE. When the frameworks were completed, the TM times were compared for inconsistencies between SMEs. The SMEs were then reassembled to resolve the discrepancies. Their consensus generated the final dataset of TMs.

### Results

The TM framework can be used to temporally profile one OE (i.e., for a case analysis) or several (i.e., for a trend analysis). The dataset of TMs identified by the SMEs was used to calculate time spans between TMs (TMTSs) for each OE. Averages across OEs were then calculated for several TMTS to determine if this approach would reveal more about OEs beyond currently available information.

Examples are shown in Table 3 through Table 6. In each table, the first time used to calculate the TMTSs is the TM in the table's caption. The second time used to calculate a TMTS is the TM shown in the body of the table (i.e., a, b, c, d). The number is the calculated time spans between the time of the first TM and second TM (in hours : minutes : seconds). The tables show the average time span and the median<sup>3</sup> for the intervals. Minimum and maximum intervals were calculated for some examples to determine if they added additional information. The

median value's similarity to the average, minimum and maximum values suggests how the value of interest is distributed in the sample. For example, in Table 3, the median values of each TMTS are closer to the average values than to either the minimum or maximum values. However, Table 4 illustrates how the median TMTS can be lower than the average. This suggests that the analyst should examine the individual OEs to determine what situation resulted in this data.

Table 3 shows some calculated time spans, beginning with the time the controller takes position responsibility. For example, row a) in Table 3 describes when the relieving controller first issued a control instruction to one of the aircraft that was later involved in the OE. The average TMTS (0:23:51) shows this action was taken within about 20 min of the controller taking over the position. Row d) of Table 3 shows that the average time interval from the time the controller assumed position responsibility to the time separation was lost averaged about 28 min (0:28:30) in this sample of OEs. These values are similar to the national data for the controller's average time on position prior to an OE. However, the intervals ranged from 1 min 38 sec to 1 hr 27 min and 32 sec in this sample.

Table 4 describes three TMTS to profile a communications pattern between the controller and one of the aircraft involved in the OE (A/C1). Row a) shows the average time between the receiving controller's first instruction to A/C1 and the point at which separation was not ensured to have been relatively short (0:01:31). In some OEs in this sample, separation was not ensured between A/C1 and A/C2 prior to the relieving controller's first communication to A/C1, indicated by the negative value for at least one OE in the sample (-0:05:29). Negative values indicate that the second TM used in the TMTS analysis preceded the first TM in the OE.

Table 5 shows the average TMTS (0:01:30) from the time of the controller's last instruction to A/C1 until separation was lost. Interestingly, for at least one OE in this sample, the interval from the controller's last instruction to the aircraft to the separation loss was 8 min and 50 sec, although most TMTS were very short, as indicated by the low median value (0:00:53) for this TMTS.

<sup>3</sup> The median is the midpoint value where half the data values are above it and half are below it.

**Table 4.** TMTS from (TM#9\_1a) 1<sup>st</sup> ATC instruction by receiving controller to A/C1 to —

	Average	Median	Min	Max
a) (TM#10) Time of first point where positive separation between A/C was not ensured.	0:01:31	0:00:53	-0:05:29 *	0:07:38
b) (TM#11a) Time of the last instruction by receiving controller to A/C1 prior to loss of separation.	0:03:08	0:02:23	0:00:00	0:10:05
c) (TM#14) Time separation lost.	0:04:38	0:04:19	0:00:31	0:10:07
* Note. The negative value indicates that TM#10 preceded TM# 9_1a in at least one OE.				

**Table 5.** TMTS from (TM#11a) Time of the last instruction by receiving controller to A/C1 prior to loss of separation to —

	Average	Median	Min	Max
a) (TM#14) Time separation lost.	0:01:30	0:00:53	0:00:01	0:08:50

**Table 6.** TMTS from (TM#10) Time of first point where positive separation between A/C was not ensured to —

	Average	Median	Min	Max
a) (TM#11a) Time of the last instruction by receiving controller to A/C1 prior to loss of separation.	0:01:36	0:00:24	-0:05:55 *	0:10:05
b) (TM#14) Time separation lost.	0:03:07	0:01:59	0:00:20	0:10:07
* Note. The negative values indicate that the second TM preceded the first TM in the OE.				

**Table 7.** TMTS from (TM#2) the time the relieving controller assumed position to —

	A/C1 (n OEs=29)			A/C2 (n OEs=20)		
	Average	Min	Max	Average	Min	Max
a) (TM#9_1a) Time of 1st instruction by receiving controller.	0:23:51	0:00:38	1:17:25			
b) (TM#10)* Time of 1 <sup>st</sup> point where positive separation between aircraft is not ensured.	0:25:23	0:00:38	1:17:25	0:25:23	0:00:38	1:17:25
c) (TM#9_1a) Time of 1st instruction by receiving controller.				0:28:1	0:07:44	1:26:53
d) (TM#11a) Time of the last instruction by receiving controller prior to loss of separation.	0:26:59	0:00:38	1:27:30			
e) (TM#14)* Time separation was lost.	0:28:30	0:01:38	1:27:32	0:28:30	0:01:38	1:27:32
f) (TM#11a) Time of the last instruction by receiving controller prior to loss of separation.				0:31:03	0:09:49	1:26:53
* Note. Shaded rows indicate TMs that involve both aircraft.						

Table 6 shows two TMTS calculated, beginning with the time when separation between the aircraft was not ensured (i.e., if nothing intervened to change the trajectory of either aircraft, they would eventually lose separation). As shown in rows a), the average interval between that time and the controller's last instruction to one of the aircraft was 1 min and 36 sec. However, looking at the minimum and maximum values shows that, in at least one OE in this sample, the controller's last instruction to one of the aircraft involved in the OE occurred 5 min and 55 sec before separation was not ensured. At the other extreme, in at least one OE in this sample, the controller's last instruction to one of the aircraft involved in the OE occurred 10 min and 05 sec after separation was not ensured.

If data from more OEs were available for TM profiling, other analyses could be conducted. For example, OEs could be grouped by other causal factors of interest, e.g., failure by the controller to detect displayed data, the controller's time on position, combined positions, weather conditions and traffic complexity factors. TMTS could then be calculated for these groups to determine whether their TMTS profiles differed.

### OE Profiling

The TM framework can be used for case analysis to understand the temporal evolution of one OE (e.g., patterns of communications between the controller and the aircraft) or for trend analysis to understand patterns across a group of OEs (e.g., factors related to "dirty" situations handed off to receiving controllers). By generating TMTS profiles between events that occurred during the OE relative to the interaction of the controller and each aircraft (A/C1, A/C2, A/C3, etc.), the results can be compared side-by-side as in Table 7, which shows average TMTSs between some of the TMs in this set. For example, the controller's first instruction to A/C1, on average, was 0:23:51 min after taking position but before the first point where no positive separation was ensured, which occurred 0:25:23 min after taking position. A/C2 was given its first control instruction, on average, approximately 5 min later, which occurred 0:28:18 min after taking position but after the first point where positive separation was not ensured.

The controller's last instruction to A/C1, on average, was 0:26:59 min after taking position and before separation was lost (at 0:28:30 min after taking position). The controller's last instruction to A/C2, on average, was 0:31:03 min after taking position. However the last instruction "prior" cannot also occur "after." This is logically inconsistent and is a statistical artifact of using small samples. Analysts should look instead at other statistics

such as the median value or mode.<sup>4</sup> This suggests that TMs should either be used for case analysis of individual traffic situations or with large samples. Future work will tease apart the aspects of this phenomenon as it pertains to OE profiling.

### Summary of Step 2

In this activity, we demonstrated how time intervals calculated from TMs could be used to profile the temporal evolution of an OE. The project relied on a convenience set of archival OE reports. Issues of missing data and small sample sizes related to using archival OE materials were identified as well as future projects for this line of research.

### Project Summary

We identified a set of TMs that could potentially occur in every OE. Moreover, all but one TM can be identified using sources of objective data available at the AT facility. Subjective assessments by the facility's staff are not needed to use this method of OE analysis.

In Step 1 of this project, we developed a framework of TMs to organize types of objective, time-based information about OEs that are routinely available at ATC en route facilities but which have not previously been systematically organized in this manner.

In Step 2, we tested the framework developed in Step 1 by using it to organize information from a small convenience sample of archival reports of en route OEs. TMs were identified for each OE and several TMTSs were calculated to demonstrate the utility of the methodology. Results demonstrated how intervals between TMs could provide additional information about how OEs evolve over time. Which two TMs are selected to calculate a TMTS depends on which dimensions of the OE interest the analyst.

Any trends in TMs and TMTSs which appear in OEs could help the OE analyst to detect potential system vulnerabilities. For example, one might want to identify trends in the following TMs and TMTSs.

#### Temporal Markers, such as:

- the point when the two aircraft were first set up on a conflicting course (that is, separation was not ensured if no one interceded and intervening actions would be required to maintain separation).
- the time when the receiving controller established communication with the aircraft.

<sup>4</sup> The mode is the value in the sample that occurred most frequently.

#### Time Spans, such as:

- the time interval from when the controller assumed the position relative to when separation was not ensured.
- the time interval between when separation was not ensured until separation was lost.
- the time interval between the onset of evasive actions and when separation was lost.

While this project was conducted to explore the possibility of using objective, temporal data to better understand OEs, several interesting questions emerged from this small sample. One trend worth exploring is whether there is a high frequency of situations (a) where controllers “set up” an OE for the next position by handing off a “dirty” situation to the receiving controller or (b) whether most OEs are received “clean” but the receiving controller then makes it “dirty” by either ensuing actions or inactions. Finding that aircraft are handed off with confliction could have several implications for mitigation and reduction. If the TM profile of an OE shows that the first point where aircraft were set on a conflicting course occurs at a particular time (such as prior to the handoff, within the first 5 min of the controller’s time on position, prior to establishing communications with the aircraft), the circumstances at that time could be examined.

Analysts could examine other interesting issues - for instance, whether aircraft involved in OEs have other temporal characteristics in common, such as time from checking on frequency to first control instruction, differences in profiles for OEs occurring during the first few minutes after a position transfer or OEs with similar causal factors.

In sum, using TMs and TMTs to analyze OEs would permit analysts to address several interesting types of questions, such as the following.

- Handoff situations: Did the responsible controller set up the conflict or inherit it? The controller handing off an aircraft must resolve any conflicts prior to the handoff to the receiving controller.
- Recovery strategies: Did the aircraft come to the receiving controller already in a confliction pattern (“dirty”) so that the controller had to become a “fixer?” If the conflict was set up before the receiving controller accepted the aircraft, strategies of the receiving controller to fix separation could be identified, contributing conditions could be identified, handoff procedures could be reviewed, performance of the handoff controller could be evaluated, etc..
- Performance and other factors: Did the aircraft situation come to the controller “clean” and the situation became “dirty” from either actions or inactions by the controller? If the conflict was set up after the controller

accepted the aircraft, then the receiving controller did not ensure separation and the reasons for that situation could be examined.

- Controller-pilot factors: When was controller-pilot communication established, if at all? TM profiles might show that aircraft involved in OEs were more (or less) likely to have communications established between controller and pilot.
- Communication loads: What was the pattern of controller-pilot communications before, during and after the OE? For example, the number of communications between the controller and the pilot(s) might be an indicator of workload or of controller efficiency. TM profiles might show that OEs differ from non-OE situations by having a higher (or lower) rate of pilot-controller communications.

This approach to analysis could be extended to a system-wide application. Other interesting questions and temporal trends are likely to be identified as larger data samples are analyzed. These trends may provide guidance for the display of additional information and formatting and may have implications for the design of enhanced decision support capability.

#### Limitations

##### Convenience sample

As noted earlier, the examples in this paper were based on a set of TMs from a small sample of ARTCC OEs. Inferences from small samples should be made carefully until the method can be tested on a larger set of OEs. For example, the average times calculated from a small number of cases makes generalization beyond the sample to other OEs difficult without verifying the results with a separate sample of OEs. Other measures, such as the median (midpoint) value, should also be examined to adjust for effects of outliers (i.e., extraordinary minimum or maximum values) on the average value.

The small sample constrained us to look at the TMs and TMTs only in a general way. Much more information would be available to identify meaningful trends if a larger set of OEs was analyzed using for this type of profile analysis. Trends evident in larger samples of OEs would be considered more robust, leading to greater confidence in mitigation strategies based on the results. A larger set of OEs would permit a better understanding of whether it makes sense to average over OEs without grouping them based on other similarities, such as causal factors.

The ARTCC operational errors we used were selected because the event chronology and a SATORI re-creation were available for each OE. However, the SMEs judged that the list would also apply to OEs in Terminal Radar Approach Control facilities, since they are also radar



environments, and possibly to OEs at air traffic tower facilities. This was not verified in this study in part because OE re-creations were not available.

#### Missing data

In this sample, data (and consequently, perhaps an important TM) could be missing for different reasons. The temporal event might have occurred during the OE but the original report omitted the necessary information, and it was not available from the SATORI for the event. Thus, the corresponding TM could not be identified later, resulting in missing data for that TM in that OE. Alternatively, a temporal event might *not* have occurred during the OE, resulting in missing data for that TM in that OE. In our sample, we cannot distinguish between these two types of missing data. Issues of missing data are not typically considered when researchers analyze OE data, but when relying on archival data only those TMs can be identified for which information is available.

#### Future Work

##### Other event types

Because we wanted to use events in OEs that could be identified objectively as temporal markers, the result was that most TMs focused on the interactions between the controller and aircraft or between two or more aircraft. Future work to test the TM set will determine whether other types of events should be included as TMs - expedited maneuvers, altitude changes, heading changes and so on. Our definition of *temporal markers* constrains this possibility somewhat because any TM candidate must satisfy the general condition that these events may differ at the point in time they occur, but they occur in some form in most, if not all, OEs and must be "objective or calculable." This is an important characteristic to enable comparison between OEs.

##### Large samples

To fully understand how to best exploit this method of analysis, it needs to be applied to a large set of OEs. For example, a large ATC facility could apply this Temporal Marker framework to all of its OEs for a year and profile OEs both individually and overall for both case and trend analysis. We could then gain a better understanding of OE profiling and be better able to evaluate whether controllers and management gained additional insights about OEs from this type of information.

##### National trends

Currently, the chronologies developed at facilities after OEs are not required to be as detailed as the TM framework nor are they as highly structured. The TM framework could help to structure the OE chronologies

if it were used as a tool to complete the final OE report. This would provide more complete archival information for OE analysis. A national database of TMs could be analyzed for trends in TMs and TMTs to expand our knowledge about how OEs evolve so that vulnerable situations could be identified and mitigated.

#### Re-creations

To exercise this approach to structuring objective events in OEs, a comprehensive re-creation capability is needed that would provide seamless visualization of traffic over time and across facility types. Currently the ARTCCs have the SATORI system, TRACONs have RAPTOR replays and some larger towers have the potential to replay traffic using the Airport Movement Area Safety System (AMASS). These are separate systems and have different levels of usability and timeliness of turnaround. Tower facilities would present the greatest challenge for this approach because they currently have limited capability to re-create traffic situations. An end-to-end integrated capability would enable a larger temporal understanding of the evolution of OEs (and potentially other types of events) that is not currently available.

## Conclusions

In sum, we believe that using the TM framework will give operational personnel and researchers another tool to identify information about factors leading to OEs. By profiling OEs in this manner, this method provides an objective method for identifying structure in high consequence, complex, dynamic events. This approach provides a means to view OEs in a new light that has the potential to directly lead to mitigation activities and to ensure continual improvement in our understanding of OEs and the OE analysis process.

## References

- Bier, V. (1998). *Proceedings of workshop on accident sequence precursors and probabilistic risk analysis*. College Park, MD: University Printing Services.
- Block, R.A. Ed. (1990). *Cognitive models of psychological time*. Hillsdale, NJ: Erlbaum.
- Dekker, S. (2002). *The field guide to human error investigations*. Burlington, VA: Ashgate.
- Dörner, D. (1996). *The logic of failure. Recognizing and avoiding error in complex situations*. Reading, MA: Perseus Books.
- Federal Aviation Administration. (2002). *Air traffic quality assurance. FAA Order 7210.56*. Washington, DC: Author.

- Federal Aviation Administration. (2004). *Air traffic control. FAA Order 7110.65*. Washington, DC: Author.
- Gibbon, J., & Allan, L. Eds. (1984). *Timing and time perception*. New York: New York Academy of Sciences.
- Harry, M., & Schroeder, R. (2000). *Six sigma*. New York: Currency.
- Klein, G.A., Orasanu, J., Calderwood, R., & Zsombok, C.E. (1993). *Decision making in action: Models and methods*. Norwood, NJ: Ablex.
- Krause, S.S. (2003). *Aircraft safety: Accident investigations, analysis & applications* (2<sup>nd</sup> ed.). New York: McGraw-Hill.
- Perrow, C. (1999). *Normal Accidents*. Princeton, NJ: Princeton University Press.
- Petersen, D. (1996). *Human error reduction and safety management* (3<sup>rd</sup> ed.). New York: Van Nostrand Reinhold.
- Phimister, J.R., Bier, V.M., & Kunreuther, H.C. Eds. (2004). *Accident precursor analysis and management*. Washington, DC: National Academies Press.
- Pounds, J., & Ferrante, A.S. (2005). FAA strategies for reducing operational error causal factors. In B. Kirwan, M. Rodgers, & D. Schäfer (Eds.), *Human factors impacts in air traffic management* (pp. 87-105). Burlington, VT: Ashgate.
- Rasmussen, J. (1980). What can be learned from human error reports? In K. Duncan, M. Gruneberg, & D. Wallis (Eds.), *Changes in working life*. London: Wiley.
- Reason, J. (1990). *Human error*. New York: Cambridge University Press.
- Reason, J. (1997). *Managing the risks of organizational accidents*. Brookfield, VT: Ashgate.
- Rodgers, M.D., & Duke, D.A. (1993). *SATORI: Situation assessment through the re-creation of incidents*. Washington, DC: Federal Aviation Administration Office of Aviation Medicine. DOT/FAA/AM-93/12.
- Rogers, M.D., & Duke, D.A. (1993). *SATORI: Situation assessment through the re-creation of incidents*. Journal of Air Traffic Control, October-December, 10-14.
- Sagan, S.D. (1993). *The limits of safety*. Princeton, NJ: Princeton University Press.
- Salas, E., & Klein, G. (2001). *Linking expertise and naturalistic decision making*. Mahwah, NJ: Lawrence Erlbaum.
- Smolensky, M.W. (1993). Toward the physiological measurement of situation awareness: The case for eye movement measurements. *Proceedings of the Human Factors and Ergonomics Society 37th Annual Meeting, Seattle, Washington*. Santa Monica, CA: Human Factors and Ergonomics Society.