Modeling the Air Traffic Controller's Cognitive Projection Process

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by

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Abstract

Cognitive projection enables the operator of a supervisory control system, such as air traffic control, to use predicted future behavior of the system to make decisions about if and how to control the system. New procedures and technologies being implemented in the air traffic control system innately affect the information used for projection and the type of projection required from the controller. Because cognitive projection is not well-understood, launching these projection-impacting technologies and procedures could result in the reluctance of the air traffic controllers to accept these advancements or limit the system performance.

A Projection Process Model and a Projection Error Concept were proposed to describe the controller's projection process and the contextual system influences on the projection process. The two primary influences on the projection process were the information/display system and task-based projection requirements. A mismatch between the information/display system states and the task-based projection requirements was described through a cognitive transform concept. The projection process itself is composed of the state mental model and the time into the future over which the projection is made.

Hypotheses based on the assumptions of the Projection Process Model and Projection Error Concept were probed through an experiment using an ATC task paradigm. Results were consistent with the proposed models. They suggested that the controllers were able to incorporate higher-level dynamics into the state mental models used for projection and that the quality of the state mental model used was marginally influenced by the error tolerance required in the task.

The application of the Projection Process Model and Projection Error Concept was then illustrated through the analysis of the impact on projection from two ATC domain examples of technology and procedure implementation. The Constant Descent Approach Procedure in the TRACON impacted the intent, projection timespan, and abstractions used in the mental model of the controllers. The Oceanic ATC surveillance, communication and workstation improvements resulted in an impact on the states to be projected, intent, projection timespan, and human/automation projection responsibility. Suggestions for improved transition for the projection process were then provided based on the analysis.

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Acronyms

ADS	Automatic Dependent Surveillance
ADS-A	Automatic Dependent Surveillance- Address
ARTCC	Air Route Traffic Control Center
ATC	Air Traffic Control
ATOP	Advanced Technologies and Oceanic Procedures
CAA	Civil Aviation Administration
CCM	Cognitive Clocking Model
CDA	Constant Descent Approach
CDTI	Cockpit Display of Traffic Information
CME	Cognitive Motion Extrapolation
ETA	Estimated Time of Arrival
FAA	Federal Aviation Administration
FDPS	Flight Data Processing System
FMS	Flight Management System
HF	High Frequency
IFR	Instrument Flight Rules
ILS	Instrument Landing System
IP	Interruption Paradigm
ISI	Inter-stimulus Interval
LOA	Letters of Agreement
MD	Miss Distance
MNPS	Minimum Navigational Performance Standards
NASA	National Aeronautics and Space Administration
PIREP	Pilot Report
RNAV	Area Navigation
SA	Situation Awareness
SATCOM	Satellite Communication

SID	Standard Instrument Departure
SOP	Standard Operating Procedure
STAR	Standard Terminal Arrival Routing
TMA	Traffic Management Advisor
TRACON	Terminal Radar Approach Control
TTC	Time-to-Contact
VHF	Very High Frequency

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CHAPTER 1: Introduction to Projection in Air Traffic Control

In complex, dynamic, safety-critical systems such as air traffic control, an understanding of the current and future behavior of the system is necessary to control the system effectively. The process that enables this understanding is the cognitive projection process. For the purposes of this thesis, projection is defined as the prediction of the evolution of a state of a dynamic system into the future. One of the primary tasks of the air traffic controller is to perform conflict projection to ensure that no aircraft will penetrate the minimum separation standards with another aircraft. In Air Traffic Control (ATC), this projection process provides a predicted future behavior on which to base control actions.

Improved communications, navigation, and surveillance technologies accompanied by advanced decision support tools enable system performance-enhancing procedures to be implemented in the ATC system. Some of these advancements may affect the information used in projection, the task for which projection is required, or the ATC projection process itself. Improved surveillance systems such as Automatic Dependent Surveillance (ADS) allow the information used in projection to be updated more frequently. Changing the oceanic controllers' information display from flight strips to a situation display changes the information from temporal state information to spatial state information, which may influence the controller to perform a spatial rather than a temporal projection (FAA, 2004; FAA, 2005). In the En Route Centers, the separation requirements that the controllers must meet during congestion are changing from a spatial "miles-in-trail" requirement to a temporal "minutes-in-trail" requirement which changes the task for which projection is required (Abbott, 2002; Mann, Stevenson, Futato, & McMillan, 2002; Farley, Foster, Hoang, & Lee, 2001). Noise abatement procedures implemented in the TRACON environment remove the segments of straight and level, constant velocity flight, which changes the dynamic behavior of the aircraft, influencing how the controllers project these aircraft (Clarke, Ho, Ren, Brown, Elmer, Tong, & Wat, 2005; Clarke, 1997).

It is important to consider the effect that these changes in information support and procedures have on the cognitive process of projection in air traffic control. Negative impact of new procedures on the controller's projection process may limit the performance of the system. For example, field tests of the noise abatement procedures have resulted in the finding that traffic throughput using these approaches can be less than the throughput using the normal ILS procedure. One potential reason for the loss in efficiency is that the controllers had difficulty predicting the future behavior of aircraft in continuous descent and continuous deceleration.

Therefore, the purpose of this thesis is to better understand the air traffic control projection task to allow the development of useful workstation and procedural requirements to support the projection task.

1.1 Role of Projection in a Supervisory Control System

The air traffic control system is an example of a supervisory control system. According to Sheridan (1992), a supervisory control system is a system "that is controlled by 1 or more human operators that are intermittently programming and continually receiving information from a computer that itself closes an autonomous control loop through artificial effectors and sensors to the controlled process or task environment".

Figure 1.1 depicts an example of such a system. In this schematic, the system is surveilled through sensors and then this sensory information is displayed to the human controller. The human controller then cognitively decides what action to take on the system and subsequently performs a control action that changes the way in which the system behaves.

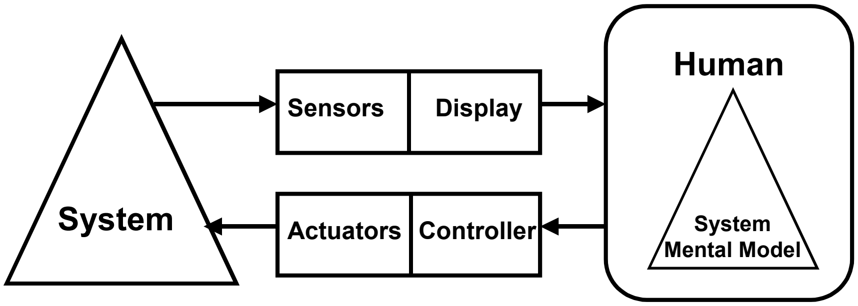


Figure 1.1: Human Supervisory Control System

To understand the information and what to do about the information presented with respect to the operator's goals of safety and efficiency, the human must understand how to project current state information into expected future behavior of the system. The construct by which this evolution occurs has been termed the "mental model" by researchers and is illustrated in Figure 1.1. The mental model, an elusive concept in human machine interaction literature, is defined in this context as the operator's conceptual, dynamic representation of a physical system that is used to understand the current state of the system and predict future states of the system; There may be multiple mental models, and they are innately fuzzy and incomplete (Moray, 1998; Norman, 1983; Doyle & Ford, 1987; Wickens & Hollands, 2000). The prediction of the future state of the system provides key information on which to base future actions by the human on the system. Understanding the operator's projection task is therefore key to designing quality information requirements for information support systems.

1.2 ATC as a supervisory control system

The ATC system can be mapped using the terminology of the supervisory control system. Figure 1.2 shows the ATC represented in similar terms to Sheridan's supervisory control system in Figure 1.1. The "system" is the ATC operational context in the gray box on the left. Within this context are the aircraft and the pilots. The aircraft in the system exhibit dynamic behavior changing over time, and the behaviors are impacted by the pilot operator, the environment, and supervisory control commands issued by the controller. The system "sensors" are the ATC surveillance systems, which are within the Information/Display System block. The ATC surveillance systems are not continuously monitoring the state of the system, but are discretely updating this information depending on the limitations of the radar or other reporting system used in the ATC domain. The "displays" are also in this block and are comprised not only of the radar/situation display and flight strips that the controller sees visually, but also any auditory or other means of receiving information about the state of the system.

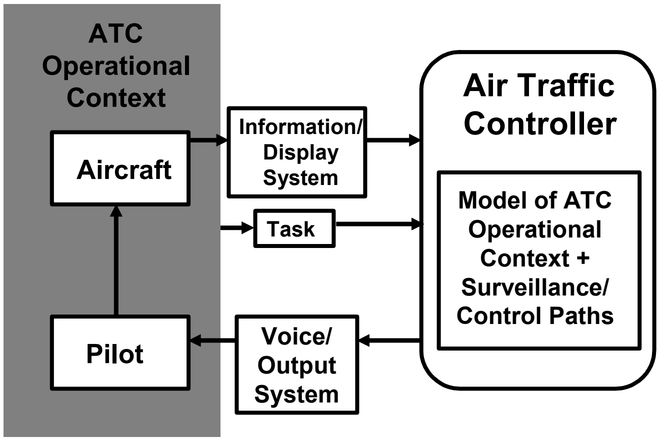


Figure 1.2: ATC as a supervisory control system.

Another input besides the information/display states is the task of the controller, which informs the air traffic controller of the goals of the system and the requirements to which the system must be controlled. In air traffic control, the goals are safety and efficiency of the system. One of the primary tasks of the controller, which will be focused on in this thesis, is the separation and sequencing of aircraft to maintain a minimum separation requirement. This information about the task and the system states is then incorporated into the air traffic controller's mental model of the operational context and interface systems, which are represented as the "system mental model" in Figure 1.1. The controller then determines if a control action is required and if so, what type and magnitude, based upon the task requirements. The control actions are issued through the voice/output system in ATC, which is the "controller" aspect of the system in Figure 1.1. These control commands are then implemented by the pilots, or the "actuators" onto the aircraft.

1.3 Research Questions

Projection is a critical cognitive process that allows the operator to predict future behavior of the system that is used to make decisions about if and how to control the system. Failing to adequately understand the operator's projection process can result in poor information support for this process and/or rejection of the information support tool by the operator. It is therefore critical to give consideration to the cognitive implications that the information support transitions, such as when procedures change the aircraft dynamic behavior from level-segment to continuous descent/deceleration and when ATC operations change from spatial to temporal, have on the controller's projection process. The purpose of this thesis is to:

- Investigate how air traffic control projection is currently performed in various ATC environments
- Understand how context affects the projection process
- Identify means of supporting the projection process in future information systems

CHAPTER 2: Review of Projection Research

Projection is a critical task in everyday life. The ability to project behaviors into the future is required for avoiding traffic, catching baseballs, navigating a computer desktop with a mouse, and even placing your feet while running. It is no surprise, therefore, to find that the projection task has been examined in both the theoretical and applied research circles since the mid 1950's.

This chapter will examine some of the key findings of this research, beginning with understanding about projection from basic research in section 2.1. In section 2.2, the more applied concepts of projection will be reviewed as they relate to supervisory control of complex systems, including air traffic control.

2.1 Basic Research Examining Projection

Psychological research has been able to develop a better understanding of the cognitive mechanisms underlying the projection process as well as contextual factors that may influence how dynamic objects are projected. In the next sections, research will be reviewed that has investigated the effect on projection of the system's dynamic behavior, the update rate of the information system, and the task of the operator. Let us first consider the known projection patterns and biases that humans exhibit when predicting evolving dynamics.

2.1.1 Projecting accelerating objects

Objects that exhibit dynamic behavior will likely exhibit accelerating and decelerating behaviors. It has been found that humans can have a difficult time projecting the behavior of accelerating/decelerating objects. Gottsdanker (1954) provided a task that required participants to track a pair of parallel lines and continue the constant velocity or accelerating pattern after the lines had disappeared. Even if the pattern exhibited acceleration during the visible portion of the path, the participants would extrapolate their motion with constant velocity. This provided performance that is consistent with underestimating velocity in accelerating targets. Wagenaar and Timmers (1979) performed experiments investigating the ability of participants to extrapolate exponential functions. They found that participants consistently underestimated exponential growth functions, even when the growth information was presented in a graphical format. Instead, a linear extrapolation was made based on the last perceived velocity. Figure 2.1 depicts this phenomenon of linear extrapolation.

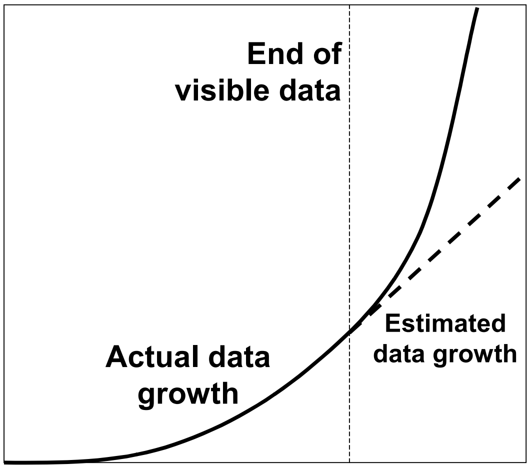


Figure 2.1: Misperception of exponential growth, as reported by Wagenaar & Timmers (1979).

Rosenbaum (1975) provided evidence that in a constant velocity extrapolation, accuracy remained high regardless of the amount of time that the target was visible or concealed. When the target accelerated or decelerated, accuracy decreased with increasing acceleration/deceleration and increased target concealment. Rosenbaum also claimed that data from his experiments suggest that acceleration can be directly encoded by the visual system, but this claim was refuted by several subsequent studies (Runeson, 1975; Jagacinski, Johnson & Miller, 1983; Werkhoven, Snippe, & Toet, 1992, Benguigui, Ripoll, & Broderick, 2003).

Using a paradigm consisting of judging which of two targets would arrive at an intersection point first, Runeson (1975) tested a hypothesis that a motion consisting of acceleration then constant velocity appears to the observer as constant velocity throughout. He suggests that a “natural motion” stereotype is used for predicting object motion, and since acceleration is not directly perceivable by the visual system, this stereotype biases all motion judgments.

Jagacinski, et al. (1983) further explored this theory and that suggested by Gottsdanker (1954) and Wagenaar & Timmers (1979) by asking participants to view a moving target, and then when the target disappeared, the participant was asked to press a button when the target would pass a particular point further along the trajectory. The target followed either a constant velocity trajectory or a linearly accelerating trajectory. Jagacinski compared the proposed internal models depicted in Figure 2.2: the “consistent with real system” model of that followed by the target, the “acceleration + coast” model based upon the “natural motion” model proposed by Runeson, and the “constant velocity segments” model proposed by Gottsdanker. Both constant velocity and accelerating trajectories resulted in data that most closely matched the "acceleration + coast" model, indicating that it appears that acceleration can be incorporated into projection in some cases. Jagacinski also manipulated whether feedback about the prediction was provided to the participant. In the cases in which feedback was withheld, the responses were lengthened temporally, proportional to the equivalent conditions when feedback was provided. An internal model consisting of the parameters *T* (period of acceleration) and *a* (acceleration constant) was proposed to describe the data in the experiments and is consistent with the "acceleration + coast" model.

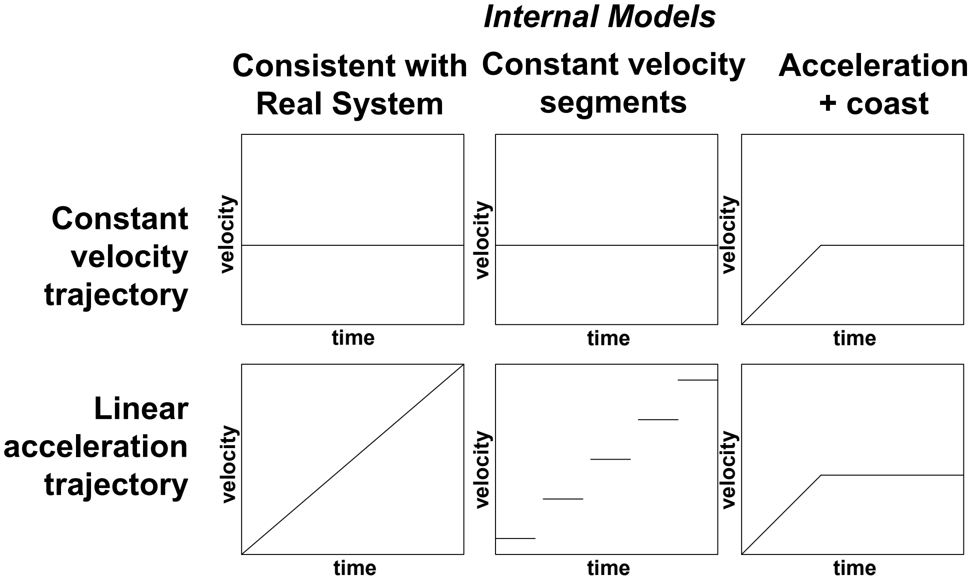


Figure 2.2 Comparing internal acceleration models (Adapted from figure 3 in Jagacinski, et al., 1983).

Other data from psychophysical experimentation suggest that these accelerations are not perceived directly, but are inferred from changes in perceived velocity (Gottsdanker, 1954; Werkhoven, et al., 1992). It was suggested by Werkhoven, et al. (1992) that acceleration was determined by monitoring the variance of a temporally varying speed signal over a relatively long time period (>100 msec).

Using a collision prediction paradigm, Gottsdanker & Edwards (1956) suggested that participants were using neither velocity nor acceleration, but final observed relative position between targets to predict the miss distance between targets.

Each of these studies described above used a display that provided near-continuous information. Projecting objects using dynamic information with longer time between information updates, such as those used in ATC, requires special consideration.

2.1.2 Influence of information update rate on projection

When considering the projection of non-continuous information updates, there are two parameters to consider. Figure 2.3 depicts the parameters of stimulus presentation and inter-stimulus interval. Experimentalists have varied both parameters to determine how motion is processed at different levels of each parameter. A third parameter, "update time," is also added to discuss ATC information/display systems. "Update time" is composed of the total time when adding stimulus presentation and inter-stimulus interval.

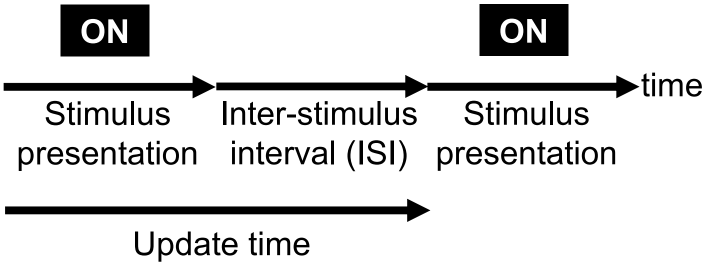


Figure 2.3: Discrete system parameters.

Limited research was found studying accuracy of the projection process while varying the length of stimulus presentation. A minimum length of initial stimulus presentation to process the stimulus adequately enough to induce the perception of "motion" between stimuli was determined to be 1000 msec by Freyd (1983). Meeting this stimulus presentation length is not an issue in ATC, whose minimum information presentation length before an update in the TRACON is 4.8 sec.

More research has been dedicated to the variation of the inter-stimulus interval and its influence on motion perception. Several categories of motion perception are discussed within the literature, depending on the time interval between information updates. Steinman, Pizlo & Pizlo (2000) outline the different types of motion perception from shortest inter-stimulus interval (ISI) to longest: simultaneity, pure movement (also referred to as φ), optimal movement (also referred to as β), partial movement, and succession. Possibly applicable to ATC, apparent motion (similar to β) is defined as a perceptual illusion in which the ISI between static stimuli is short enough such that motion preceptors perceive continuous motion, as in the movies (Wertheimer, 1912). Motion does not have to be perceived on a display to be used semantically. Implicit motion is defined as the motion that is represented within a static picture (e.g, a photo of a person serving a tennis ball) (Freyd, 1983).

Freyd and colleagues performed a series of experiments exploring the influence of ISI variation on stimulus discrimination accuracy and response time. Freyd (1983) asked participants to view a pair of static photos of a particular action sequence, and on the final photo the participant was asked to judge whether it was "same" or "different" from the initial photo. Action sequences included a person performing various actions (e.g., jumping from a wall, dropping a light bulb) or waves crashing. The second photo shown was either a photo further along temporally in the action sequence, a photo from previously in the action sequence, or the same photo. The data from this experiment suggested that it was harder for a participant to judge difference in a forward action sequence over a difference in a backward action sequence. Freyd proposes that a reason for these results is that participants exhibit "representational momentum." This phenomenon occurs when "the final location of an object undergoing real or implied motion is systematically distorted or shifted 'forward' along the path of motion" (Gray & Thornton, 2001). Consistent with Wagenaar & Timmers (1979), Freyd (1987) discussed findings that indicated that the magnitude of the memory shift is a linear function of the implied velocity of the object displacement between updates.

This study was replicated with the use of rotating rectangles in the first experiment presented in Freyd & Finke (1984), finding similar results to Freyd (1983). In another experiment presented in Freyd & Finke (1984), the experimenters varied the ISIs between updates: 250 msec, 500 msec, & 750 msec. The similar effect to Freyd (1983) was present and strong in the 250 & 500 msec cases, but was not present in the 750 msec case. It was found that as the ISIs were lengthened, the difficulty of judging the distractor in the direction of motion decreased, possibly due to smaller implicit angular velocity in longer ISI cases or participants having difficulty holding eye fixation in the longer cases.

In ATC, the ISI between information updates is usually instantaneous, which should encourage the perception of motion. However, a modulating factor is the length of the stimulus presentation. For a majority of the time, the controller is observing a static screen of information. Freyd (1984) suggested that longer stimulus presentation times (on the order of 250 msec) would require an ISI of close to zero to induce apparent motion. Since the minimum stimulus presentation in TRACON ATC is 4.8 sec and can be up to 30 min for oceanic ATC, it is unclear whether apparent motion biases would affect controllers at all.

Two levels of motion processing have been discussed in the literature, depending on if the motion is perceived or implied. Braddick (1980) pointed towards a low-level processor to comprehend perceived motion and higher-level (cognitive) processor to comprehend apparent & implied motion. The low-level processor is associated with specific direction-sensitive neurons that are sensitive to discontinuous stimulation. Braddick cited several studies using the "motion" of a group of dots in a random dot display as evidence of the low-level processor. In these studies, spatial displacement between the "moving" group and the reference group must be less than 15 deg, ISI must be less than 80-100 msec, and a bright field presented during the ISI can "mask" the motion effect (Braddick, 1974; Braddick 1973). Studies using a single moving target result in a different perception of motion with looser constraints on the parameters: spatial displacement may be great, ISI may be 300 msec, and there is no masking effect present. Braddick argues that if information is available from both processors, effective processing will incorporate and resolve both sets of information. Castet (1995), Adelson & Bergen (1985), and Kerzel (2003) all provided further evidence of this two-processor concept to maximize the use of motion information present in stimuli.

Thus, due to the constraints on the low-level processor, it is likely that most of the processing of discrete information by air traffic controllers is performed at the cognitive level. However, lack of projection research having a stimulus presentation length and the interaction with ISI similar to ATC prevents us from ruling out the perceptual and memory biases discussed here.

2.1.3 Influence of target velocity on projection

Another influence on the projection process is the velocity of the target to be projected. Gottsdanker (1954) found that as the velocity of the changing pattern increased, the accuracy of the participant's tracking ability also increased. The velocities used in his experiment ranged from 7.5 mm/sec to 20 mm/sec (approximately 0.86 deg/sec to 2.3 deg/sec at a viewing distance of 1 m).

Castet (1995) performed an experiment in which observers watched a light proceed along each of two LED rows and were asked to judge which light was faster. He varied both the physical speed at which the light was traveling, the spatial interval between the discrete light presentations, and also the ISI between light presentations. The velocities he used were between 2 deg/sec and 8 deg/sec. Due to the manipulation of these variables, he was able to present a light traveling at the same speed in three different combinations of presentation: a frequent light presentation during which the spatial interval between presentations and the ISI was small, an infrequent light presentation during which spatial interval between presentations and ISI was large, and a medium presentation case between the two. These results suggested that by increasing ISI and spatial interval for a particular physical speed, there was an increase in apparent speed at low velocities. This effect disappeared when the velocity was 8 deg/sec. Castet attributed this overestimation effect to the influence of "high temporal frequencies introduced by cruder sampling" (p. 1382). These higher frequencies activate the band pass filter leading to an overestimation of the speed present.

Adaptation to a particular velocity can also affect the speed estimation bias. Smith (1985 & 1987) found that when participants were adapted to test-gratings with a speed of between 1 and 40 deg/sec, the apparent speed of a moving test-grating of between 2-8 deg/sec was underestimated.

Depending on the display settings, which affect perceived velocity, and the cross-section of aircraft velocities in the particular sector, velocity estimation biases could affect how well controllers project. Most of the studies presented thusfar use velocities that are faster (at 1-8 deg/sec) than those used in ATC information/display systems (at approximately 1 deg/10 sec). Therefore, biases at the slower end (e.g., Castet's overestimation bias) may apply, but further investigation is necessary to confirm this.

Now that we have an indication of the types of cognitive processing information with different dynamics and update rates undergoes, let us turn towards understanding the proposed mechanisms by which this projection is made.

2.1.4 Projection mechanisms

Two processes suggested by projection researchers by which projection is made include the Cognitive Motion Extrapolation (CME) model and the Cognitive Clocking Model (CCM). The CME model is more of a spatial projection model that produces an expected state given a projection time, while the CCM is more temporal producing an expected time at which the system achieves a particular state. Using the CME model, observers develop an internal spatial model of the target's visible motion, then use this model to extrapolate future position when the target disappears (Schiff & Oldak, 1990; DeLucia & Liddell, 1998). Figure 2.4 depicts this model in which the spatial displacement of the system is linked with a time step, allowing spatial predictions to be made at times in the future.

Many projection researchers support the concept that some form of internal behavioral model of the moving object is used to perform the projection (DeLucia & Liddell, 1998; Gray & Thornton, 2001; Jagacinski, et al., 1983). The forms that such an internal model can take will be discussed further in section 2.2.1.

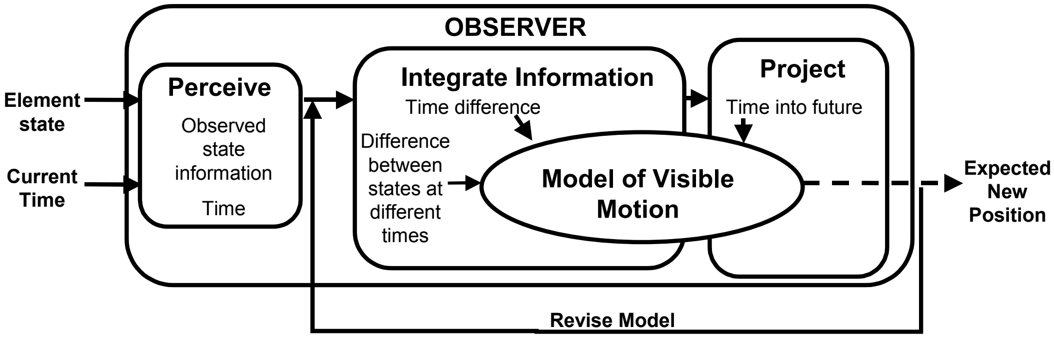


Figure 2.4: Cognitive motion extrapolation model proposed by Schiff & Oldak (1990).

The Cognitive Clocking Model (CCM) was proposed by Tresilian (1995) in which the observer estimated a visual time-to-contact (TTC) and then used a clocking mechanism to count down to that TTC. Figure 2.5 depicts the estimation process and the clocking process. Tresilian (1999) provides a thorough review of the optical attributes that have been proposed to estimate TTC. The most prevalent is the "tau hypothesis," in which Gibson (1961) proposed that TTC estimate was based upon τ(φ), the inverse of the rate of expansion of the angle φ formed by the object with respect to the observer. However in his 1999 article, Tresilian made a case for a variety of optical variables that could provide TTC estimates including: binocular τ, image size (θ), rate of change of image size ($\dot{\theta}$), optical gap (φ), optical speed ($\dot{\varphi}$), or a combination of these variables depending on the task.

Other optical variables include binocular disparity & looming (Rushton & Wann, 1999), and relative size, height in field, occlusion, & motion parallax (DeLucia, Kaiser, Bush, Meyer, & Sweet, 2003).

Research on 4-D projection processes, such as catching a baseball, have produced additional theories about projection/interception tasks and optical error-nulling methods of interception (McBeath, Shaffer, & Kaiser, 1995; Dannemiller, Babler, & Babler, 1995; McLeod, Reed, & Dienes, 2003), but this projection discussion will be limited to translatory projection processes in 3-D (excluding the depth dimension).

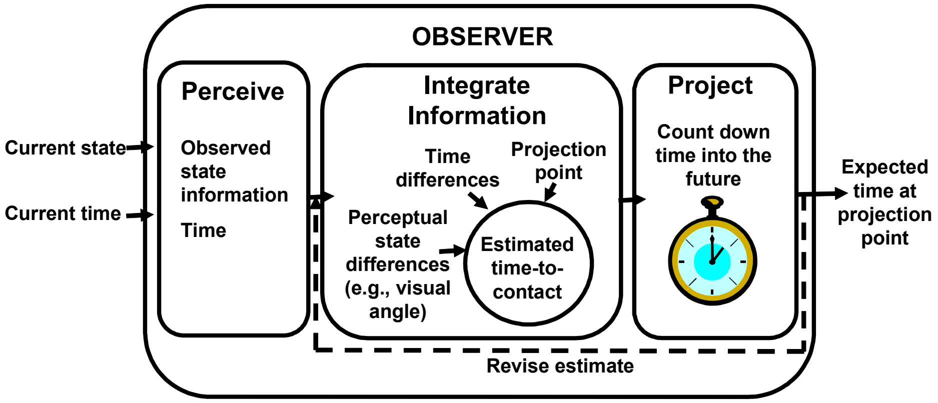


Figure 2.5: Cognitive clocking process proposed by Tresilian (1995). Estimated time-to-contact counted down by cognitive clock to produce an expected time at projection point.

Once the length of time since the last information on the target increases to 1 sec, projection becomes less accurate (Lyon & Waag, 1995; Jagacinski, et al., 1983; Gray & Thornton, 2001). In general, it has been found that in TTC estimates, observers will often underestimate TTC (at an average of about 60% of the actual TTC value), indicating that they predict the object proceeding at constant velocity will arrive at the target sooner than it actually would (Tresilian, 1995; DeLucia & Liddell, 1998; Waagenar & Timmers, 1979). This is consistent with the overestimation of velocity bias suggested by Castet (1995) in Section 2.1.3. Some of this error was accounted for once the point of occlusion was disambiguated. Gray & Thornton (2001) performed an experiment in which they indicated the point at which the target disappears (and the observer must begin his or her projection). This condition reduced the measurement error at the target disappearance point. The underestimation bias found by Gray & Thornton was explained by representational momentum. Peterken, Brown, & Bowman (1991) also presented data to support the idea that it is the *time* since the last information update that most critically affects accuracy, instead of the *distance* moved by the target since the last information update. Xu, Wickens, & Rantanen (2004) addressed the issue of how much influence time and distance until contact (or closest point of approach) had on both TTC estimation accuracy and position estimation at closest point of approach (miss distance, MD). Their data suggested that there was a greater influence of time over which projection was required on TTC estimation and that there was a greater influence of distance over which projection was required on estimation of MD. Xu and colleagues also found an underestimation bias for both TTC and MD, which was amplified as TTC and MD increased and the speed was slower.

DeLucia & Liddell (1998) explicitly compared the CME model and the cognitive clocking model to determine if the predictive motion task would involve the CME rather than only a clocking mechanism relying on optical TTC. The predictive motion task is when an object moves toward a target, then disappears partway through the trajectory, and the observer must respond when he or she predicts that the object would collide with the target point. In their experiments, they performed an interruption paradigm (IP) task in which the object proceeds along a path for a period of time, disappears, then re-appears at either the correct location or an overshoot/undershoot location, and the observer indicates whether the object reappears at the correct location or not. This task assumes constant velocity of the object during the disappearance. In these experiments, the pattern of responses for the IP tasks was consistent with previous PM tasks, indicating that the cognitive clocking was not necessary to obtain the error pattern characterizing performance in the PM task. However, it is difficult to provide data that would exclude cognitive clocking completely, since all projection tasks have a temporal nature.

Peterken, et al. (1991) took the opposite approach and hypothesized that visual tracking of a target was not necessary for successful position estimation. In this experiment, participants were asked to perform a PM task in which an object proceeded along a trajectory and disappeared, then the participants responded at the point when the object should have passed a particular point. Feedback about accuracy of the projection was provided at the end of the trial. Half of the participants were instructed to visually track the target once it had disappeared, and the other half were instructed to look away from the screen after the object's disappearance. The results suggested that position prediction performance was highly accurate and was equal for the condition in which eye tracking was encouraged and when it was prevented.

A review of the literature suggests mixed data supporting the existence of both a model-based CME method of projection as well as an optical TTC estimate utilizing a cognitive clocking mechanism. The next section reviews some of the mitigating factors that may influence which mechanism is used during projection.

2.1.5 Influence of context on projection

The purpose of the projection may influence how the process is conducted. Tresilian (1999) provided an analysis that stated which optical variables used to calculate TTC were dependent on the type of task the observer was conducting, such as an interception task, an avoidance task, a prediction-motion task, or a relative judgment task. Once the goal of the task is determined, constraints on projection requirements can be made. Several task elements including projection precision required, situation visualization of the object dynamics, and number of objects to be projected affect how the projection is performed.

As discussed in section 2.1.1, the dynamics of the object in motion constrains the projection. Some tasks require a highly precise projection to accomplish the task goals. According to psychophysical experiments, observers are simply unable to perceive object acceleration at a low level, therefore relying on cognitive processors to incorporate it into their internal models. This difficulty limits the precision of the projection that can be produced. Other projection tasks require less precise projections, and observers are able to create a 2-parameter model of the object behavior (e.g., the "acceleration + coast" model evaluated by Jagacinski, et al., 1983) that will produce a projection that will accomplish their goal.

Peterken, et al. (1991) generated an experimental condition that removed the participant's ability to develop an optical estimate of TTC and prevented the use of the cognitive clocking mechanism. The results of Xu, et al. (2004) indicate that it was the task (either estimating time or distance of closest approach) that had the greatest effect on whether TTC or distance estimation was used.

Since context has been found to be a determining factor in even the most general of projection tasks, it is important to consider the research findings of how projection is accomplished by the highly-trained operators of safety-critical complex systems.

2.2 Projection in Complex Systems

Complex systems, defined in this case as controlled systems with multiple interacting and dynamic elements, present an especially difficult projection problem to the observer. In section 2.1, the intricacies of and biases associated with predicting the simple dynamics of a target moving across a screen was discussed. Projecting the behavior of a complex system becomes significantly more difficult when considering the interacting dynamic behavior of the system itself as well as the methods that expert operators have developed in training and through experience to predict the future behavior of the system sufficiently to perform his or her task.

In Endsley's Situation Awareness concept, the projection process is the "highest level" of SA and will only be successful if the perception and comprehension processes are adequately completed. Much of the literature in the SA area suggests that an internal model of the system, or "mental model", supports the projection task of the operator (Endsley, 1995a & b; Endsley & Garland, 2000; Mogford, 1997; Jones, Quoetone, Ferree, Magsig, & Bunting, 2003).

2.2.1 Mental Models

The concept of a mental model was discussed briefly in section 1.1. This discussion will reiterate the purpose of a mental model, relay current knowledge on how mental models are acquired and used during projection tasks, and outline some problems that may result due to incorrect mental models.

The term "mental model" has been presented in research since the 1950's when Johnson-Laird proposed the concept (1983). Since then, the term has acquired numerous meanings and connotations, similar to "situation awareness". To avoid entanglement in the misuse of the term, for the purposes of our discussion mental model will be defined as the operator's conceptual, dynamic representation of a physical system that is used to comprehend the current state and predict future states of the system. (Adapted from Moray, 1998; Norman, 1983; Doyle & Ford, 1987.) The mental model can be thought of as a "black box" (Rouse & Morris, 1986).

Operators develop the mental model of a system to allow them to understand enough about the functional behavior of the system to take the input perceived from the environment and evolve the current state of the system into the future. The complex nature of some systems, such as nuclear power plants, aircraft, and the ATC system, prevents the operator from understanding every function of the system to develop a mental replicate of the system. Limitations of the operator's attention, processing capabilities, memory and workload require that the amount of information with which the operator interacts is reduced to allow efficient completion of the projection task. In these cases, a functional abstraction of the system is created by the operator to fulfill the goals of the task. For example, if a pilot is trying to determine if he or she is providing the correct throttle pressure to intercept the glide slope, then the pilot must include knowledge about the aerodynamics of the aircraft and the understanding of how the aircraft responds to throttle commands in the abstraction. However, the knowledge that the pilot has about the air conditioning system on the aircraft can be abstracted out of his or her model to complete this task.

Evidence of this use of "abstractions" or "heuristics" in projection is suggested by data described by Law, Pelegrino, Mitchell, Fischer, McDonald, & Hunt (1993). In a "simple" projection situation in which two objects on intersecting paths were proceeding at constant velocity, it was apparent to the participant that the object closest to the intersection point would reach the point first using distance as the task-relevant state. In more "difficult" projection situations, the objects were not at the same velocity, therefore the participant had to incorporate information about time into the projection to produce an accurate prediction. Law and colleagues interpreted their data to suggest that in this case, participants would use a "distance over speed" bias that would cause them to use a heuristic of considering the most salient state (distance) over a less-salient state (velocity). Using this heuristic resulted in a poorer projection performance: a participant projected a closer & slower object to have a shorter TTC than a farther & faster object, even when the latter arrived at the intersection point first.

Because these mental models are created ad hoc for the purpose of the task at hand and it is natural that these models are fuzzy and incomplete, there is potential for inconsistencies between the mental model of the operator and the function of the system. These inconsistencies can produce a poor projection that in turn leads to a poor decision. Mismatches between the mental model and actual system are common, even in safety-critical systems. Sarter & Woods (1994) discuss "automation surprises", in which the behavior of an aircraft Flight Management System (FMS) surprised even expert pilots with unexpected mode changes. Process control accidents, such as those of Three Mile Island & Bhopal (Leveson 1995), have also illustrated that a functional understanding of the system and that a transparent interface to understand the current state of the systems is critical, particularly in an emergency situation.

Further discussion of the heuristics and biases that controllers have been found to exhibit are discussed more fully in the rest of the chapter.

2.2.2 Projection in the Aviation & ATC domain

Averty (2005) performed a study in the air traffic control area to determine if controllers use a consistent underlying core projection mechanism in the task of conflict projection. In this experiment, controllers viewed a pair of intersecting aircraft, and they were asked to judge whether the aircraft were in conflict or not. The judgment was not only binary, but the participants were also asked to register their certainty in the conflict judgment. Varied in this experiment were the minimum distance at the closest point of approach, the lateral separation when aircraft reach 1000 ft vertical separation, and the timespan over which the controllers were required to predict. Overall consistency in conflict judgments across controllers was found, though variability was quite high between individuals. As the prediction timespan decreased, uncertainty about the judgment decreased, conflict prediction accuracy increased, and variability in conflict prediction accuracy decreased.

A framework for considering how information requirements vary as pilots predict over time into the future in the context of providing weather information was proposed by Vigeant-Langlois & Hansman (2004) and can be seen in Figure 2.6. Over a short projection timespan, the "persistence" region, the state of the weather system can be assumed to be the same or have changed negligibly since the time of information production. Further into the future, a set of dynamic rules can be applied to the changing system state to achieve a relatively sound projection with a level of uncertainty in the "deterministic" region. At some point in the future, these rules no longer effectively describe the dynamics and the projection is best performed probabilistically. After the "limit of deterministic predictability," the slope of the uncertainty growth curve steeply increases. An extension of this framework will be considered for the projection of aircraft into the future by the air traffic controller.

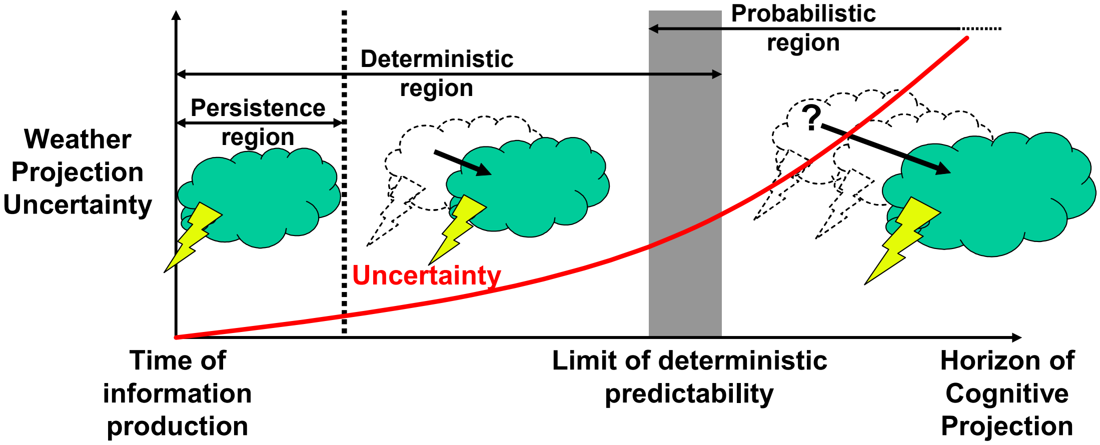


Figure 2.6: Representation of weather projection into the future (from Vigeant-Langlois & Hansman, 2004).

Since the controllers appear to have a similar, if variable, projection capability, other researchers have addressed possible overarching ATC strategies. Two identified by Nunes & Mogford (2003) were strategies for trajectory predictions and altitude comparisons. In the trajectory predictions, they referred to the airspace structure as a key element to aid conflict detections. The influence of structure as a way to clarify the intended trajectory is discussed in detail in Reynolds, Histon, Davison & Hansman (2001). The time comparison strategies discussed by Nunes & Mogford included spatial-temporal heuristics to determine the time an aircraft will arrive at a particular point. Simple distance comparisons could be used with aircraft traveling at the same speed. Because of the digital nature of the altitude information, arithmetic comparisons are used to determine separation in this domain. However, as discussed in Davison & Hansman (2001), aircraft location on a particular procedural routing may indicate by default the altitude of the aircraft on that portion of the route. Procedural routings, by design, tend to separate the flows of aircraft particularly in congested airspace such as the terminal area.

Few studies have addressed the biases that controllers exhibit in their conflict projection task. Xu and colleagues (2004) address the issue of traffic conflict projection in the aircraft domain, specifically of a pilot's conflict detection between aircraft displayed on a Cockpit Display of Traffic Information (CDTI). Pilots were asked to view a developing conflict scenario and at a point when the scenario freezes, identify the time at which the aircraft were closest in approach and the location of the closest point of approach. Varied in this experiment were conflict angle, the relative speed of the two aircraft, the "intruder" traffic's distance from the closest point of approach (prediction distance), and the separation at the closest point of approach. One main result from this study was confirmation of the "distance-over-speed" bias. This bias states that for two aircraft in conflict, the aircraft that is closer to the intersection point will arrive first, even if the further aircraft is traveling at a faster speed. Thus, in judging TTC, distance information is better integrated into the projection over speed information. In addition, there was a tendency to underestimate both separation at the closest point of approach and the time at closest point of approach, particularly as prediction timespan increased. This result exhibited the risk-averse tendency to assume a conflict until further information is available, consistent with the results of Averty (2005). In addition, at slower relative speeds, the estimate of time to closest approach point was worse than when aircraft traveling at faster relative speeds, with a slightly less negative effect on estimate of minimum separation distance.

2.3 Summary of Issues and Biases Affecting the ATC Projection Process

The previous sections have discussed various studies suggesting different biases that may affect the accuracy and certainty of a controller's projection. The following is a summary of the potential biases & issues to which research in this literature review has suggested that air traffic controllers might be subject during their projection task:

Dynamics biases: Acceleration may not be able to be perceived and is difficult to cognitively integrate into the projection (Gottsdanker, 1954; Werkhoven, et al., 1992). The aircraft velocity on an ATC screen can be quite slow, at approximately 1 deg/10 sec. Research has found that targets moving at slower speeds result in an overestimation of velocity, negatively affecting both distance and particularly temporal projection accuracy (Gottsdanker, 1954; Castet, 1995, Xu, et al., 2004). Adaptation to a particular range of speeds can also bias the speed estimation if confronted with a speed outside the typical range (Smith 1985 & 1987). The "distance-over-speed" bias can also affect the projection, in which the controller may be more likely to estimate a closer, slower aircraft will reach an intersection point before a farther, faster aircraft (Xu, et al., 2004).

Space/time issues: Estimating a time at a future spatial position likely uses a cognitive clocking mechanism, while estimating a spatial position at a time in the future likely uses a spatial model to project in time (Schiff & Oldak, 1990; DeLucia & Liddell, 1998; Tresilian, 1995 & 1999; Peterken et al., 1991). The separate nature of these mechanisms may complicate projections that may require both a temporal and spatial projection, or require a mixture of the two types.

Projection timespan: Research suggests that increasing the projection timespan increases the projection error (Averty, 2005; Lyon & Waag, 1995; Jagacinski, et al., 1983; Gray & Thornton, 2001), operator uncertainty in the projection (Averty, 2005), and the likelihood of falling prey to other biases (Rosenbaum, 1975).

Apparent motion issues: It is unclear whether the lengthy stimulus presentation time of the ATC display would prevent apparent motion from being present. If apparent motion or implied motion is present, biases such as representational momentum may affect the controller (Gray & Thornton, 2001; Freyd, 1987). Representational momentum is a memory bias that causes the observer to shift object further along its path of motion earlier than it should be, leading to an overestimation of velocity.

ATC contextual influence: Since ATC has goals and rules that are specific to this domain, biases particular to ATC arise. Controllers may exhibit risk aversion due to projection uncertainty, which is a task-appropriate response that leads the controller to plan an action leading the system robustly to a safe state (Averty, 2005; Xu, et al., 2004; Davison Reynolds, Reynolds, & Hansman, 2005). The rule-based environment of ATC allows the controller to rely on additional intent information about the aircraft that is available from the ATC structure, which is not usually available in other domains (Reynolds, Histon, Davison & Hansman, 2001; Nunes & Mogford, 2003).

In this chapter, the projection process has been reviewed and discussed, from the very basic extrapolation of a target moving across a computer screen to the projection of a complex supervisory control system whose safe operation affects thousands, even millions of lives. In the next chapter, an introduction to the air traffic control domains will be presented, and the principles of the projection process learned through the literature can be applied to these particular domains in the following chapters.

CHAPTER 3: TRACON and Oceanic ATC Domain Introduction

To develop a General Projection Process Model, understanding of the different domains within ATC is required. The TRACON and Oceanic ATC domains will be used as example domains from which the contextual influences on projection can be analyzed. This chapter introduces the key aspects of the TRACON and Oceanic ATC domains applicable to the projection process, as discovered from the site visits conducted.

3.1 Domain Investigation Procedure

Site visits were performed at Terminal Radar Approach CONtrol (TRACON) facilities and at oceanic facilities to understand the influence of context on a General Projection Process Model created and to specifically probe the projection process in different ATC environments. TRACON site visits included four visits to Boston and two visits to New York. Oceanic site visits included four visits to New York, one visit to Oakland, one visit to the Shanwick oceanic area in Prestwick, Scotland, and five visits to Reykjavik, Iceland.

The site visits consisted of focused interviews with controllers and training personnel as well as observations of live operations. During observations, notes were made on information used by the controllers from displays, other controllers, and other sources, as well as controller output including commands issued and information stored. Directed interview questions were created to elicit information on projection and the following areas: goals, processes, information, plan, situation awareness, workload, & communication. The information gathered was used to populate a domain-specific projection-centered process model. Once these domain process models were created, concepts consistent across the models were incorporated into the general process model.

An information transformation analysis was also performed in each of the domains to determine how the information provided to the controller would have to be processed to accomplish his or her tasks with respect to the projection process.

3.2 TRACON Domain Introduction

The TRACON is the ATC facility that serves the airspace around major airports. The TRACON airspace covers approximately 40 nm radius from the airport, with sectors splitting the airspace laterally and vertically between controllers. The controller for which the ATC context will be analyzed in this study is the final approach controller. The approach controller in the TRACON facility is responsible for spacing and sequencing the aircraft arriving at the airport, meeting the goals of safety and efficiency. This controller's tasks are to maximize the throughput of the aircraft so that as many aircraft as possible land at the airport while maintaining separation between aircraft according to the procedures throughout the approach. The Boston TRACON will be used to illustrate this domain with attention drawn to common TRACON aspects that are not present in Boston.

In the next sections, a description of the information/display systems, separation minima, structure & procedures, and a projection example will be provided.

3.2.1 Information/Display System

The primary source of information for the TRACON controller is the radar display, which provides state information on air traffic, weather, and other environment information. A diagram of radar display state information is provided in Figure 3.1. the aircraft's current position is indicated by the sector identifier letter in the upper picture ("H" in this case) and altitude in 100's of feet is in the datablock. Aircraft velocity can either be found in the datablock (in 10's of knots) o r by the distance between the current position and the previous position. Acceleration can be determined by comparing the changing velocity between previous position updates.

The information on this display is discretely updated due to limitations of the radar system. Aircraft positions are surveilled through primary and secondary radar systems. The primary radar system used in the TRACON is an ASR-9 radar with a range of approximately 100 nm and a rate of rotation of 4.8 sec. The rotation rate limits the frequency of radar display information update. Therefore, in the TRACON radar display system, there is a "stimulus presentation time" of 4.8 sec, then a near instantaneous "inter-stimulus interval" combining to form an update time of 4.8 sec, as described in Chapter 2.

To surveill aircraft, a pulse is transmitted from the radar antenna, focused by the antenna into a narrow 2 degree wide and 40 degree high beam. This pulse reflects off of objects and returns to the antenna. The time between transmission and reception allows the radar to determine the distance of the object from the radar. Azimuth of the object is determined by bearing of the antenna when the reflection is received. Because of the 2 degree width of the pulse, objects further away are illuminated by a wider beam than those close to the radar. Primary radar is also subject to ground clutter issues, weather conditions, and other signal-obscuring variables.

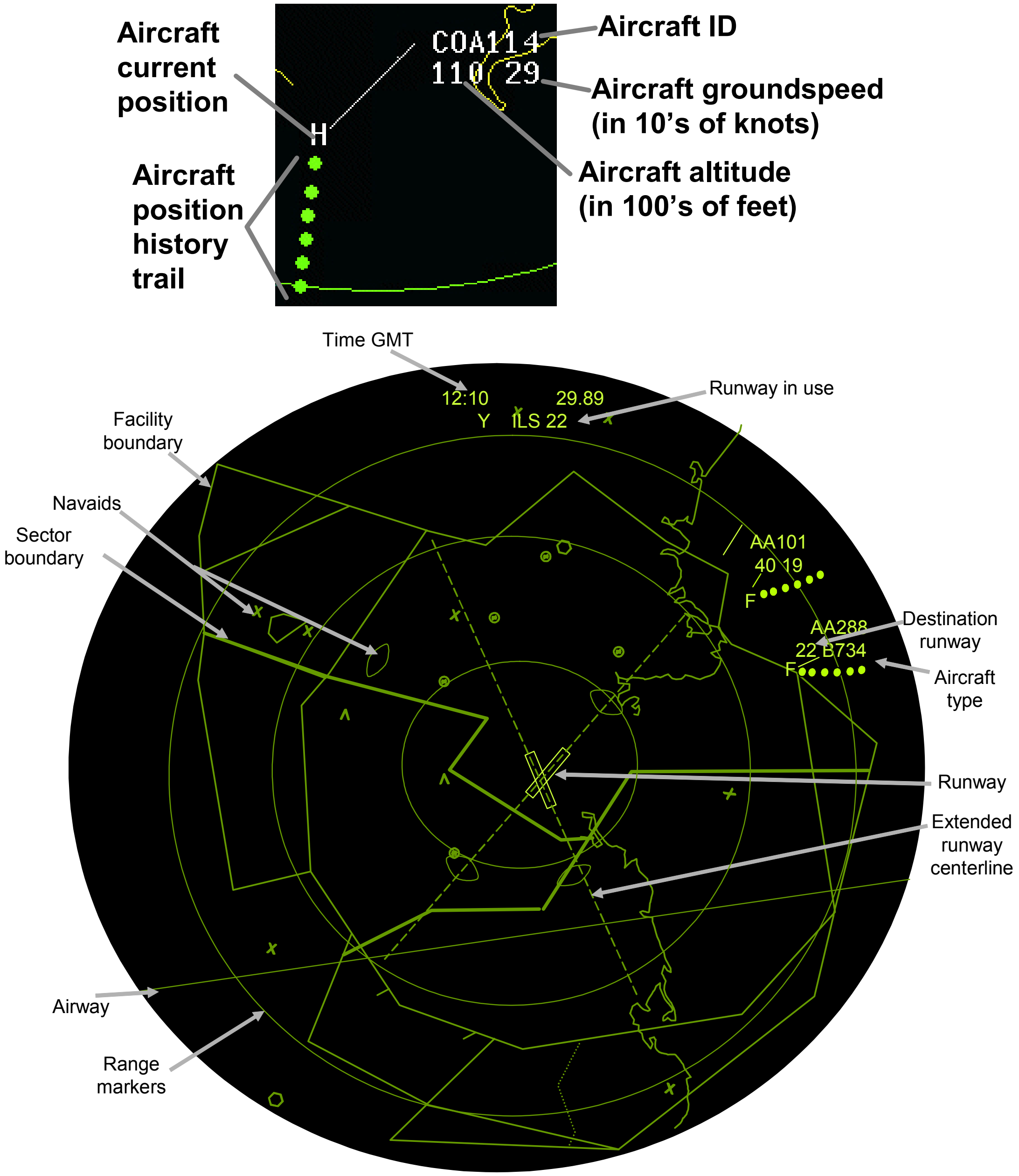


Figure 3.1 Radar display information for TRACON controller.

Controllers use secondary radar systems to address this problem and to provide additional altitude information. One of the secondary radars is located on the top of the ASR-9 radar system, and thus has the same rotation frequency. The other secondary radar is in a fixed location and is used for side-lobe suppression, preventing unwanted transmissions. The interrogator sends out a set of 2 pulses with different modes determined by the time interval between the pulses. U.S. civilian air traffic use Mode C interval, which is 21 microseconds. The aircraft equipped with transponders receive these pulses and determine whether or not to respond, depending on the mode. The response includes the transponder code and the altitude code if equipped. This information is then filtered and correlated with airport and flight plan information in the Host Computer Data Processing system. An in-depth discussion of the surveillance systems and process are available in Nolan (2004).

Mode C altitude information received from the secondary radar is provided in the aircraft's datablock. Groundspeed (also in the datablock) is a smoothed estimate based on difference in current and past position information divided by the rotation time of the radar.

The other primary source of information is through Very High Frequency (VHF) radio communications. VHF communications exhibit very little delay, such that it is similar to speaking through a telephone to the pilot. This is the primary means of issuing control commands to the pilot, such as vectors and altitude/speed clearances. The controller receives readback from the pilots for commands issued through VHF communications. Other information received from VHF communications include pilots informing controllers that they have the runway in sight, pilot reports (PIREPs) on current weather/turbulence conditions, an aircraft's fuel criticality/emergency, and visual sightings of other aircraft. The controllers also receive requests from pilots through VHF communications for changes in flight plan, altitude, or destination.

Secondary sources of information for the TRACON controller include flight strips and other controllers. Flight strips may or may not be used in a TRACON facility, depending on the standard operating procedures (SOPs) in a particular facility. If used, the flight strips provide information about the flight plan and clearances issued to each aircraft. Some of the key information available on the flight strips includes aircraft ID, flight plan/destination, estimated time of arrival at particular fixes, and cleared altitude. Other controllers also provide information on an event-based frequency. Information on aircraft handoffs, flow restrictions, runway changes, and special situations (emergencies, weather-related re-routings) are normally passed verbally or through telephone by controllers when they are not in close physical proximity to do so.

3.2.2 Separation Minima

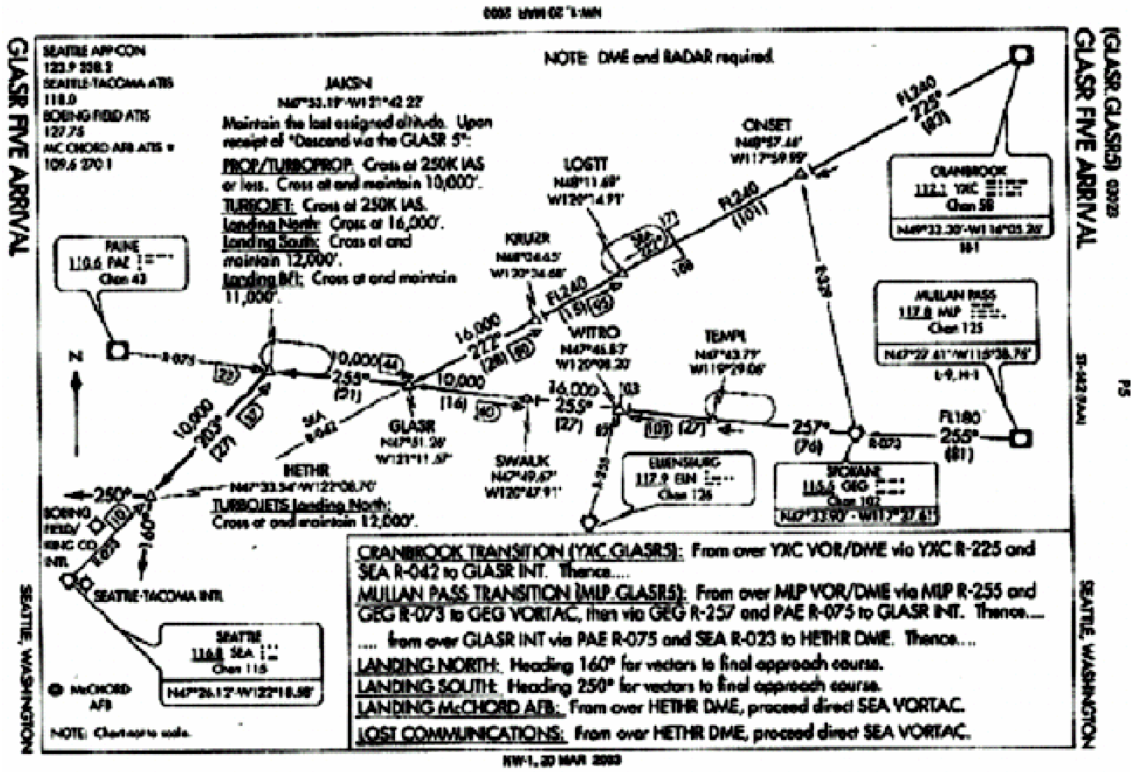
Separation requirements are a key piece of information for maintaining separation and efficiency in air traffic. The controller must ensure that these separation requirements are met for safety purposes, but the controller must also minimize the separation of aircraft on routes to ensure maximum efficiency. The first part of Appendix A outlines the TRACON separation requirements in detail, as listed in the FAA 7110.65. For the TRACON restrictions, one notices that a majority of the restrictions are spatial in nature, requiring a minimum distance to be kept between aircraft laterally and vertically. Approach separation requirements are also listed that are dependent on the type of aircraft leading and following.

TRACONs, especially facilities near busy airports, are also subject to occasional additional separation restrictions to minimize the traffic on downstream facilities. These congestion restrictions are both spatial and temporal in nature, often in terms of "miles-in-trail" or "minutes-in-trail". The controller must ensure that these restrictions are met between aircraft at the exit point of his or her sector into the sector/facility issuing the restriction. Some TRACONs, including Dallas-Fort Worth and Philadelphia, have NASA's Traffic Management Advisor (TMA) or the Multi-center TMA which advises controllers on temporal sequencing of the traffic during congested periods, however at the time of the site visit, Boston did not.

3.2.3 Procedures and the ILS

Procedures and the Instrument Landing System (ILS) are important to the TRACON controller for providing a default plan in their sector to aid in developing an expectation of how traffic will and should flow to meet separation and efficiency restrictions. Some of these critical procedures in the TRACON are the Standard Terminal Arrival Routings (STARs), Standard Instrument Departures (SIDs), Standard Instrument Approach Procedures, Letters of Agreement (LOAs), and the Standard Operating Procedures (SOPs). These procedures are documented in training materials including FAA 7110.65 and the Boston TRACON Standard Operating Procedures, and they were observed in use during the site visits.

The Standard Terminal Arrival Routings (STARs) are procedures that are known both to controllers and to pilots that provide the appropriate procedure for flying from an entry fix to the ILS when landing at an airport. An example STAR for Seattle-Tacoma International Airport is provided in Figure 3.2. It provides lateral route and the descent profile on which the correct ILS glide slope and localizer can be captured. The SID is a similar procedure provided for departures.



Maintain the last assigned altitude. Upon receipt of "Descend via the GLASR 5":
PROP/TURBOPROP: Cross at 250K IAS or less. Cross at and maintain 10,000'.
TURBOJET: Cross at 250K IAS.
Landing North: Cross at 16,000'.
Landing South: Cross at and maintain 12,000'.
Landing BFI: Cross at and maintain 11,000'.

TURBOJETS landing North: Cross at and maintain 12,000'.

CRANBROOK TRANSITION (YXC.GLASR5): From over YXC VOR/DME via YXC R-225 and SEA R-042 to GLASR INT. Thence....
MULLAN PASS TRANSITION (MLP.GLASR5): From over MLP VOR/DME via MLP R-255 and GEG R-073 to GEG VORTAC, then via GEG R-257 and PAE R-075 to GLASR INT. Thence....
.... from over GLASR INT via PAE R-075 and SEA R-023 to HETHR DME. Thence...
LANDING NORTH: Heading 160° for vectors to final approach course.
LANDING SOUTH: Heading 250° for vectors to final approach course.
LANDING McCHORD AFB: From over HETHR DME, proceed direct SEA VORTAC.
LOST COMMUNICATIONS: From over HETHR DME, proceed direct SEA VORTAC.

Figure 3.2: Standard Terminal Arrival Route (STAR) for Seattle-Tacoma International Airport.

The Standard ILS Final Approach Procedure provides lateral and vertical trajectory information to the pilot and controller for a particular instrument approach on a runway, where the STAR procedure ends. Figure 3.3 depicts a procedure for ILS Runway 4R in Boston. The center of the diagram shows the final approach path with the appropriate headings, ILS marker beacons, and the airport indicated. The bottom left portion of the diagram shows the altitude profile between the marker beacons.

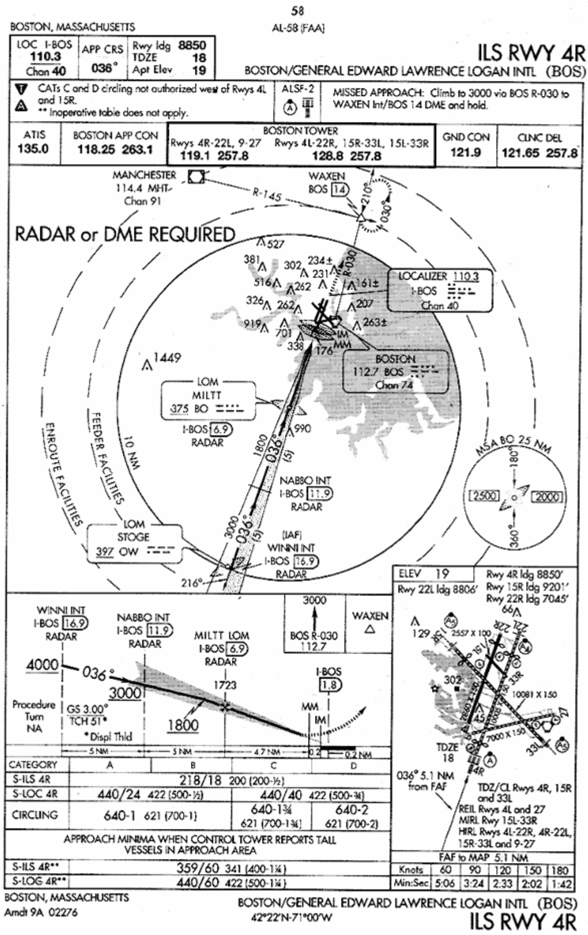


Figure 3.3: Standard ILS Final Approach Procedure for Runway 4R in Boston.

The Instrument Landing System (ILS) is a physical system consisting of a localizer, glide slope, and marker beacons designed to aid pilots achieve the best lateral and vertical descent to land at a runway. It is important for controllers because once the pilot has reported that the aircraft has "captured the ILS," the remaining aircraft trajectory to the runway is very clear and precise.

Letters of Agreement (LOAs) are official agreements about procedures between ATC facilities. These LOAs can establish entry and exit points, how to transfer control of airspace, and what the default acceptable amount of traffic should be without notification when other procedures do not specify these issues.

Standard Operating Procedures (SOPs) are within facility documentation that set up default traffic flows within the facility between sectors for the different runway configurations. Figure 3.4 depicts an example SOP traffic flow routing for the landing Runways 33L/R at Boston Logan. The SOP provides entry fixes, altitude profiles, and a general lateral route for the flows of jets and propeller aircraft.

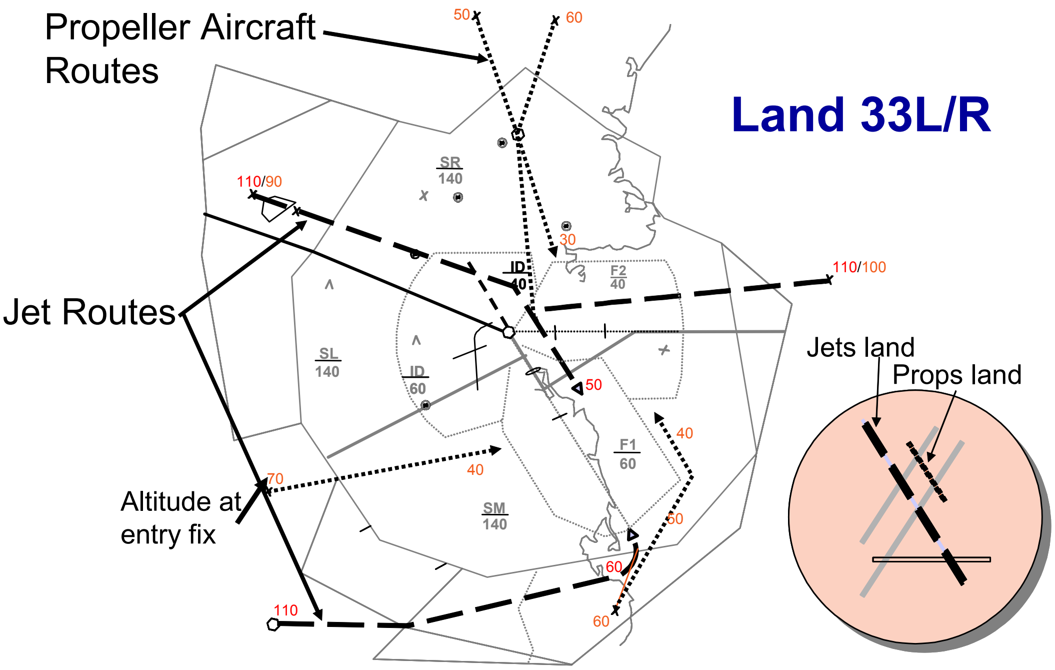


Figure 3.4: Boston TRACON SOP for the traffic flows for landing Runway 33L/R. (courtesy of Boston TRACON training)

3.2.4 Control Commands Available

The TRACON controller is able to control the aircraft in the sector at several different levels. The types of control available include position-based control, velocity-based control, trajectory-based control, and constraint-based control. Examples of the types of control commands are provide in Table 1. This categorization was made based upon lists of available control commands in the FAA 7110.65 and voice recordings made of Boston's Final Approach frequency over a period of 8 hours. At the tactical level, position-based control allows the controller to make a short-term, immediate change to the aircraft's behavior, which is useful in last-minute alterations to the system state to optimize spacing. Higher-level control commands, such as trajectory control, allow the controller to issue one command to achieve a behavior linked by a set of states.

Type of Control Command	**Command Example**
Position-based	*Vertical:* Descent and maintain <altitude> feet
	Lateral: Turn left/right to <heading> degrees
Velocity-based	*Longitudinal:* Reduce/Increase speed to <speed> knots
	Vertical: Expedite descent
Trajectory-based	Cleared ILS <runway>
Constraint-based	*Temporal:* … until/after/before <time>

	Lateral: … until <fix>
	Altitude: … at/above/below <altitude> feet
	Coordination: … until advised by <unit>

Table 1: Control command examples for the TRACON controller.

3.2.5 Projection Example

In this section, an example of a typical TRACON projection will be described that illustrates the use of information available to the controller as well as the projection process itself, when it could be verbally described by the controller.

The Final Approach controller in Boston is presented with the following situation in Figure 3.5 on the radar screen. The two aircraft in the sector at first glance appear to be on a collision course. The controller needs to project the aircraft into the future, evaluate the expected separation, and make a plan for actions that may be needed to resolve any potential loss of separation while successfully vectoring the aircraft to land. The controller first perceives the situation on the radar display, identifying the current position of the aircraft, their relation to one another and sector landmarks, and identifying their recent position histories. The controller also must understand the context in which the aircraft are operating. The TRACON is currently using a Land 33R/L configuration at the airport. As seen on either the datablocks or the flight strips, both of the aircraft have filed a flight plan requesting to land at Logan airport. This indicates that both aircraft will be following one of the routes in the Boston SOPs for this runway configuration (Figure 3.4). Based on the aircrafts' current positions crosschecking with the aircraft datablock, the controller can determine the aircraft type and which specific route they are following. Associated with this specific SOP routing is the controller's plan of action to ensure that the aircraft conform to this routing on the approach until the ILS is captured.

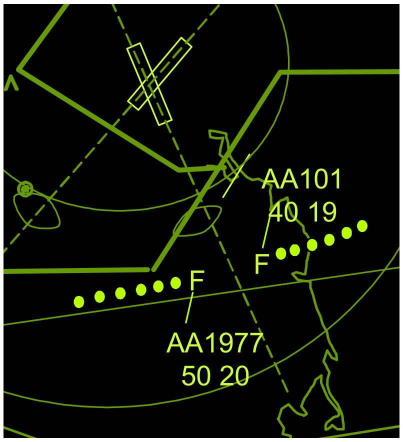


Figure 3.5: Radar screen for TRACON projection example.

Projection is required to determine the paths of the aircraft into the future so that separation can be evaluated into the future. Once the projection is made, a plan can be made if future separation is too great or too little to satisfy safety & efficiency requirements. Controllers can use different strategies to perform the projection, however two common strategies used are altitude projection and lateral projection. Because of the digital information about altitude, straight arithmetic comparisons can be made on the current separation. The two aircraft are separated by 1000 ft, which is the minimum, and are conforming with the SOP altitude profiles for jets and props on these routes. According to the controller's plan, the aircraft are supposed to remain at these altitudes until they capture the ILS. The controller has a dynamic abstraction that states that the pilots in the two aircraft will follow the previous altitude command until they are cleared for a different altitude (or to land, in this case). Once they are cleared to land, they can intercept the glide slope which will clearly define the vertical trajectory to the ground. While the aircraft are currently vertically separated, the controller realizes that when the aircraft intercept the glide slope, vertical separation will no longer be applicable. In addition, once the aircraft are turned onto final, there is little lateral or vertical control that the controller can exert onto the aircraft without overworking the pilot during this high workload portion of the flight. Therefore, the controller realizes that either a speed reduction command or a lengthened turn is in order. Thus, the controller needs to project laterally as well.

The current lateral separation can be determined by comparing the distance between the primary radar returns of the aircraft with the distance between the rings on the display, which are known to be 10 nm between two rings, or the controller could use the distance estimation tool. The controller may estimate the current separation to be approximately 3 nm, which is the minimum separation allowable laterally. After a controller develops experience controlling, there is an intuitive understanding of distance on the display and how it relates to distance in the real world for particular display settings. The next step is to project the lateral position of each aircraft forward in time. The controller can use a combination of historical based projection and intent-based projection for their overall lateral projection. The historical projection is based on the observed dynamics from the history trail of the aircraft. Reasonable estimates of heading and speed can be made based on a comparison of the current position (at time = 0) and the position at the last radar update (at time = -1). This extrapolation can be extended forward in time with a degree of certainty into the future. If the remainder of the history trail indicates that the aircraft is accelerating, decelerating or turning, the controller may make modifications to the constant velocity extrapolation to account for this information, though there was no clear or consistent strategy elicited about how this was done. Digital information about aircraft speed may also help the controller to determine how far to extrapolate the position into the future from past experience.

The other type of projection that a controller can incorporate into the lateral projection is the intent-based projection. Because of the structure and procedures in the TRACON airspace, a clear expectation of aircraft behavior can be determined as long as appropriate commands are issued and the aircraft conforms to the STAR and any commands issued by the controller. Mentally integrating the information from the SOP and the STAR, the controller determines that both aircraft will be soon requested to make a turn onto the final approach. In addition, both aircraft will need to slow down to meet the speed target for final approach. The final approach controller also considers the winds that may affect the aircraft. Strong winds on the runway may cause the aircraft to make elongated turns onto final. A cross-wind situation would slow down one aircraft, but speed up the other, requiring the controller to account for this difference in the extrapolation. The intent-based projection allows the controller to project the aircrafts' trajectories with greater accuracy and certainty further into the future than if they only used the observable history, which would have become quickly inaccurate in this case due to the future dynamic behavior involved.

3.3 Oceanic Domain Introduction

The Oceanic facilities cover much more airspace than a TRACON facility. Figure 3.6 depicts the airspace of three of the oceanic facilities studied during the site visits. Most of the oceanic controllers handle traffic that is in cruise flight, but there are some facilities, such as Reykjavik, that also control departures and landings. One of the primary tasks of the oceanic controller is monitoring the separation of aircraft crossing the oceans. In the following description of information/systems, separation minima, procedures, and projection example, the Reykjavik facility will be used with attention drawn to areas in which other facilities differ.

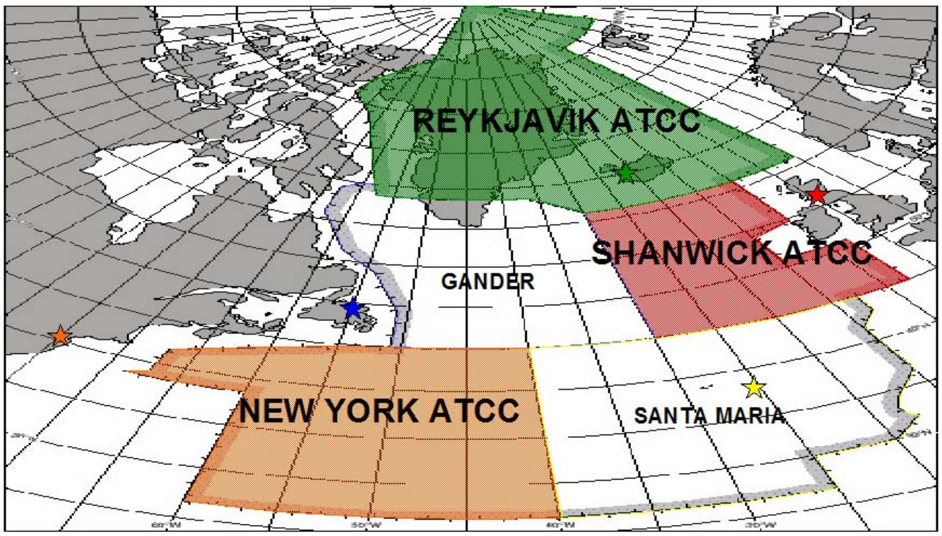


Figure 3.6: Oceanic ATC facilities controlling air traffic in the north Atlantic Ocean.

3.3.1 Information/Display System

The Information/Display System for the Oceanic air traffic controller is quite different from the TRACON. In the current oceanic ATC domain, the primary means of ensuring separation is through flight strips, not the radar/situation display. Though some oceanic facilities continue to have paper flight strips, recently updated facilities have switched to electronic flight strips, as shown in Figure 3.7. The key surveillance states on the oceanic flight strip are also provided in Figure 3.7. The flight strips show the last position and time reported, the lateral route, and the estimated time of arrivals at future reporting points. Cleared true airspeed or Mach number and cleared altitude (in 100's of feet) is also displayed on the flight strip.

Since radar surveillance is not available over large sections of oceanic airspace, at every 10 degrees of longitude/latitude, aircraft are required to report their current position and their estimated time of arrival (ETA) at the next 10 degree point. This surveillance method results in a new time/position update approximately every 30 minutes, depending on route of flight and speed. If a pilot has failed to report by approximately 10 minutes past the ETA, the controller is alerted and the pilot is contacted. Pilots also must report a new ETA if the previous ETA deviates by greater than 10 minutes between reporting points. Facilities using electronic flight strips often combine this feature with weather information (current winds, visibility, clouds, & temperature) updated either daily or hourly and electronic messaging capabilities, as in the Icelandic Flight Data Processing System (FDPS). Oceanic controllers may control up to 60 aircraft in a sector, thus making the automatic position update capability of the electronic flight strips convenient. The number of aircraft in a sector also makes not only the information within a flight strip important, but also the arrangement of the flight strips. In some facilities, flight strips are arranged first by altitude, then by the time they reach the reporting point.

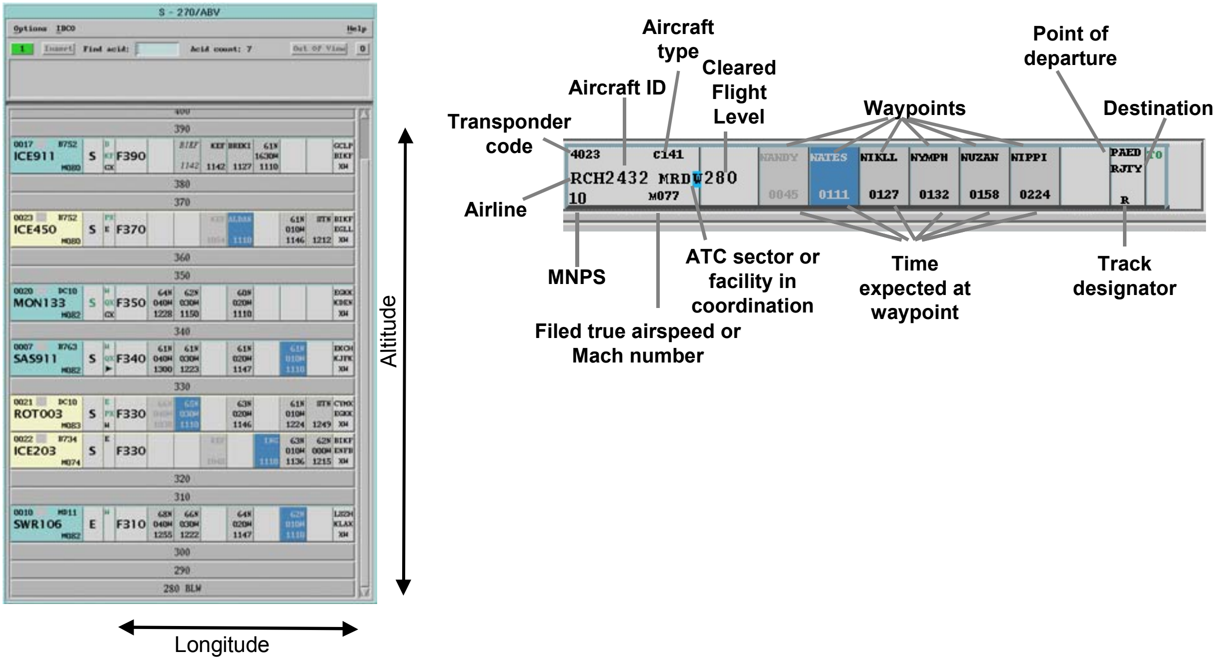


Figure 3.7: Electronic flight strips used in Oceanic ATC (from Icelandic FDPS).

The other primary information source is through the communication system that is available at the time. Control commands are given by controller to the pilot through the communication system, similar to the TRACON domain, albeit less frequently due to communication relay delay issues over the oceans. Some areas of the oceanic facilities have access to VHF communications if the aircraft is not too far from a ground station, however, many areas are only covered by low-quality High Frequency (HF) radio communications as shown in Figure 3.8. In areas only covered by HF, communications relay operators listen to the pilots' HF communications, and then the relay operators convey the information electronically or by interphone to the oceanic controllers. If the controllers need to issue commands to the pilots, they are issued through the relay operator as well. SATCOM is also generally available to most flights and this form of communication has a minimum delay associated with it. However, it is quite expensive, so airlines are reluctant to use this for routine communications. Figure 3.9 schematically depicts the oceanic controller/pilot communication situation.

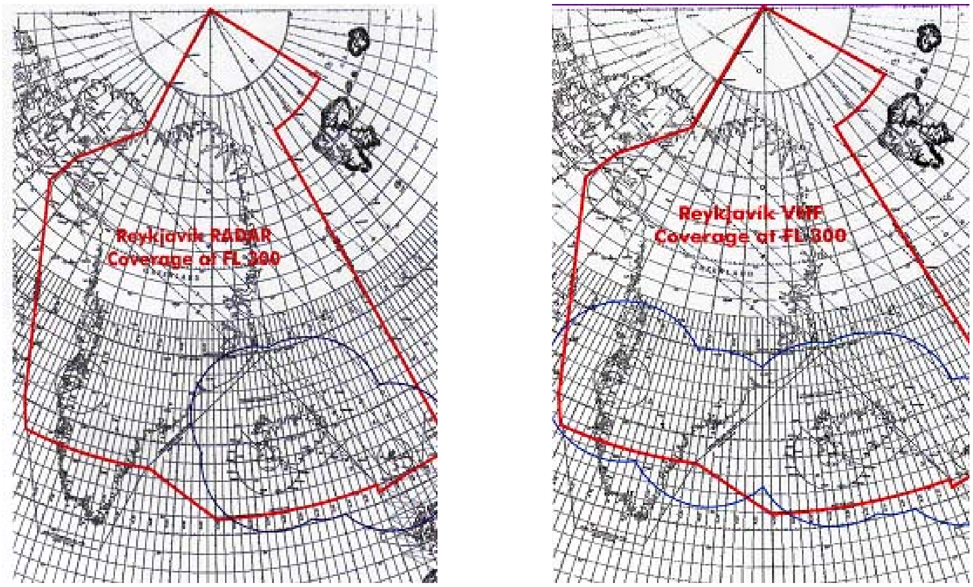


Figure 3.8: Radar & VHF coverage areas (overlapping circular outlines) for Reykjavik oceanic facility (courtesy Icelandic CAA).

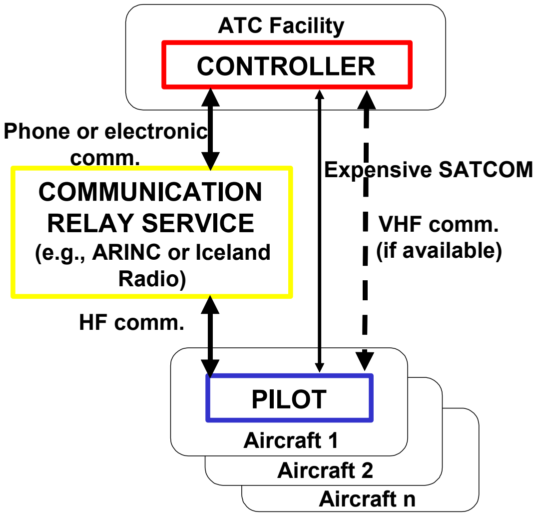


Figure 3.9: Oceanic pilot/controller communications.

Secondary information sources for the oceanic controller include the situation display, oceanic sector maps, and other controllers. The situation display is a spatial representation of the flight strip information that may be combined with available radar data. As shown in Figure 3.10, aircraft are shown as diamonds, with tails that represent the distance the aircraft travels in 10 minutes. Algorithms interpolate the aircraft's estimated "current" position based on last reported position and ETA at next position. If the dynamics of the aircraft change between updates, it is possible that once the new update arrives the blip will experience a "jump" to correct the error of the estimation algorithm. In the facilities visited, controllers were not allowed to use the situation display as a primary means of ensuring separation, therefore it remains a "situation awareness" tool that may be initially consulted to grasp the "big picture" before taking control of a sector. The other controllers contribute information on an event-based frequency about handoffs, point outs, temporary airspace allocation, emergencies, constraints from other facilities, and special operations occurring.

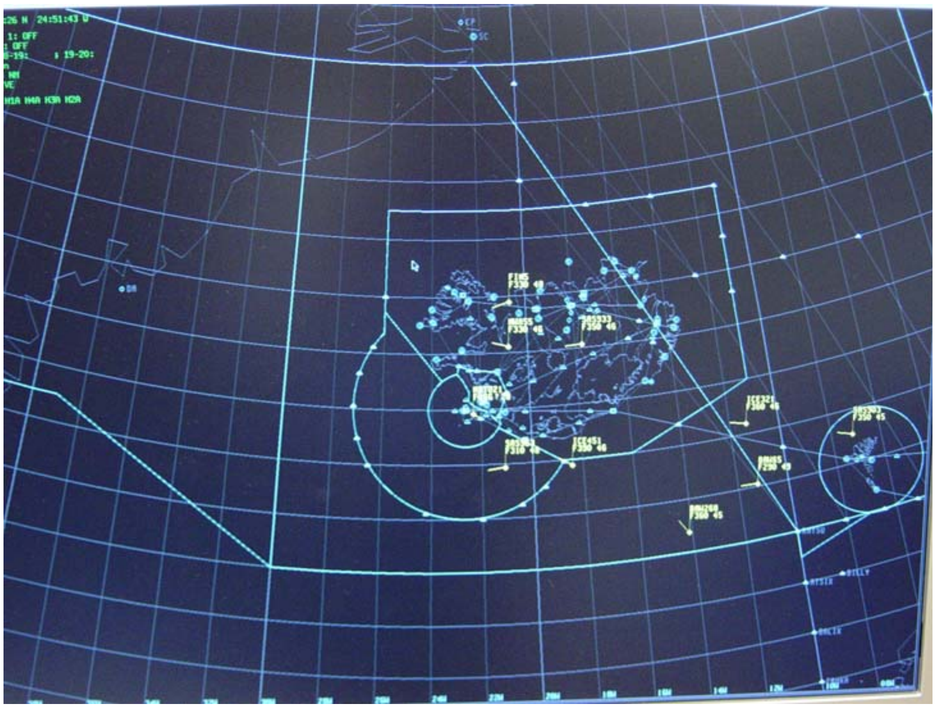


Figure 3.10: Icelandic oceanic situation display.

3.3.2 Separation Minima

An extensive list of separation minima applicable in the oceanic airspace are provided at the end of Appendix A. In comparison to the TRACON minima, one can see that there are still some lateral and vertical spatial minima that are applicable, but most of the oceanic minima are temporal minima applicable to the longitudinal separation. This is because the oceanic routings are quite rigid, therefore most of the aircraft traveling to and from the same areas are on the same routing, making longitudinal separation most applicable. Besides the type of minima, the magnitude of the minima is different. Due to surveillance limitations and the nature of oceanic operations, the minima are much larger. There is also a Mach Number Technique described in Appendix A that legally modifies temporal separation minima for two aircraft to ensure separation in cases in which the trailing aircraft is faster.

There is less of a concern with congestion restrictions in the oceanic areas except at the entry & exit points to the facilities. Because of the vast amounts of airspace involved, finding areas for aircraft to hold at the exit points usually is not much of an issue. Oceanic restrictions on upstream domestic facilities and time assignments to aircraft to regulate traffic usually prevent traffic overloading at the entry points to the oceanic areas.

3.3.3 Procedures

Because of the regular demand for particular oceanic routings and the amount of traffic involved, procedures over the oceans is a critical element to smooth operations. The procedural backbone to oceanic operations in the North Atlantic is the oceanic track structure. An example of these oceanic tracks is depicted in Figure 3.11. These tracks are separated laterally by 60 nm, the minimum lateral separation in non-radar airspace. The tracks are determined jointly by the ATC oceanic facilities twice per day to make maximum use of the jet stream when flying east or to avoid it flying west in the North Atlantic. The tracks also aim to take into account the flight plans of a majority of the oceanic traffic. When flying in the North Atlantic, most aircraft will fly one of these ATC preferred lateral routings or else they will be assigned undesirable altitudes to fly north to south or another lateral routing. While the oceanic tracks make determining lateral trajectory simpler, the volume of traffic on the tracks can cause congestion in the vertical flight levels as well.

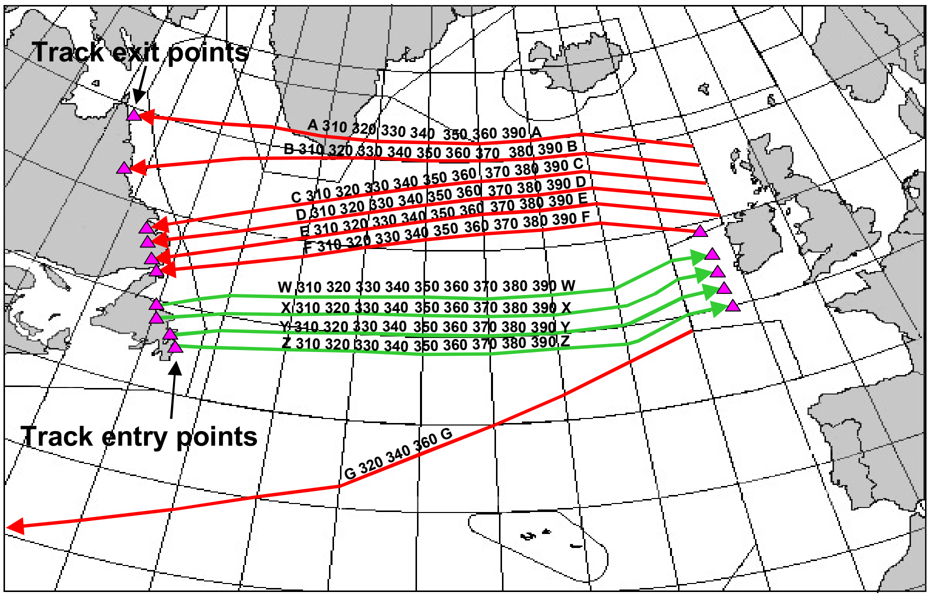


Figure 3.11: Example of North Atlantic Oceanic Track Structure.

The oceanic tracks determine overall lateral trajectory, however, it is the position reporting procedures that allow the controllers to identify where the aircraft are on that trajectory for a given time. Speed and altitude are often assigned based on pilots' filed flight plans or requests unless congestion dictates that the controller must alter it.

Outside the area of the tracks structure, there exist standard procedural jet routes that are stationary. These are used in the Caribbean areas and over the Pacific Ocean. Lack of traffic demand to some Pacific destinations can allow more flexible direct routings at the controller’s discretion.

3.3.4 Control Commands Available

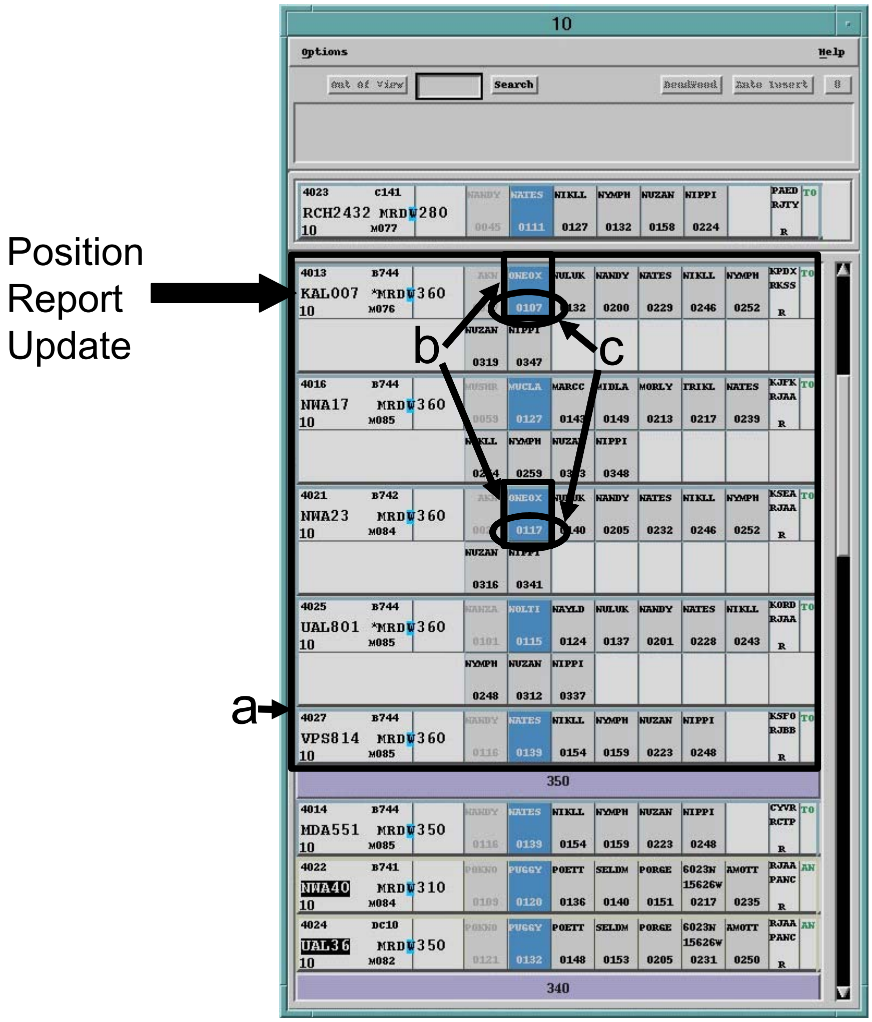
The control commands available to the oceanic controller are similar to those available to the TRACON controller in Table 1. Oceanic controllers tend to manipulate altitude and speed rather than heading due to the lateral route structure. For additional surveillance information a controller can request that an aircraft report when passing a particular fix.

3.3.5 Projection Example

The typical longitudinal oceanic projection is much more proceduralized than its counterpart in the TRACON. Flight data processing algorithms use the reported time and position and the estimated time at the next position to extrapolate expected times at subsequent positions automatically. The oceanic conflict detection procedure uses the natural arrangement of the flight strips and the flight strip matrix to identify potential separation problems. This procedure is used when an aircraft enters the sector or when a new position report arrives. Step “a” in Figure 3.12 shows how the flight strip of the aircraft of interest is put electronically into its flight level grouping. If there are other aircraft in the flight level, step “b” is comparing the waypoints of the aircraft to find matching waypoints from other aircraft in the group. If there is a matching waypoint between aircraft, step “c” is comparing the times at that particular waypoint to ensure that there is temporal separation for this case.

A more complex projection is required if an aircraft is crossing laterally at one of the tracks’ flight levels. In this case, spatial separation minima apply. However, because the conflict detection procedure using the flight strips breaks down during projection of a lateral crossing, an alternative method is used. The oceanic controllers have access to a situation display which has lateral separation information available, but they are not officially allowed to use the situation display for separation purposes. Therefore, the controllers have a laminated map of the airspace and draw the flight plans of the aircraft of interest on the map. The intersection point of the aircraft is identified. The controllers then use the flight strip time predictions to cognitively interpolate the time of the crossing aircraft at the intersection point. Then the controller estimates the lateral position of the tracks aircraft at this time, again, by interpolating between position report point predictions. The spatial distance projected at intersection is then evaluated against the separation minima for the pair of aircraft. This method is rarely used during congested operations due to the workload on the controller to monitor the crossing and the uncertainty associated with the estimations, and instead the crossing aircraft is told to cross at a flight level not associated with the tracks traffic.

These examples illustrated how Reykjavik controllers performed the projection during the site visits. As surveillance over the oceans improves with ADS technology, it is likely that more oceanic facilities will be using the situation display as a separation tool, as is the case in the U.S.'s ATOP workstations. In these cases, except for some special consideration towards surveillance mixtures, it is likely that future oceanic projection will tend more towards the TRACON projection example.



4023 C141 RCH2432 MRDW280 10 M077	NANDY 0045	NATES 0111	NIKLL 0127	NYMPH 0132	NUZAN 0158	NIPPI 0224		PAED RJTY R	TO
4013 B744 KAL007 *MRDW360 10 M076	AKN	ONEOX 0107	ULUK 132	NANDY 0200	NATES 0229	NIKLL 0246	NYMPH 0252	KPDX RKSS R	TO
	NUZAN 0319	NIPPI 0347							
4016 B744 NWA17 MRDW360 10 M085	MUSHR 0059	MUCLA 0127	MARCC 014	MIDLA 0149	MORLY 0213	TRIKL 0217	NATES 0239	KJFK RJAA R	TO
	N KLL 02 4	NYMPH 0259	NUZA 03 3	NIPPI 0348					
4021 B742 NWA23 MRDW360 10 M084	AKN 00	ONEOX 0117	NU UK 140	NANDY 0205	NATES 0232	NIKLL 0246	NYMPH 0252	KSEA RJAA R	TO
	NUZAN 0316	NIPPI 0341							
4025 B744 UAL801 *MRDW360 10 M085	NANZA 0101	NOLTI 0115	NAYLD 0124	NULUK 0137	NANDY 0201	NATES 0228	NIKLL 0243	KORD RJAA R	TO
	NYMPH 0248	NUZAN 0312	NIPPI 0337						
4027 B744 VPS814 MRDW360 10 M085	NANDY 0116	NATES 0139	NIKLL 0154	NYMPH 0159	NUZAN 0223	NIPPI 0248		KSFO RJBB R	TO
350									
4014 B744 MDA551 MRDW350 10 M085	NANDY 0116	NATES 0139	NIKLL 0154	NYMPH 0159	NUZAN 0223	NIPPI 0248		CYVR RCTP R	TO
4022 B741 NWA40 MRDW310 10 M084	POKNO 0109	PUGGY 0120	POETT 0136	SELDM 0140	PORGE 0151	6023N 15626W 0217	AMOTT 0235	RJAA PANC R	AN
4024 DC10 UAL36 MRDW350 10 M082	POKNO 0121	PUGGY 0132	POETT 0148	SELDM 0153	PORGE 0205	6023N 15626W 0231	AMOTT 0250	RJAA PANC R	AN
340									

Figure 3.12: Oceanic flight strips for procedural projection example (Icelandic FDPS system).

In this chapter, an introduction to the TRACON and Oceanic ATC domains was provided. While providing a significant amount of information to the controllers, the information/display systems also have their limitations caused by surveillance or display presentation. The projection examples provided indications about some of the issues that controllers can face operating within the constraints of information/display systems, separation minima, and control availability. The next chapter will look closer at how the projection process is accomplished and how these contextual impacts on projection can be systematically considered.

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CHAPTER 4: Projection Process Model & Projection Error Concept

This chapter will introduce the General Projection Process Model and the Projection Error Concept. They will then be used to describe the ATC projection process using examples from the TRACON and Oceanic ATC domains.

4.1 Introduction to General Projection Process Model & Projection Error Concept

A General Projection Process Model and a Projection Error Concept were created to describe the projection process as observed from the site visits and known from the literature. The General Projection Process Model is a model that provides an information processing view of the ATC system with the controller as a critical component of the system. This model was created to identify the requirements of the projection process and to describe how the projection process is accomplished. The Projection Error Concept was created to look specifically at how the context influences the construction of the mental model to project to the requirements of a particular task.

4.1.1 General Projection Process Model Development

The primary means to study the projection process and its contextual influences was the development of a cognitive projection process model. Information processing models allow the researcher to observe input to and output from the controller and then logically deduce the information transformation that must occur to produce the output, given the input. One may further constrain the cognitive process through the analysis of training procedures and workplace artifacts, which may indicate how the transformation occurs. Artifacts are defined as documentation that can contribute information to how an operator performs a task, such as training manuals and documented standard operating procedures. These observable indicators of cognitive activity are represented in Figure 4.1.

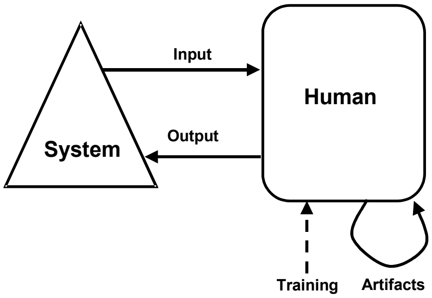

Figure 4.1: Observable Indicators of Cognitive Activity

Before defining the information processing model for the air traffic controller, the boundaries of the model must also be determined. Because we are concerned with the projection of an individual controller and the context of that projection, the model includes the tactical air traffic controller and the people and systems that provide input to the controller or upon which the controller performs his or her air traffic control task. A General Projection Process Model was created based upon past literature, including Endsley's (1995a & 1995b) Situation Awareness Model, Pawlak's (1996) Decision Processes Model, and Histon's (2001) concept of structure. This model was subsequently revised through the study of two ATC domain examples. The projection process model is intended to apply to supervisory control systems with operator information that is discretely-updated.

4.1.2 General Projection Process Model

Figure 4.2 depicts the General Projection Process Model for an air traffic controller. An overview of the system and its processes will be described below. An in-depth discussion of the specific inputs to and process of Projection itself will be explored further in Sections 4.2 and 4.3.

In the left gray box is the **ATC Operational Context**, which is the real-world "system" that the operator controls and within whose constraints the operator must work. The **Air Traffic Situation** consists of the air traffic and the physical environment in which they operate (e.g., mountains, weather, airport, ILS beam). **Structure** is defined as a set of constraints (either physical or human-imposed) that limits the evolution of the dynamics of the system. Examples of physical structure include runways, navigation aids, terrain or obstructions. Examples of human-imposed structure include airspace boundaries, procedures and standard flight levels. Each of these examples of structure establishes constraints such that, if violated, either physical or system laws will have been broken resulting in loss of life or significant reprimands. Thus, structure enables the controller to expect the aircraft to remain within the constraints under normal circumstances.

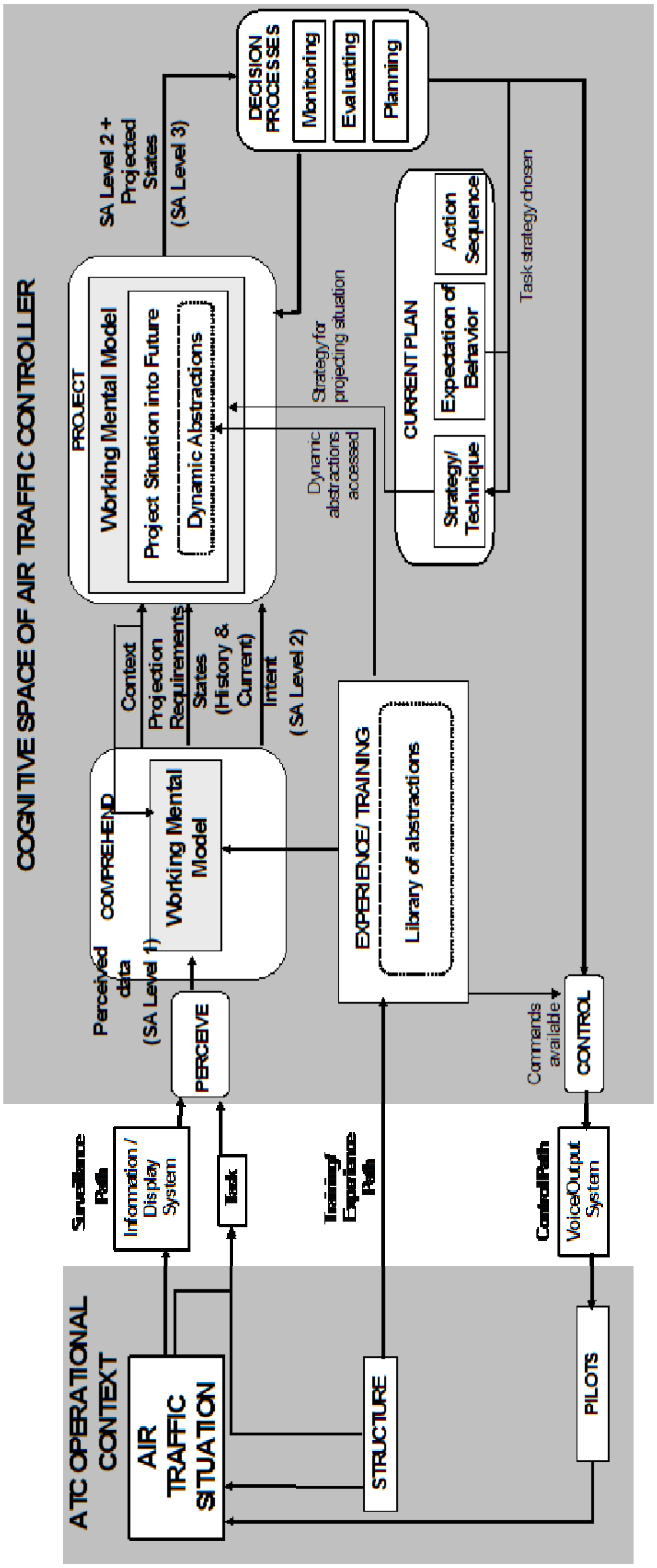

Figure 4.2 General Projection Process Model

Knowledge of structure is provided to the controller primarily during training and refined with experience. Air Traffic Situation data is provided to the controller dynamically through an **Information/Display system**. The controller also has a **Task** that includes what the controller is supposed to be controlling and how to control it. The task is determined both by the current Air Traffic Situation and the Structure of the system.

In this model, information is fed into the controller through **Perception**, primarily through the auditory and visual modalities. This information is then **Comprehended** in relation to the tasks of the controller. A **Projection** of the immediate future state of the system is then created using current state and intent information from the environment that feeds task-based mental models of the system entities. Understanding the purpose for which the projection is needed also influences how the Projection is accomplished. The separation minima to be evaluated against and the available control commands influence the state, quality, and timespan of the Projection. Gathering and using this information to project into the future was termed the Maintenance of Situation Awareness by Endsley (1995a & 1995b).

Comprehension and Projection are enabled by the **Mental Model** of the controller. The Mental Model is the controller's model of the system dynamics that allows the controller to understand the current state and evolve this state into the future. Reducing the system dynamics to a manageable yet effective model is accomplished through abstraction. How to abstract the system into task-relevant models is acquired through training and experience with the system and the task, and these abstractions are stored in the Library of Abstractions in Experience/Training until required by the controller.

The projection created is then **Monitored** against the controller's Current Plan. If the projection is not entirely consistent with the Current Plan, the future state of the system is then **Evaluated** with respect to the controller's threshold of acceptability. If the projected state of the system is in conflict with the set constraints, **Planning** is then used to generate an action that not only will return the projected state adequately within the boundaries, but that will also minimize the monitoring requirements imposed on the controller.

In the model, the **Current Plan** is generated by the controller's planning process and is greatly influenced by past experience. The Current Plan represents the controller's internal representation of a time-dependent schedule of events and commands to be implemented as well as the resulting aircraft trajectories that will ensure that the air traffic situation evolves in an efficient and conflict-free manner. The Standard Operating Procedures (SOPs) and other procedures that specify routings and altitude profiles can form a basis for the air traffic controller's Current Plan. When a clearance is issued to the aircraft, a combination of the clearance and the state/trajectory cleared forms the aircraft's intent. The intent then becomes part of the aircraft's expected behavior within the Current Plan, which subsequently informs the Projection. The Current Plan also encompasses the particular strategy that a controller chooses to use to complete the task. There may be several ways to accomplish a task, and the controller may test different strategies in different situations to maximize their task performance while minimizing cognitive load.

The Current Plan then feeds the **Action Implementation** process, determining the time at which the controller commands the pilots, either through voice or through information tools (e.g., datalink).

Pilots then directly control the air traffic through manual control or some degree of automation, closing the loop of the system.

4.1.3 Projection Error Concept

A Projection Error Concept is also proposed to describe how a projection process is influenced by contextual constraints of the task and environment. These contextual constraints include information/display system update rate, projection timespan required by the task, and the controller's error tolerance. Key constructs of this concept are then probed in an ATC projection experiment in the next chapter.

To perform a projection, the operator must identify the state to project, the quality of projection required, and the time over which projection is required. Each of these requirements is influenced by the task and the Decision Processes. As the operator projects further into the future, projection error increases due to introductions of error through inaccurate state, velocity, and acceleration estimations. Projection error can be defined in different ways depending on the situation. In the Projection Process Model, it can be defined as the difference between the projected states from SA Level 3 and the actual state evolution of the system. A controller's job is to separate the blips on the radar screen, so projection error can also be defined as the difference between the projected states from SA Level 3 and the state evolution *surveilled* from the Information/Display System.

The Projection Error Concept can be used to describe either of these error types. The Projection Error Concept in Figure 4.3 shows the increasing error in projecting when using a particular **State Mental Model** as a function of time. Even as the time of projection approaches zero, there is a baseline **Measurement Error** that is present due to the error in estimation of the current state of the system. The slope of the error growth is due to errors in velocity and acceleration estimates. **Task Time** (T_{task}) is the time over which a projection is required for the task. **Update time** (T_{update}) is the time until the controller will receive another discrete information update on the state of the system.

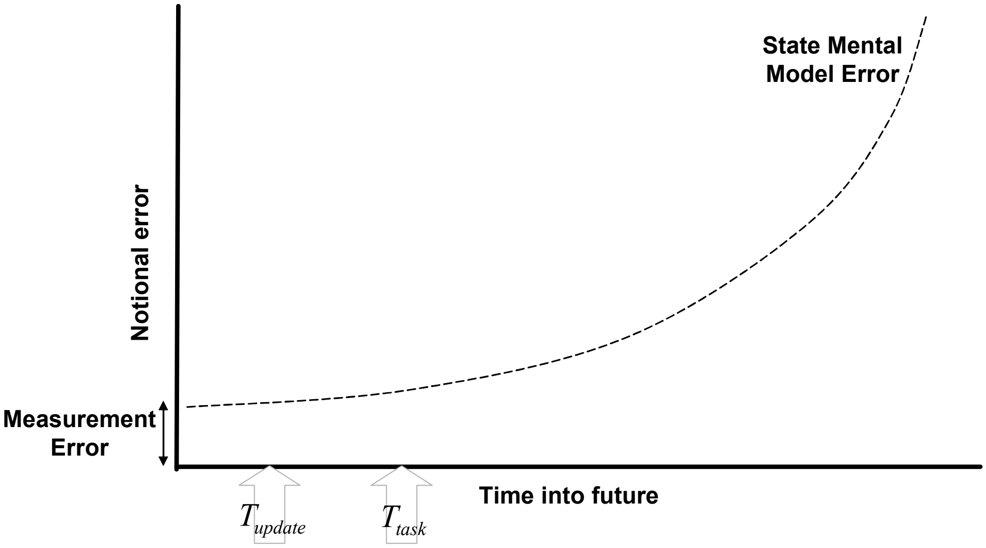

Figure 4.3: Projection Error Concept

The remainder of the chapter will focus on an in-depth discussion of, first, the projection inputs in Section 4.2 and then the projection process itself in Section 4.3 as depicted in Figure 4.4.

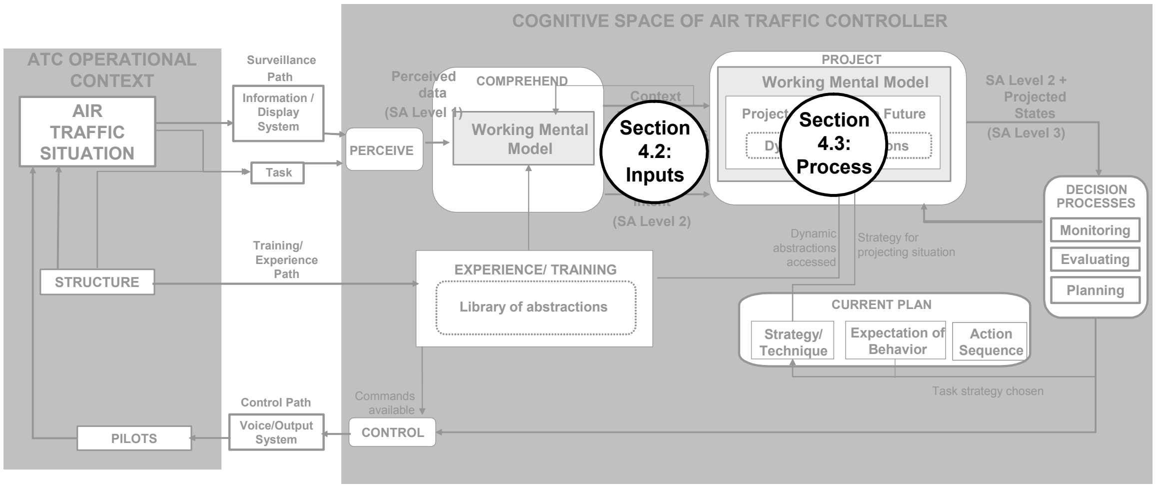

Figure 4.4: Chapter 4 outline.

4.2 Input to Controller’s Projection Process

The input to the controller’s cognitive processes from Figure 4.2 informs the controller’s understanding of the system state and also influences how the projection is performed. An information transform concept is suggested to describe how information is transformed into the controller’s mental model of the current state of the system. In addition, this section discusses two critical inputs to projection, the States from the Information/Display System and the Task-based Projection Requirements, and how consistency between these inputs simplifies the controller’s task.

4.2.1 Information Transform Concept

To develop an understanding of the current state of the system, the controller must know how to relate the graphic and verbal information from the information/display system to the state of the real system. An information transform concept is proposed to provide insight to the cognitive information manipulations required to effectively perform the task. A transform is a mapping between the system and its state representation or between state representations.

If we define $\vec{x}$ as a state vector of a system representation, $\vec{x}_R$ could specify all information that is found in the "real system." Such an $\vec{x}_R$ for an aircraft could be defined as in Reynolds & Hansman (2001) as:

$$\vec{x}_R = \begin{bmatrix} Position = R_1(t) \\ Velocity = V_1(t) \\ Acceleration = A_1(t) \\ Target = T_1(t) \\ Intent = I_1(t) \\ Destination = D_1(t) \\ . \\ . \\ . \end{bmatrix}$$

In a supervisory control system, this system state information is displayed to the operator through an information/display system. Thus, some states related to a subgroup of $\vec{x}_R$ are displayed to the operator as $\vec{x}_D$. It is important to consider observability of the states of the system. What states that are observable as $\vec{x}_D$ are often defined by the surveillance systems and the ability to obtain measurements of states from $\vec{x}_R$. When designing the information/display system, decisions are then made how to display these surveilled states to the operator. Thus, from $\vec{x}_R$ to $\vec{x}_D$ an information transformation must occur, and this transform is indicated as T_D^R. Some information may be filtered out in this transform and some information may be combined to estimate new states. The measurement of the $\vec{x}_R$ by the surveillance system also results in a certain amount of error from the actual $\vec{x}_R$. Using matrix transform notation, the transformation can be expressed mathematically as:

$$T_D^R \cdot \vec{x}_R = \vec{x}_D$$

In air traffic control, there are a series of information transformations that must occur for the controller to effectively accomplish the task. These transformation spaces are depicted in Figure 4.5. The Real System, $\vec{x}_R$, is on the left. The radar or other surveillance systems in the domain determine the states that are transformed into what the controller sees on the information/display system, $\vec{x}_D$. The controller is provided with a particular task or set of tasks to accomplish, and these tasks require knowledge of particular current and future states, $\vec{x}_P$. The controller must cognitively transform the display states into the states of the Problem Space to accomplish the task. To act upon the system, the controller must also transform $\vec{x}_P$ into system-recognizable command states, $\vec{x}_C$. The system then implements these commands, affecting the future $\vec{x}_R$.

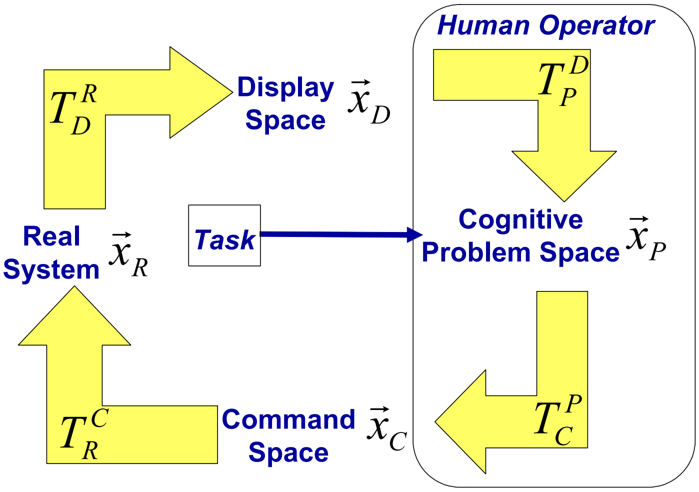

Figure 4.5: Transformation spaces in ATC.

These transforms can also be represented within the construct of the ATC Process Model, as depicted in Figure 4.6. The Information/Display System transforms real world states into states that the controller sees on the display. The controller cognitively transforms perceived display states into states relevant to the task in the Comprehension process. Logically, if the display states are similar or the same as the states required for the task, a minimal transformation is required reducing the effort required by the controller. Once the problem space states have been Projected, Evaluated & Monitored, the controller must decide what the desirable system state is in the future. In the Planning process, this desired state is transformed into commands to the current state to achieve the desired state. Once issued, these commands are then transformed by the pilots and the aircraft into new Real System states.

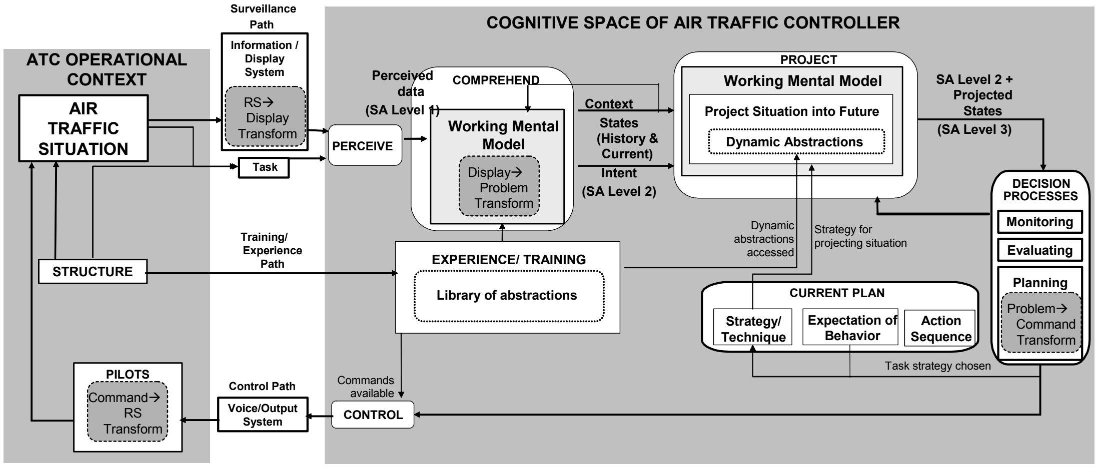

Figure 4.6: Transforms within ATC Projection Process Model.

While it is difficult to identify how a controller performs the cognitive transformations, we can gain insight from the transformations that are observable and make some deductions about the cognitive transformations. Understanding the Real System to Display Space transformation (T_D^R) allows the controller to reduce state estimation uncertainty resulting from the surveillance & display systems. For example, if a controller understands that as the aircraft is further from the radar, the bearing becomes more uncertain, the controller can incorporate this information into the aircraft position estimate used in projection.

Several attributes can be elicited from the Real System to Display Space transformation (T_D^R). These attributes include coordinate system, update rate, analogous relationship preservation, and dynamic relationship preservation. When displaying aircraft state information, the Information/Display system is assigned a particular coordinate system, which allows certain dimensions to be more observable than others. The radar/situation display exhibits a north-up, x-y coordinate system. The flight strips in Iceland exhibit groupings by altitude between flight strips, and position report times are organized by longitude within the flight strip. Another attribute of the transform is the rate at which information is updated. With frequent surveillance, the update rate can be nearly continuous. In ATC, surveillance limits the update rate to 4.8 sec for the TRACON and up to 30 min between position reports for the Oceanic domain. Information updates can also be synchronous, as in the TRACON or asynchronous, as in the Oceanic facilities. The analogous relationship preservation between the Real System and the Display Space is also represented in the transform. Described effectively by the Principle of Pictorial Realism (Roscoe, 1968), analogous relationship is how closely the display resembles the system it represents, ecologically. The radar/situation display has a close analogous relationship to the real world because there is a correspondence between elements & distances on the display and the elements & distances in the real world. There is less of an analogous correspondence in the flight strips, except for the geographical and altitude organization of the flight strips. How closely the display resembles the system dynamically is another transform attribute. This dynamic relationship preservation is supported by the Principle of the Moving Part (Roscoe, 1968). The radar/situation display has a close dynamic relationship to the real world, particularly as the display update rate increases. However, there is no inherent dynamic relationship represented in the flight strips except for updates of aircraft position and velocity, digitally.

There must be knowledge of the Real System to Display Space transform attributes to comprehend what the Information/Display System is presenting to the controller. By understanding what is presented in the Information/Display System and what the task requirements are, one can identify different ways the cognitive Display Space to Problem Space transform (T_P^D) may be constructed. One way to view the transform is partly as an inverse transform of the Real System to Display Space transform, $\left[T_D^R\right]^{-1}$. Because the controller only has a model of how this transform occurs, it is notated as $\left[\hat{T}_D^R\right]^{-1}$. This inverse transform takes the displayed information and directly maps it back to what it represents in the real system, in the state vector $\vec{x}_R$. Once the controller understands what is in the Real System, then the states relevant to the task can be integrated/extracted.

Another way to think about the Display Space to Problem Space transform is when the controller only thinks about what is presented on the display and transforms the Display Space directly to the Problem Space, T_P^D . This is exhibited when the controller describes the task as "separating the blips."

Once the controller perceives and interprets the states provided from the information/display systems, this information is comprehended as the mental model of the current situation. Strategies from training and task-based requirements allow the controller to filter and integrate the information/display states into an understanding of the current system state relevant to the task. The Information/Display System is only one of the critical inputs needed to make a useful projection. Let us now consider the inputs themselves, the Information/Display System and the Task-based Projection Requirements.

4.2.2 States from Information/Display System

Information/display systems provide system state information to the operator with a particular frequency. The information/display system provides a window for observing selected states of the system and may influence which states the controller projects. Observability is a critical attribute of system states, because the controller's mental model of the state of the system is only as good as the states that are observed. To propagate the state into the future, the controller requires knowledge of the current states of the system, including position, velocity and acceleration of those states. Knowledge of intended states is also useful, if available. The state information displayed is often limited by the surveillance capability of the system, which may or may not provide the states needed for the projection process. As discussed in the Information Transform Concept, if the states required are directly observable, then the cognitive transform between information display system and cognitive problem space is simplified. If the needed information is not directly observed, it must be inferred from the observed states, which increases uncertainty in the projection through state estimation.

Another important aspect of the information/display system is the frequency with which the information displayed is updated. Surveillance information update rate can affect the growth of the projection error. Figure 4.7 depicts the error growth for different update rates, using different state mental models for projection. If the system has a frequent update rate, the operator can re-calibrate the projection often with the new state information. If the system is updated infrequently, the error will increase from the last information update, possibly exceeding the error tolerance before receiving new information, depending on the quality of the projection mental model.

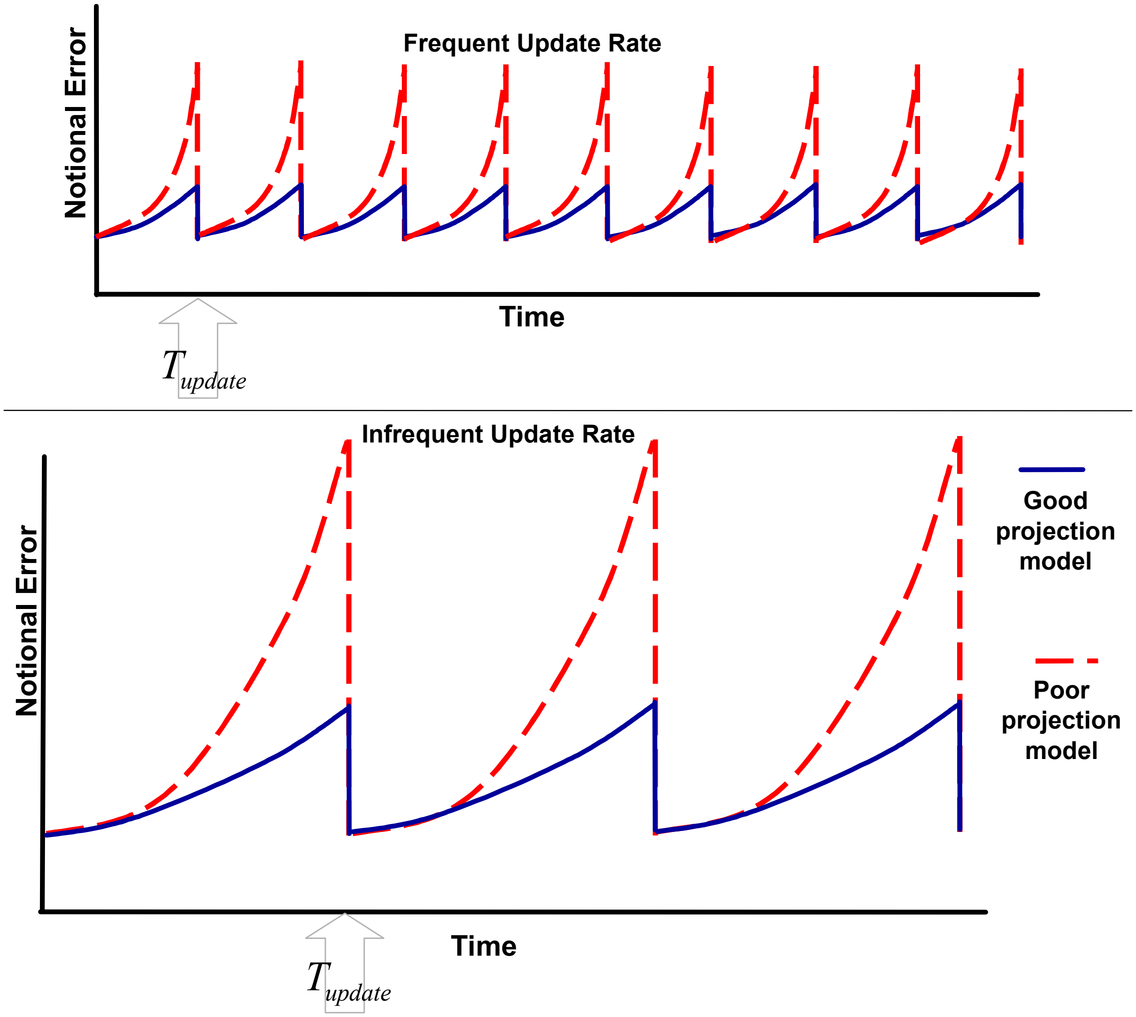

Figure 4.7: Influence of Discrete Information Update Rate on Projection Error.

What information is provided in the Information/Display System and the rate at which it is provided depends on the domain of the air traffic controller. Below, the Information/Display System for both the TRACON controller and the Oceanic controller will be presented to illustrate similarities and differences between systems in different domains. Sources of information measurement uncertainty and systematic delay in information presentation will also be indicated to illuminate issues of data management with which the controller must contend.

TRACON states and update rate available: In the TRACON, current states of the system are retrieved from the radar display, discussed in Section 3.2.1. Figure 4.8 displays the required aircraft states, including current lateral position, altitude from the datablock, direction of flight from history trail, speed from either the datablock or the distance between position histories, and acceleration from the rate of change in distance between position histories.

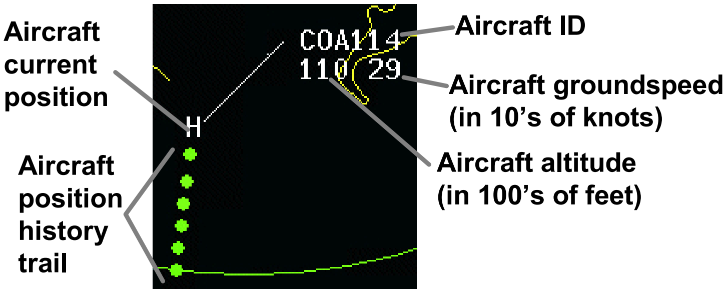

Figure 4.8: Aircraft states displayed in the TRACON. (Picture from FAA's DESIREE simulator)

There is a degree of uncertainty present in the bearing of the aircraft from the radar due to the surveillance limitations of the radar system. Speed on the display is also based on a filtered estimate from the past radar updates. There is greater certainty in the altitude state due to the fact that it is reported by a transponder from the aircraft itself.

Aircraft intended state and trajectory information in the TRACON is found in either the flight strip, the data block (usually as a single-letter destination indicator) flashing opposite to the altitude details, and the controller's Current Plan of assigned or to-be-assigned clearances.

The update frequency of the radar information is limited by the radar system, making it discretely updated every 4.8 sec.

Oceanic states and update rate available: Oceanic state information is currently found in the flight strips, as in Figure 4.9. Time at last report point, estimated times at future report points, lateral trajectory through the track designator, cleared flight level and filed true airspeed can all be found on the flight strip. One may notice that there is no information on current position, as is available in the TRACON, however there is more information on estimated times at future waypoints. Certainty of the information provided through position reports is high, due to the information received directly from the aircraft.

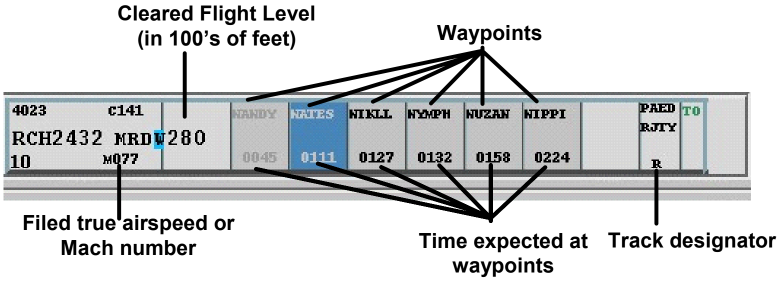

Figure 4.9: Aircraft states displayed on an Oceanic flight strip.

Oceanic intent information is clear in the lateral dimension and is available on the flight strip. Short-term speed and altitude intent information is available on the flight strip. Longer term speed and altitude information is available primarily through the controller's cognitive Current Plan of issued and to-be-issued clearances.

Few areas in the oceanic domain have radar available for surveillance purposes. For this reason, the information updates are dependent on pilot reporting, which occurs at every 10 degrees of latitude or longitude (approximately every 30 minutes). Because pilots reach the reporting points at different times, the information is also asynchronously updated. Dependence on pilots to report the information also results in pilots often reporting late or forgetting to report at all.

4.2.3 Task-based Projection Requirements

The projection of the future behavior of a system is performed to serve a purpose. In air traffic control, the projection is used to inform the decision processes of Monitoring, Evaluation, and Planning. In the Monitoring stage, the projected state is compared with the expected state from the Current Plan. If the projected state does not conform to the plan, then the projected state is Evaluated against task-based requirements. If the projected state exceeds the limits of the requirements, the controller must Plan to execute a control action that returns the projected state within the task-based requirements. The parameters of the expected state within the Current Plan are driven by the task-based requirements. Similarly, the planned control actions are executed to return the projected system behavior to within the constraints of the task-based requirements. Thus, the task-based requirements provide an important input to projection in the TRACON and Oceanic air traffic control domains. There are two aspects of the task-based requirements that are particularly useful for the projection task: the required state and the projection error tolerance.

What state or states that the operator projects depends on the task in progress, the restrictions associated with that task, and the control actions available to the operator. If the task involves Evaluation of a particular state, then this state would be the projection state of interest. The domain may have a particular task restriction against which the projection must be Evaluated. This restriction would then influence the dimension or units of the state of interest. The control available to the operator may also influence what specific state to project, particularly once the projection has been Evaluated and the operator must Plan an action on the system.

ATC example: The air traffic controller may be in the process of predicting whether there will be a loss in separation between two aircraft. In this case, the particular state of interest would be relative separation. The dimension of the state would depend on the restrictions associated with the task. There may be vertical and lateral restrictions for this type of conflict, which would lead the controller to be interested in relative vertical separation and relative lateral separation. If the available control action was vertical, but not lateral, control, then the controller would be particularly interested in the vertical relative separation projection for the Planning process. In addition, the control availability may not include controlling the relative separation state, so projection of individual aircraft states would also be required for the Planning process.

Error tolerance determined from the particular task also influences the projection. Error Tolerance is the maximum deviation of a state from the Current Plan at which an action to resolve the future state behavior is performed by the operator to effectively accomplish the task. This task, for example, may be to keep the system state within a constrained state-space. Situational aspects have an influence on the error tolerance. One aspect is the magnitude of the task restriction that the projection must be Evaluated against in a particular operating environment. Another aspect is the proximity of the state to a constraint or restriction. The closer a state is to a constraint, the more critical the error tolerance of a projection is to ensure that the element does not penetrate the constraint. A third situational aspect affecting error tolerance is the safety buffer of the individual operator performing the projection.

ATC Example: One example scenario is in Figure 4.10, in which the air traffic controller projects the state of lateral separation between aircraft that are getting progressively closer. In certain circumstances in the TRACON, the separation restriction would be 3 nm. The controller may add on a personal safety buffer (e.g., 1 nm). Therefore, the controller would want to keep the relative lateral separation state between aircraft above the error tolerance of 4 nm. In this scenario, as uncertainty grows into the future, the chance that uncertainty in the projected state will penetrate the error tolerance increases. As long as this time is far enough into the future to allow the controller to correct the state before penetration, the controller can effectively control the system.

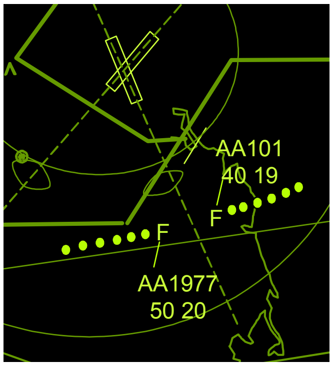

Figure 4.10: Example TRACON ATC scenario in which the lateral separation state is progressively reducing.

Lateral separation requirements in the TRACON are on the order of 3-5 nm, and over the oceans they are 60 nm due to communication and surveillance limitations and the timescale over which ATC situations evolve. This sets the projection error tolerance at quite different levels for each of these domains. However, if an aircraft must be laterally separated by 3 nm from another aircraft, but there is no other aircraft in the controller's sector, then the lateral separation projection error tolerance with another aircraft for that situation is not particularly critical. In ATC, because of the safety-critical nature of the system and the consequences to the controller if separation minima are penetrated, the controller may add on a "buffer" to ensure these minima are not penetrated.

In many systems, there are multiple overlapping requirements that an operator must meet to perform the task effectively. In general, the operator must meet the most constricting error tolerance for a particular state projection. Considering the vertical separation state, an air traffic controller may evaluate the separation between Aircraft 1 and Aircraft 2 above or between Aircraft 1 and the ground below. The controller's immediate concern would be to consider both the separation requirements from each of these elements and also Aircraft 1's vertical state proximity from these separation restrictions to identify the restriction that the aircraft is in most danger of penetrating. This would define the projection error tolerance for vertical separation in that particular situation.

4.2.4 Spatial/Temporal Information & Requirement Mismatch

There is occasionally a mismatch between the state displayed and the state of the requirement. Figure 4.11 shows an example of this mismatch dilemma. In some ATC environments, the primary information/display system is spatial, such as a radar display. In other environments, specifically the oceanic environment, the primary information/display system is temporal in nature. If there is a spatial restriction, such as "miles-in-trail," applicable in the spatial information/display environment, then there is a clear mapping between restriction and state displayed. However, if a temporal restriction is applicable, a space/time mismatch occurs. In some environments, such as Traffic Management Advisor (TMA) equipped TRACONs, an additional decision support tool is provided that gives temporal support in a primarily spatial information/display system environment.

The transform concept can be used to identify the cognitive issues with spatial/temporal mismatch between information system and task requirements. The Display to Problem Space transform is complicated in situations of mismatch, because there is now not only the task of integrating and filtering information, but there is also a coordinate transformation required. This mismatch concept also applies to the Problem Space to Control Space transform. If there are limited control actions available when using a particular coordinate frame, this transform is complicated if a coordinate transformation is required when planning a control action sequence.

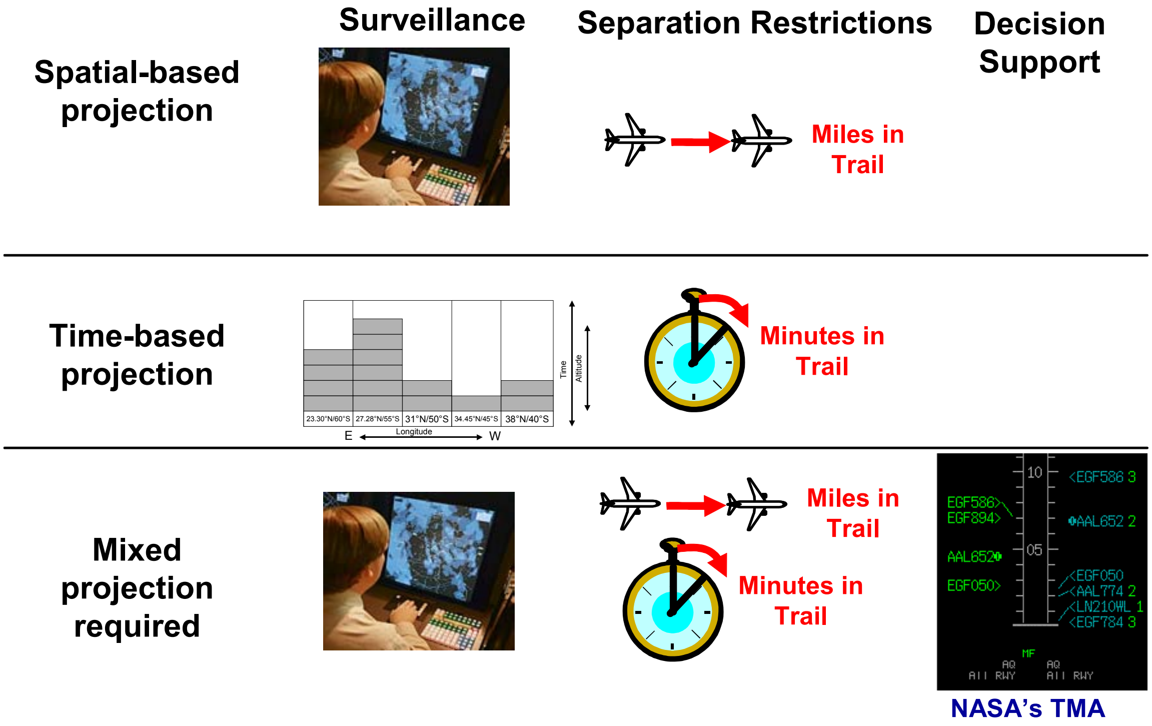

Figure 4.11: Spatial/Temporal Mismatch Examples.

There are a couple of ways that the controllers have been found to deal with this mismatch. In the TRACON, the display is primarily spatial in nature with separation restrictions that are primarily spatial. In the cases in which controllers are required to apply time-based metering restrictions (without appropriate temporal information/display support), the controllers transform these temporal restrictions into their spatial equivalents and perform the task using the spatial transformation of the restrictions. For example, if a controller has a 10 minutes-in-trail requirement, he or she would use a rule-of-thumb to transform this to a "miles-in-trail" restriction, which, at a particular velocity, would be the temporal equivalent. However, this heuristic strategy introduces uncertainty into the restriction and the controller's projection will have to account for this, possibly in the reduction of the error tolerance.

The Oceanic controllers also face a similar situation when aircraft perform lateral crossings over the oceans, as described in the projection example in Section 3.3.5. Their flight strips give time of arrival at longitudinal waypoints, but they must meet a spatial separation restriction in lateral crossings (as in Oceanic Lateral Separation Minima, Appendix A). Instead of transforming the restriction like the TRACON controllers, oceanic controllers were observed transforming the displayed information. The controllers represent the temporal flight strip information on a plastic map with a wax pencil to allow evaluation of the spatial restriction. Again, error is introduced into the projection when the controller interpolates between position report points, which must be addressed by the controller through robust planning.

Some consequences in mismatch situations include increased workload on the controller due to additional transformation requirements and possible added system inefficiency due to errors in the transform.

In Section 4.2, the projection inputs and requirements were discussed with specific references to the TRACON and Oceanic ATC domains, and in the next section, the projection process itself will be addressed.

4.3 Projection Process

There is not a single method of performing the projection process. Influences from the Information/Display System, the Task-based Projection Requirements, the system's constraints, and training all affect how the controller projects. In this section, a discussion of the different ways projection can be performed and how the context from Section 4.2 influences the projection will be presented. The discussion is parsed into the two key elements that enable the projection: the mental model and the time into the future.

4.3.1 State Mental Models

To generate an accurate projection of the system state over the deterministic time period, a model of the system state's dynamic behavior must be used. This model or these models are used in place of the accurate representation of the actual system dynamics. It would be impossible for an air traffic controller to develop a mental replicate of one aircraft's dynamics in a stochastic weather environment while extracting information from the interactions of several aircraft. On the other hand, this quality of projection is not required for the task. Thus a simplified mental model utilizing dynamic abstractions is used for the task projection.

There are several abstractions on which the controller's state mental model can be based, including observed history, experience, and controller-pilot contracts. The use of each of these bases was observed during the site visits. After a radar screen has been updated, the controller can view not only the aircraft's current position, but also several past positions using the history markers. Altitude information is absent in these history markers, but the controller can receive information about the aircraft's past heading and speed. One reasonable way a controller can construct a model of behavior over a short timespan is by simply extrapolating this observed history trend. An example history trend is depicted in Figure 4.12. The simplest extrapolation is a constant velocity extrapolation in which distance and bearing between the current position and the previous position update is used to propagate the position from the current position to the next position update. This constant velocity model is also consistent with Gottsdanker

(1954), Wagenaar & Timmers (1979), & Rosenbaum’s (1975) findings discussed in Section 2.1.1 that participants’ projections reflect the use of constant velocity extrapolation.

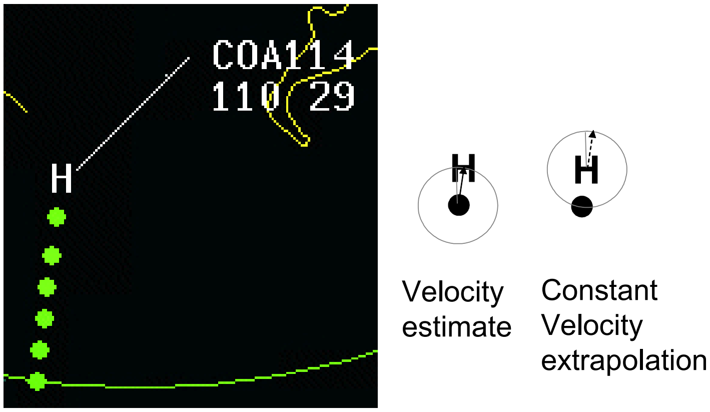

Figure 4.12: Example aircraft history (From FAA's DESIREE simulator).

A slightly more descriptive abstraction that the controllers may use is a model with constant acceleration modifications. If it appears that the aircraft is changing velocity, the controller can modify the constant velocity extrapolation with an estimate of how much the aircraft will be accelerating or decelerating. This estimate can be established from the remaining history track provided for the aircraft, indicating how quickly the aircraft is turning, speeding up, or slowing down.

A critical element upon which to base the controller’s mental model is the controller-pilot command contract. Once the controller issues a command and the pilot has read the command back to the controller, a contract between the two parties has been established in which the state, trajectory, or constraint specified in the command becomes part of the intended future behavior of the aircraft. Depending on the specificity of the command, the intention is either a state, a linked set of states, or an avoidance region of states in the aircraft’s future that may or may not be linked with a particular time. The controller-pilot contract may not only help in establishing the deterministic mental model, but it may also allow the controller to prolong the applicability of deterministic prediction.

Another basis for the controller’s mental model is the experience that the controllers have developed with the system over time. One important class of this type is agent-based models. Given information on a particular aircraft, the controller can modify the mental model to account for the behavior implied by that piece of information. For example, controllers that hear uncertainty in a pilot’s voice or see that the pilot is flying a training aircraft from a local airport may assume that the pilot is a novice. Through experience, controllers have developed a mental model of the “novice pilot” that might include slower response to control commands, greater difficulty in comprehending and executing complex control commands, and unfamiliarity with standard procedures. This may cause the controller to modify the deterministic model for that particular aircraft to have a greater uncertainty in trajectory than if the pilot flying that aircraft were experienced. Besides the pilots, agent-based models can also be informed by aircraft type and even airline.

Experience with the environment in which the aircraft flies also allows the controllers to further hone their mental models. If the controller has information on the states of the environment that affects the aircrafts' dynamics, the mental model of an aircraft flying in the environment can be better constructed. A particularly useful environmental abstraction used in ATC is the effect of wind on the aircraft. Knowledge of wind velocity allows the controller to compensate for this in the projection of the future state of the aircraft. Strong headwinds slow an aircraft down, while strong tailwinds have the opposite effect. Having an accurate model of the effect of crosswinds on an aircraft allows the controller to project how an aircraft will make the turn onto the final approach. Other environment-based models examples include the effects on aircraft of weather states such as icing and convective weather.

To perform a projection for the task, the controller must have a mental model of the evolution of the task-required state. The task-required state may be a single state, multiple states, or an integration of states. How accurate this mental model is determines how quickly the error in the Projection Error Concept deviates from the baseline measurement error. Figure 4.13 depicts a comparison of two state mental models. The "low-quality" mental model produces a steep increase in error if the system is highly dynamic. The "high-quality" model produces a slightly less steep error growth in this situation, depending on the fidelity of the dynamics estimates. However, in the case in which the system is exhibiting simple straight and level flight, the mental model incorporating only lower-level dynamics estimates may produce an equally high quality of projection as one that incorporates higher-level dynamics.

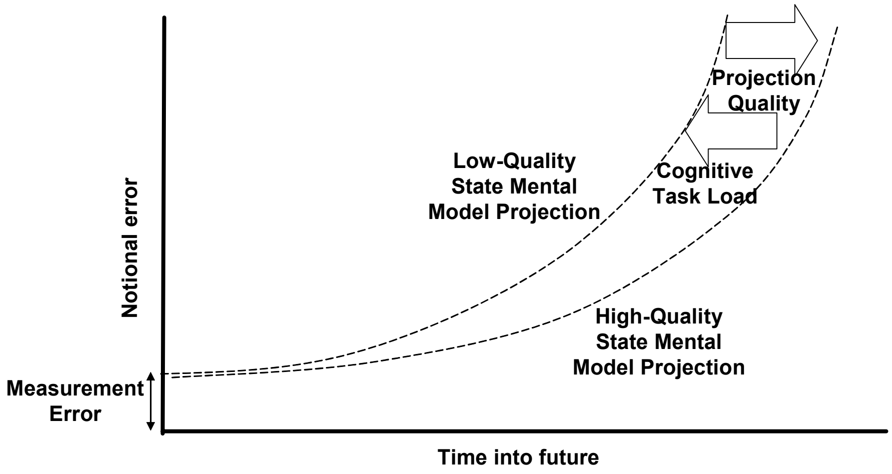

Figure 4.13: Varying quality of state mental model when a state is dynamic.

When the system is dynamic, the highest quality mental model is one that incorporates the higher levels of dynamics to produce the least projection error. Unfortunately, by increasing the levels of dynamics incorporated into the mental model, the cognitive load induced by this high quality mental model is likely to be greater than a model that only incorporates low-level dynamics. The quality of state mental model used in a given projection depends both on available cognitive resources and the task requirement.

4.3.2 Time in the future

The process of projection evolves the state of a system not at the current time, but over a particular timespan into the future. How far into the future a projection is required may influence the method of projection used. Figure 4.14 depicts how uncertainty of the projection grows as the projection timespan requirement increases.

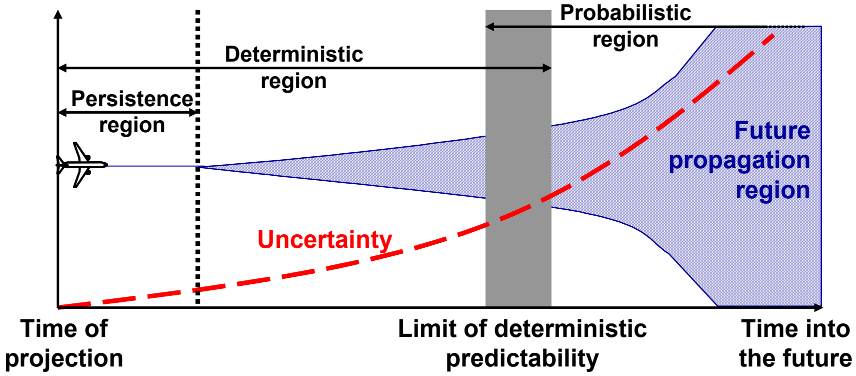

Figure 4.14: Projection uncertainty over time into the future (Adapted from Vigeant-Langlois & Hansman, 2004).

Several system factors determine how far into the future the controller projects, including information update rate, execution time, and degree of tactical control available to the controller. The less frequently the controller receives information about the system, the longer into the future the controller must project to ensure task requirements are being met until the time of the next update. Since the update rate of aircraft positions over the oceans is on the order of 30 minutes, a much longer projection time is required when compared to a TRACON controller whose aircraft positions are updated every 4.8 sec.

If the time required to execute a control is long, the projection time must also be long. The lengthy projection time ensures that the system remains within the task requirements until a correction to the system can be made. Execution time is affected both by control relay time and the system's dynamics. Control relay time is the time between when a control command is issued and when it is received by the system. In an environment only covered by HF and complicated by a relay operator, the control relay time between oceanic controller and pilot can be several minutes, while in a VHF environment relay time is almost instantaneous. The system's dynamics can affect execution time, because in a responsive system the control command takes effect with very little delay, while in a system with greater lag the desired state takes longer to achieve. The responsiveness of the aircraft does not change across ATC domains, however it can vary depending on the velocity and configuration of the aircraft. Pilot delays in implementing the commands can also increase the execution time.

The more tactical control that is available to the controller the less time the controller is required to project into the future. Controllers can issue commands by state (e.g., altitude, heading, speed), trajectory (e.g., ILS arrival trajectory or oceanic track), or region (e.g., special use airspace or Class B airspace). In most ATC environments, the controller is able to issue any or a combination of these commands. Due to procedural constraints or system implementation capabilities, the controller may not have access to certain commands. For example, in certain Continuous Descent Approach procedures the controller may only clear or abort the procedure without control over states or trajectory of the aircraft. In another example, once an aircraft has joined an oceanic track, there is little maneuverability in the lateral dimension available to the controller without the complications of removing the aircraft from the track. In situations such as these, the projection time requirement is lengthened.

Within each of these temporal regions, projection is performed differently. In the persistence region, the controller uses the last surveilled state. In the probabilistic region, the controller must consider multiple future states with the likelihood of these states varying. Between these regions, in the deterministic region, a "most likely" state evolution can be generated based upon the controller's mental model of the system behavior.

Time over which projection is made into the future is also incorporated in the Projection Error Concept. The time over which projection is required by the task (T_{task}) is particularly critical to the projection. T_{task} is determined, at a minimum, by the task and system constraints (e.g., surveillance update rate, system dynamics, and control relay time) as discussed above. It can also be determined by a particular task (e.g., projection to a metering time). To perform the task effectively, it is important that the growth of the projection uncertainty into the future over the period of T_{task} remains within the operator's error tolerance for that particular task.

The next chapter describes an experiment that probes some of the key assumptions from the General Projection Process Model and the Projection Error Concept.

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CHAPTER 5: Experimental Probe of Projection Model & Error Concept

Based upon ATC field visits and information analysis, a General Projection Process Model and Projection Error Concept were created. They were created based upon three assumptions. The first research-supported assumption is that projection error grows as the timespan over which projection is required increases (Averty, 2005; Lyon & Waag, 1995; Jagacinski, et al., 1983; Gray & Thornton, 2001). The other two assumptions are based upon field observations and controller input:

- The rate at which projection error grows is dependent on the state mental model of the controller.
- Error tolerance influences the quality of the mental model used by the controller, and therefore affects the error growth.

An ATC experimental probe was used to validate some of the assumptions used in the model. In particular, the controller's projection strategy (and projection error growth rate) with differing system dynamics was of interest and the influence of error tolerance on projection error growth.

5.1.1 Experimental Facility & Task

The experimental task was based on an ATC conflict projection task similar to the tasks performed in the studies by Averty (2005) and Xu, et al. (2004) to access task-specific cognitive projection mechanisms. It was programmed in MATLAB using a low-fidelity ATC part-task simulation, whose core program was built by Chris Tsonis of the MIT Humans and Automation Laboratory. In this task, the participant watches two "aircraft" represented by small (white) squares proceed along flight paths, as shown in Figure 5.1 below. Aircraft 1 flies left to right on the horizontal (green) flight path. Aircraft 2 flies from top to bottom on the vertical (green) flight path. Participants were told that while the horizontal aircraft may accelerate, decelerate or proceed at constant velocity, the vertical aircraft always proceeds at constant velocity throughout the scenario (though the velocity may vary between scenarios). The (white) dots behind the aircraft indicate the aircraft's positions on previous information updates. Before the horizontal aircraft crosses each (blue) of three long vertical Projection lines on the horizontal aircraft's flight path, the participant must predict where it will be when the vertical aircraft crosses the horizontal aircraft's flight path. To record this prediction, the participant can move two (magenta) brackets with a mouse and click at the correct predicted position. Participants were told that potential positions for the horizontal aircraft will only be between the Projection 3 line and the end of the horizontal aircraft's flight path. At the end of the scenario, the participant will have made three projections. Each scenario lasted between 30 sec to 3 min and there were 60 scenarios total. A grid unit was equal to approximately 1.5 inches on the actual computer screen. The width of the display was 6.5 inches, or 17.5 degrees of visual angle at a viewing distance of 1 m.

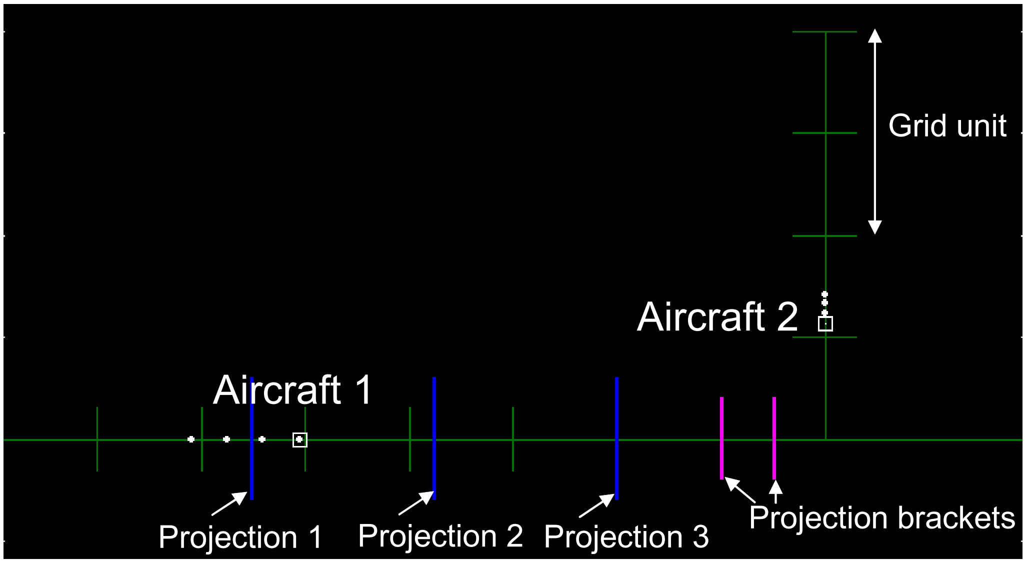

Figure 5.1: Experimental Display shows Aircraft 1 and 2 on intersecting flightpaths.

5.1.2 Participants

Participants for the experiment were 10 French Air Traffic Control students (8 males and 2 females). These students were fully trained with their final certification test not more than two months away. Two were en route center controllers, four were tower controllers, and four were both tower and approach controllers. The controller group averaged 11.5 months experience controlling in facilities.

5.1.3 Experimental Design & Independent Variables

This experiment was a repeated measures design. To investigate the difference in projection error slopes for different system dynamics, the acceleration profile of the horizontal aircraft was varied. The horizontal aircraft could either be accelerating slow (6.47×10^{-4} deg/sec^2 with a viewing distance of 1 m), accelerating fast at twice the rate (1.48×10^{-3} deg/sec^2), decelerating (-6.47×10^{-4} deg/sec^2), or proceeding at constant velocity. Due to possible influence of the cognitive clocking mechanism from Tresilian

(1995), initial velocity of the horizontal aircraft was also varied at either 0.17 deg/sec, 0.35 deg/sec, or 0.71 deg/sec. The simulation speed was increased due to limited time available with the controllers, so the speed was about 10 times that of a typical ATC display. To investigate the influence of error tolerance, the width of the brackets used to make the projection was varied at 1.01 deg, 2.01 deg, or 4.02 deg. Update rate of the information provided was also varied at 1 sec, 2 sec, or 4 sec, with stimulus presentation and inter-stimulus interval similar to an ATC radar display. Figure 5.2 shows how the independent variables were allocated across scenarios. Due to limited time with the controllers, the matrix was not able to be completely filled. Where the horizontal aircraft was when the vertical aircraft crossed its flightpath was counterbalanced across scenarios through manipulation of the speed of the vertical aircraft. Across scenarios, the closest point of approach was equally distributed around zero. The time over which projection was required was also sampled three times, with each prediction made. This time varied across scenarios, depending on the velocity of the two aircraft.

		Bracket width								
		1x			2x			4x		
		Update Rate								
Acceleration	**Velocity**	1x	2x	4x	1x	2x	4x	1x	2x	4x
Accelerating 1x	1x	1	▨	2	3	▨	4	5	▨	6
	2x	▨	7	▨	▨	8	▨	▨	9	▨
	4x	10	11	12	13	14	15	16	17	18
2x	1x	19	▨	20	21	▨	22	23	▨	24
	2x	▨	25	▨	▨	26	▨	▨	27	▨
	4x	28	29	30	31	32	33	34	35	36
Con. Vel.	1x	37	▨	38	39	▨	40	41	▨	42
	2x	▨	43	▨	▨	44	▨	▨	45	▨
	4x	46	47	48	49	50	51	52	53	54
Decelerating	1x	55	▨	56						
	2x	▨	57	▨						
	4x	58	59	60						

Figure 5.2: Experimental Design Matrix.

5.1.4 Dependent Variables

Location and time of the participant's projection was recorded. The primary variable measured in this experiment was the error between the participant's prediction and the actual location of the horizontal aircraft when the vertical aircraft crossed its flightpath. Projection Error = predicted position – actual position. More specifically, a negative measure indicated that the controller projected the aircraft to be going slower than it actually did, and a positive measure implied a "faster" bias. Subjective data were also measured in questionnaires provided after the experiment inquiring about the difficulty of the scenarios and if the controller's strategy changed with the scenarios.

5.1.5 Experimental Hypotheses

The hypotheses to be explored by this experiment are:

State Mental Models: Different dynamic conditions of the horizontal aircraft will produce different projection error growth rates, depending on the strategy of projection in a particular dynamic condition. Gottsdanker (1954) and Werkhoven et al. (1992) have suggested that an acceleration estimate may be difficult for operators to incorporate into their projection model. Results from Wagenaar & Timmers (1979) indicate that operators use a constant velocity strategy, possibly due to difficulties incorporating acceleration. If error patterns between dynamics conditions are indistinguishable, this would indicate that the participant could fully compensate for the higher order of dynamics. If the aircraft is accelerating, the constant velocity projection would result in the controller predicting that the aircraft was going slower than it actually was (a negative error trend). If the aircraft is decelerating, the constant velocity projection would result in a positive error trend, indicating that the controller was predicting the aircraft was traveling faster than it actually was.

Error Tolerance: For a given dynamics condition, decreasing the bracket width (i.e., reducing error tolerance or threshold) should force the participant to use a higher quality state mental model for projection, reducing the growth of projection error. Likewise, with wider brackets, a lower quality state mental model could be used and the error would still remain within the error tolerance while conserving cognitive resources.

Projection Timespan: The previous research has suggested that as the projection timespan increases, projection error also increases (Averty, 2005; Lyon & Waag, 1995; Jagacinski, et al., 1983; Gray & Thornton, 2001).

Impact of Velocity: Due to the influence of the cognitive clocking mechanism from literature (Tresilian, 1995; Xu, et al., 2004; Peterken, et al., 1991), it is possible that velocity could influence the projection error pattern. Targets moving at slower velocities have been found to result in an operator's overestimation of velocity, negatively affecting projection performance (Gottsdanker, 1954; Castet, 1995; Xu et al., 2004). In addition, Freyd (1983) found that the magnitude of the "representational momentum" memory shift increased linearly with increasing final velocity. This could cause the controller overestimate velocity as the aircraft velocity increases. However, “representational momentum” bias appears to only affect situations in which apparent motion is perceived (update rates less than 1000 msec), which is unlikely in the ATC context.

Information Update Rate: Little information is known about the effect of discrete information update rate greater than 1 sec intervals on projection. It is possible that a frequent update rate could allow better observability of the system dynamics, therefore allowing higher quality mental models to be created, reducing the projection error growth.

5.1.6 Results & Discussion

The primary measurement in this experiment was projection error. In the following results, projection error is defined as *Predicted position – Actual position* of the horizontal aircraft when the vertical aircraft crosses the horizontal aircraft’s flightpath. Error throughout the results is measured in “grid units,” in which a grid unit is shown in Figure 5.1 and approximately equaled 1.5 inches on the actual screen (approx. 4.5 nm in a typical TRACON display setting). To test the hypotheses, differences in error have been analyzed for the projection time variable, the dynamics conditions, initial velocity conditions, error tolerance conditions, and update rate conditions. After these analyses, a multiple regression using the significantly contributing variables was performed.

<u>Projection time variable:</u>

Past literature has found that the projection error grows the further into the future that the projection is made. The signed projection error is shown over time in Figure 5.3 across all conditions. Each data point represents the average projection error over 10 controllers for each of the scenarios. There is a slight negative bias to the projection error, indicating that, in general, there was a bias to underestimate aircraft velocity (i.e., project the horizontal aircraft was flying slower than it actually was). The results suggested that the controllers had a slower bias both for all of the cases, regardless of the actual dynamics. One explanation for these results could be due to the speed of the vertical aircraft. The relative speeds between the two aircraft could be quite different, particularly when the horizontal aircraft was proceeding at a fast velocity. Therefore, it is possible that the horizontal aircraft’s speed was biased to be slower due to adaptation to the consistently slower speed of the vertical aircraft. Biases due to motion adaptation are consistent with results of Smith (1985 & 1987) that stated that when participants were used to predicting a test-grating between 1 and 40 deg/sec they would underestimate the apparent speed of a test-grating with a speed of between 2-8 deg/sec.

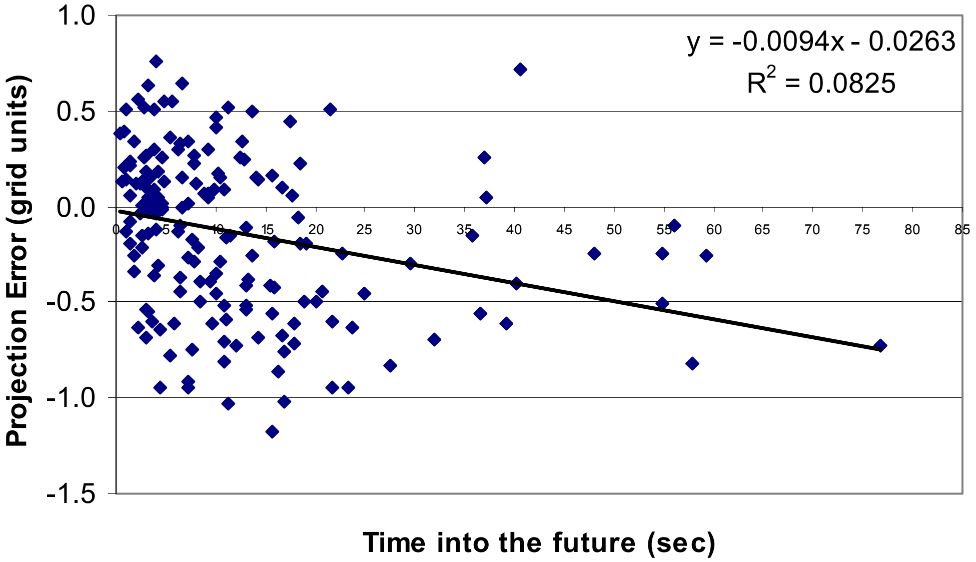

Figure 5.3: Projection Error over time across all conditions.

Figure 5.4 shows the signed projection error averaged across controllers grouped by the projections made by each of the three projection markers on Aircraft 1's flightpath. Using a single factor within subjects ANOVA, the differences between the signed projection error means of the projection time conditions were found to be non-significant: F(2,1281) = 0.44. This indicates that, statistically, the controllers were equally good (or poor) at projecting aircraft up to about 80 sec into the future as they were at projecting aircraft only a few seconds into the future. This is contrary to the previous literature that suggested the longer the time into the future the operators were required to project, the more the projection accuracy suffered (Averty, 2005; Lyon & Waag, 1995; Jagacinski, et al., 1983; Gray & Thornton, 2001). This could be that controllers naturally have a high quality model of the dynamics reducing the error of projection into the future. However, considering Figure 5.3, the variability even at short projection timespans is quite high, which could be the result of high baseline measurement error that could obscure the error due to projection timespan. This variability is somewhat taken into account as the data is separated into independent variable conditions in the following sections.

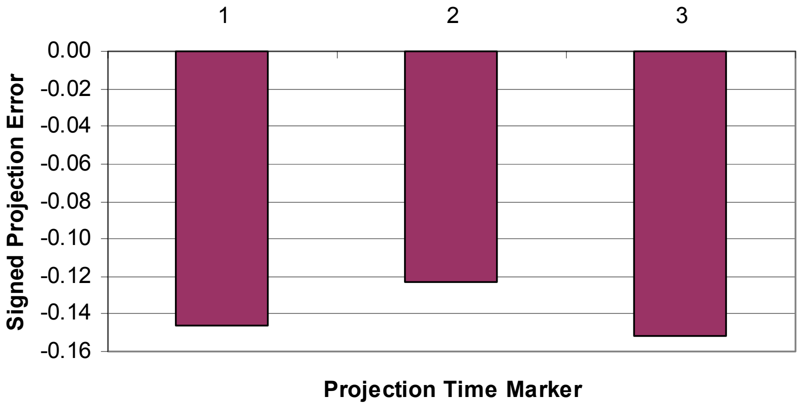

Figure 5.4: Means of projection time markers.

Dynamics conditions:

Using a single factor within subjects ANOVA, the differences between the signed projection error means of the dynamics conditions were found to be significant: F(3, 1281)= 15.56, $p<0.01$. Figure 5.5 depicts a comparison of the means of the dynamics conditions for both signed and absolute projection error collapsed across subjects. Figure 5.6 shows the signed projection error averaged across 10 participants for each data point and separated into dynamics conditions.

As discussed in the previous section, the sign of the projection error tends to be negative, signifying that the controllers were underestimating velocity of the aircraft. The exception to this is in the decelerating condition in Figure 5.6; whereas the other conditions' error starts at about zero and get progressively negative, the decelerating case's error starts slightly positive and crosses over to negative. This suggests that at short projection timespans, the controller is underestimating the deceleration that is taking place (overestimating velocity).

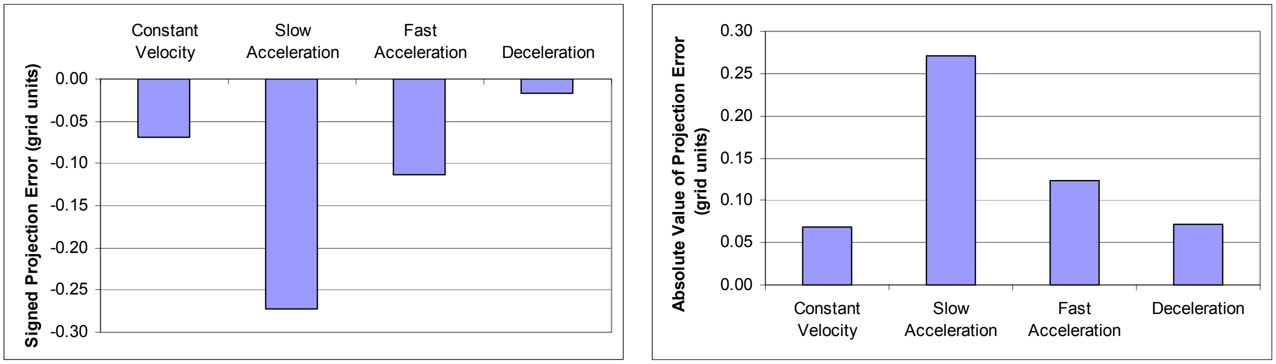

Figure 5.5: Means of the dynamics conditions.

Constant velocity condition exhibited close to zero projection error in Figure 5.5, indicating that the controllers were quite good at projecting when the horizontal aircraft exhibited these dynamics. The projection error for the deceleration case appears to be as low as that of the constant velocity case in Figure 5.5. However, considering the mean error across controllers for the individual scenarios in Figure 5.6, it appears that the overall mean error is low due to a sign-crossover of the error.

The acceleration cases were both at least twice the magnitude of error as the constant velocity case, signifying use of a poorer state mental model with inaccurate acceleration components. The greatest mean projection error was the slow acceleration condition at approximately 0.27 grid units, which translates into about 0.5 in on the display. The display setting would transform what this error would be in nautical miles. A typical TRACON display could be set such that 1 in on the display approximately equals 3 nm in the real environment. This would result in the average error for the slow acceleration case being on the order of 1.5 nm, assuming that the results would generalize to the TRACON control for this display setting. Since the TRACON horizontal separation standards are 3 nm, this is a fairly significant projection error. The overall difference in error between the constant velocity condition and the acceleration conditions could suggest difficulty discriminating between the acceleration cases and/or building projection models of the separate cases.

The slow acceleration case was the most difficult, being over twice the mean signed error of the fast acceleration case. It may have been difficult for the controller to detect that the horizontal aircraft was accelerating in the slower case, using the strategy for constant velocity. Because the error for the fast acceleration condition was less, this may indicate that the controllers were able to compensate for the acceleration somewhat, at least in the fast condition.

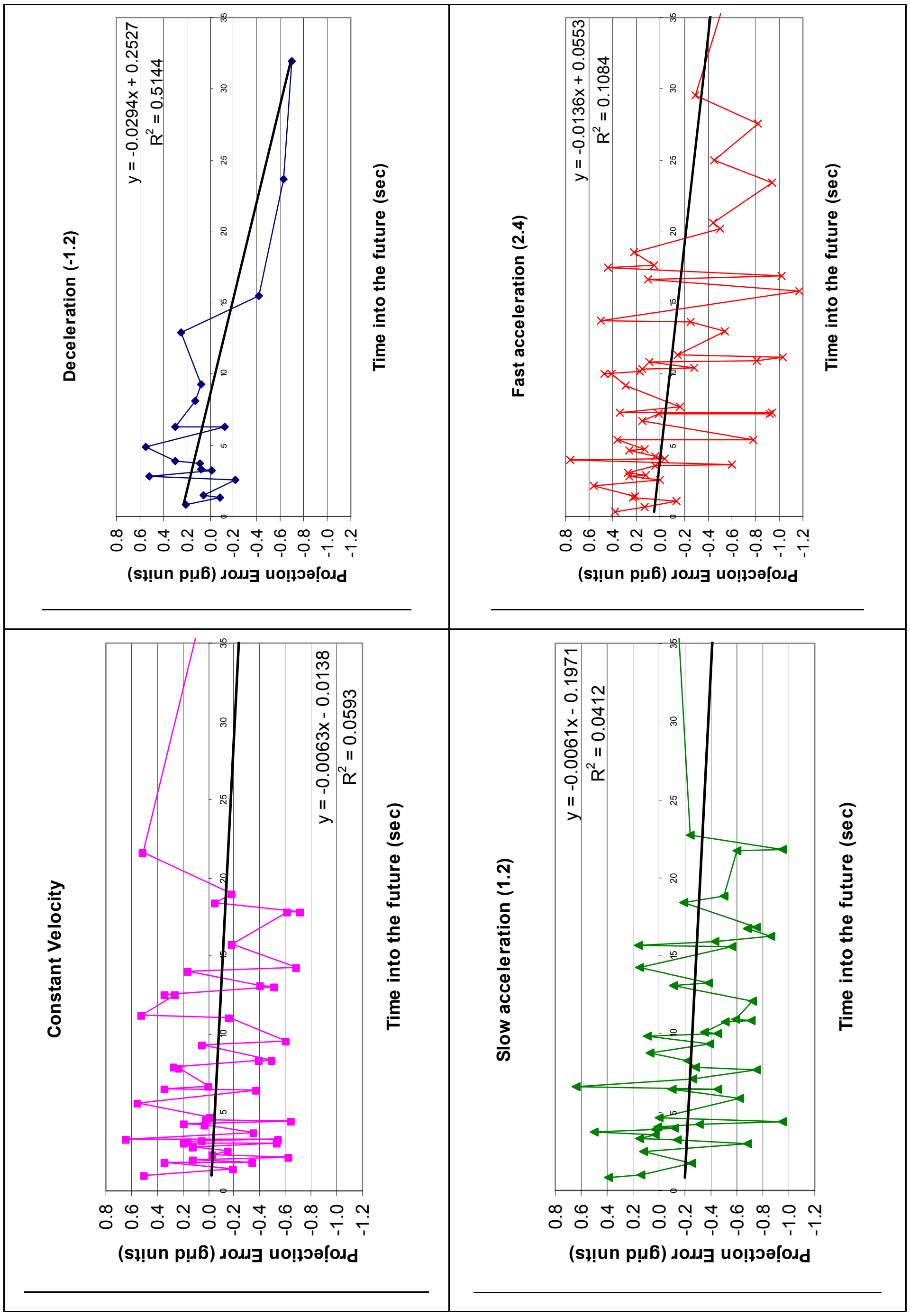

Figure 5.6: Projection error over time split into dynamics conditions.

In general, the results except for the deceleration condition are inconsistent with the "representational momentum" bias found in Gray & Thornton (2001) and Freyd (1983) in which there was a tendency to project that the velocity was faster than it actually was. The error results for the deceleration case are consistent with the concept of "representational momentum" in which an observer's memory for the final position of an object in motion is biased in the direction of the motion. The projection error in the decelerating case could be as a result of the controller's errant state mental model of extrapolating the aircraft with an even slower velocity than it was actually exhibiting due to a bias in the acceleration component of the model. However, the constant velocity and acceleration cases exhibited the opposite effect. If consistent with representational momentum, once the controllers perceived the acceleration, the projection should have been biased in the direction that the aircraft were traveling faster than they actually were.

Figure 5.7 compares the controllers' projections with a constant velocity extrapolation for several experimental scenarios. Each data point represents an average over controllers' signed projection error for a particular projection time ("blue" or "black" points) or what the constant velocity extrapolated error would be if the controller used the velocity of Aircraft 1 at the time of the projection ("magenta" or "grey" points). Figure 5.7 depicts the constant velocity model and the projection error data for the slow, medium, and fast initial velocity across the three columns, and for fast acceleration, slow acceleration, and deceleration down the three rows. A controller's adherence to a constant velocity extrapolation (CVE) appears to be heavily driven by the initial velocity, such that with fast velocities (right column) the CVE closely matches the controller's data (and produces growing errors with longer intervals, as would be predicted by a CVE). For both the medium and slow initial velocities, however, controller error is considerably less than what the CVE strategy would predict. The one exception to this conclusion is in the lower left where, again, a CVE is followed with a slowly decelerating aircraft, and again, the longer projection times produce progressively greater error (now negative).

These results indicate that in some scenarios, controllers can predict with constant velocity, consistent with previous research by Wagenaar & Timmers (1979) and others. However, some scenarios provided results that were consistent with Gottsdanker (1954) and Werkhoven (1992) indicating that acceleration could be integrated, with some difficulty as evidenced from the higher error over the constant velocity condition and the scenarios in which the projection error was worse than the constant velocity extrapolation. The ability to integrate acceleration into projection could be due to the nature of the ATC projection task. In the ATC task, the controllers are required to meet particular constraints and they are given feedback and receive consequences when they do not meet these constraints. Due to extended training in this environment, controllers may have developed skills to create more accurate state mental models than the participants in other psychological experiments.

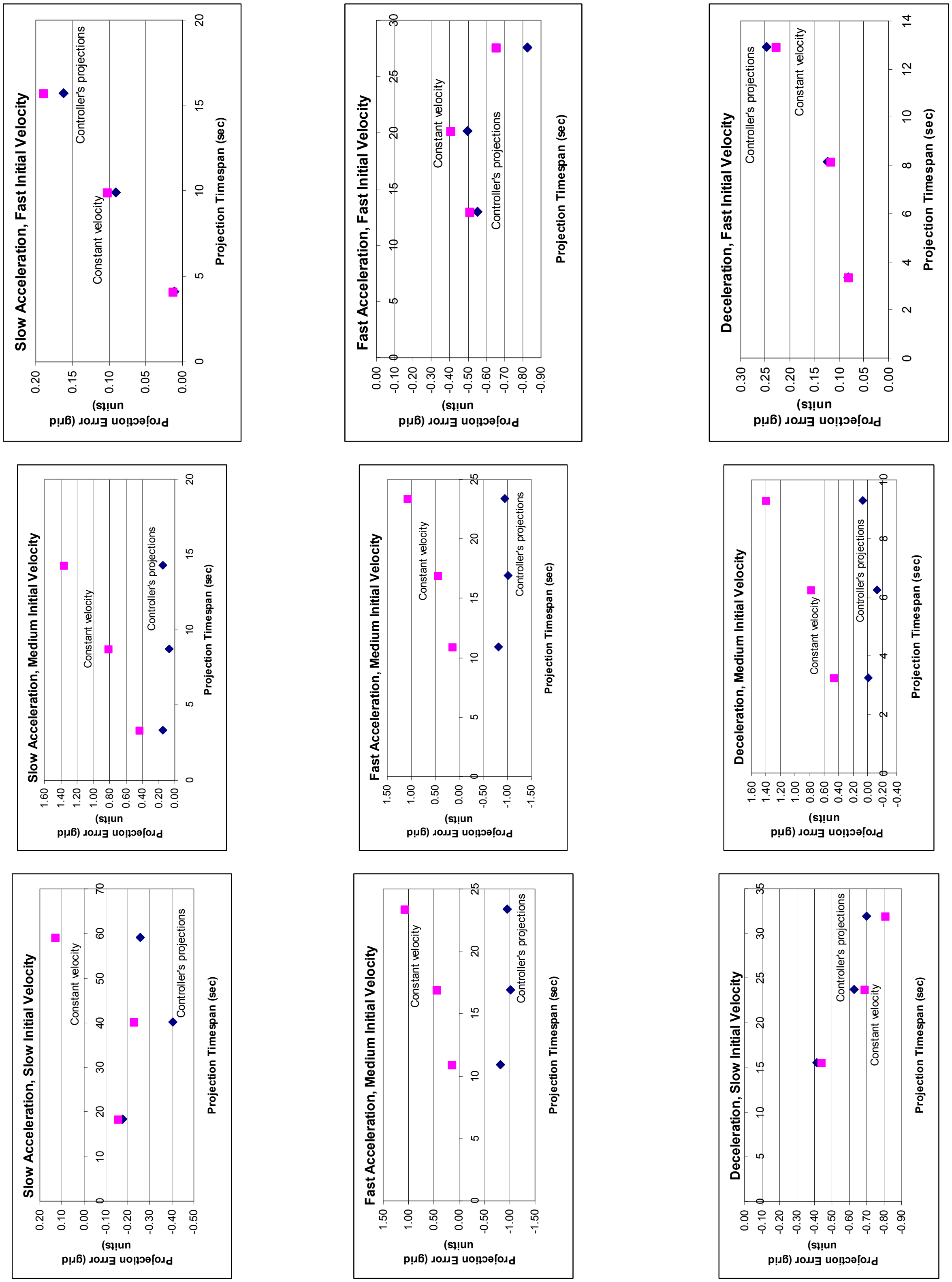

Figure 5.7: Comparison of controllers' projection error compared with constant velocity extrapolation.

Velocity conditions:

Another variable manipulated in this experiment was the initial velocity of the horizontal aircraft, which could either be a baseline "slow" velocity, a "medium" velocity that is twice that of the slow, or a "fast" velocity that is four times that of the slow. The signed projection error means across all scenarios and controllers separated into initial velocity conditions are provided in Figure 5.8.

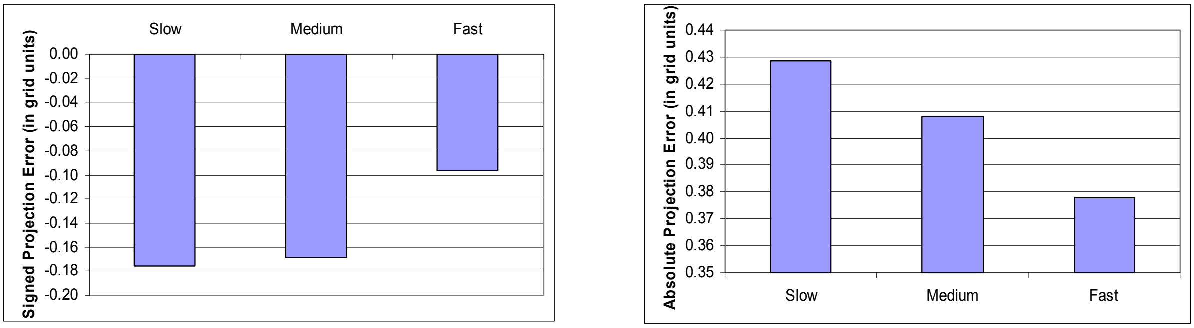

Figure 5.8: Means of the initial velocity conditions.

Using a single factor within subjects ANOVA, the differences between the signed projection error means of the velocity conditions were found to be significant: $F(2, 1281)= 4.18$, $p<0.05$. According to Figure 5.8, the faster the initial velocity of the horizontal aircraft, the lower the projection error, which is consistent with the results of Gottsdanker (1954). These data are inconsistent with the effects of the "representational momentum" bias, but this may be because of the difficulty of accurately clocking at slower tempos, consistent with Freyd's (1983) findings.

Table 5.1 shows results of repeated measures two-factor ANOVAs that were performed between the dynamics/timespan, dynamics/initial velocity, and timespan/initial velocity on signed projection error to determine if any interactions between variables were significant. There was a significant interaction between aircraft 1's dynamics and its initial velocity ($F(6,1281)=2.31$, $p<0.05$). Figure 5.9 shows this interaction in which the signed projection error data shown were averaged across controllers and the projection timespan variable was collapsed. During the fast velocity case, in every condition except the constant velocity condition, velocity was estimated to be higher than in the previous cases. For the acceleration conditions, this resulted in less projection error in the fast velocity case, but in the deceleration case, the error crossed over to overestimation of velocity. The constant velocity condition appeared to have the opposite effect for the fast initial velocity condition, resulting in an underestimation of velocity. The changing projection error as velocity is increased in the acceleration cases is consistent with the "representational momentum" hypothesis of Freyd (1983). However, the error in the decelerating case should be in the opposite direction for this hypothesis to explain the behavior. An alternative to a direction of motion hypothesis to explain the data is that as initial velocity increases, the controller is biased to increase their velocity estimate. Since there is no change in velocity in the constant velocity condition, the bias would not apply in that case.

Dynamics/Timespan interaction	F(6,1281) = 0.96, no significance
Dynamics/Initial velocity interaction	F(6,1281) = 2.31, $p<0.05$
Timespan/Initial velocity interaction	F(4,1284) = 0.20, no significance

Table 5.1: Two-way ANOVA variable interaction results.

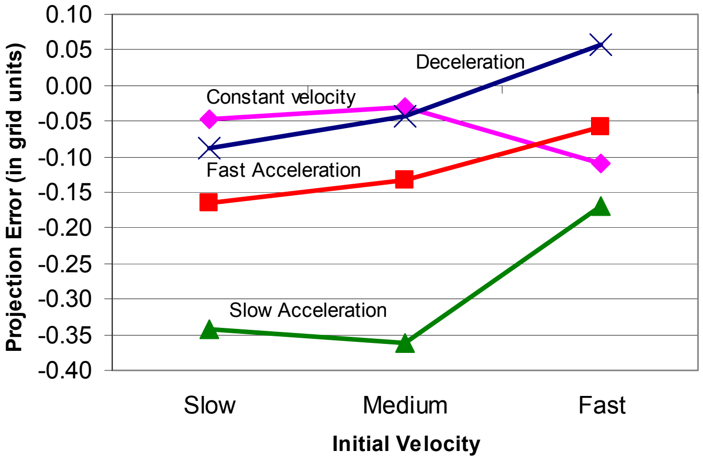

Figure 5.9: Interaction between dynamics and initial velocity on signed projection error.

<u>Error tolerance conditions:</u>

Bracket width was also a variable manipulated in the experimental design to determine the effect of error tolerance on projection strategy. Figure 5.10 shows the signed and absolute projection error means for the different error tolerance conditions shown in comparison with the "error tolerance" as determined by the bracket width for the task. All of the signed means fell within the error tolerance for the task. There was a general trend that the larger the error tolerance, the greater the projection error. A repeated measures single factor ANOVA was performed, and it was found that there was only a marginal difference between the signed projection error means: F(2,174)= 2.98, $p<0.10$.

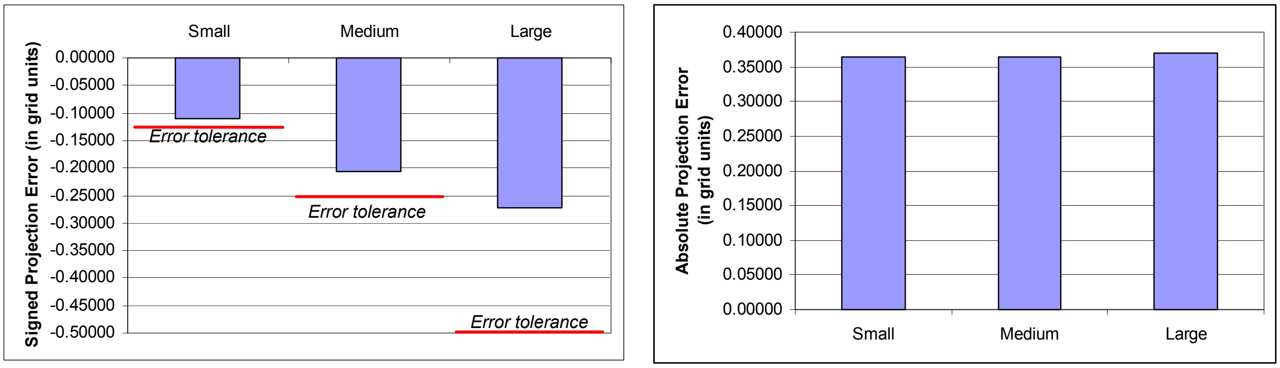

Figure 5.10: Means for error tolerance conditions.

One explanation for the muted difference found in this experiment was that the participants were told to project to the best of their ability, therefore the controllers would have put their best prediction in the center of the bracket for each projection. In addition, it is possible that the controller's ability to dedicate all of his or her cognitive resources to the task reduced differences between the conditions. Dividing the controller's attention between the projection task and a secondary task may result in a bigger difference between the means of the error tolerance conditions, due to the controller being required to "satisfice" on the projection task.

However, the general trend of the data from this experiment is consistent with the hypothesis that more stringent requirements influences the controller to alter projection strategy to ensure that projection error is within the error tolerance for the task. This is consistent with the predictions of the Projection Error Concept, which suggested that reducing error tolerance would lead the controller to improve the quality of the state mental model used for projection, thereby reducing projection error. The observed trend indicates that addressing these experimental issues in a follow-up experiment could yield clear significant results indicating the influence of error tolerance on quality of the state mental model.

Update rate conditions:

Update rate was varied in this experiment to provide projection data in the discrete region of information update frequency. Figure 5.11 depicts the means of the signed projection error for each of the update rate conditions. A repeated measures single factor ANOVA was performed and it was found that there was no effect of update rate on signed projection error for this experiment.

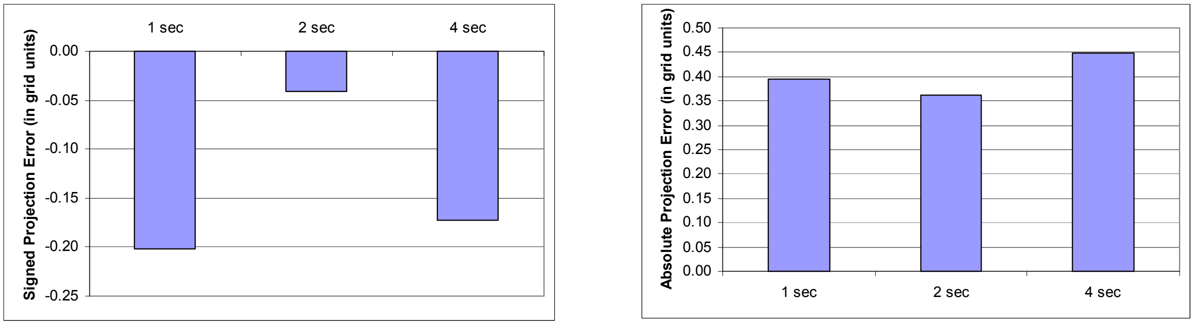

Figure 5.11: Means for the update rate conditions.

It was hypothesized that with a more frequent information update the participants could have developed a more accurate state mental model of the aircraft dynamics and therefore projected more accurately reducing projection error. However, in this experiment it appears that compared to other variables such as the dynamics of the horizontal aircraft and the initial velocity, update rate played little role in the state mental model development. It did appear to, however, affect whether apparent motion biases affected projection performance in this experiment. The lengthy "stimulus presentation," even though it was counteracted with near instantaneous "inter-stimulus interval," seemed to remove any perception of apparent motion. This is consistent with Freyd (1987), who suggested that longer stimulus presentation times (on the order of 250 msec) would require an ISI of close to zero to induce apparent motion. This appeared in the projection performance results in which "representative momentum" overestimation of velocity biases did not appear to influence controller's projection accuracy in this experiment.

Multiple regression & variable interactions:

In this experiment, it was found that the dynamics of the horizontal aircraft, initial velocity of the horizontal aircraft, and timespan of projection were the most statistically influential variables on projection error. These variables were then incorporated into a multiple regression of signed projection error. The following equation best describes these variables' relationship to signed projection error:

$$\textit{Signed Projection Error (in grid units)} = 3.8654 - 0.5288(\textit{Xdyn kt/sec}) - 0.0642(\textit{Xttask sec}) - 0.0043(\textit{Xinitvel kt})$$

From this multiple regression, it appears that the dynamics variable had the most impact on the development of the state mental model and therefore projection error, with the projection timespan and the initial velocity having somewhat less impact.

5.1.7 Experimental Probe Conclusions

The purpose of this experiment was to probe key concepts from the Projection Error Concept within an air traffic control paradigm to allow incorporation of contextual influences on the projection process. The hypotheses involved the state mental model used for different levels of aircraft dynamics, the impact of velocity on projection error, the influence of error tolerance on projection strategy, and the influence of update rate on projection.

This experiment has resulted in the additional insight into several aspects of Projection Error:

- **State mental model hypothesis:** Based on the projection error means, controllers appear to use different state mental models dependent on the dynamics of the system. From the error results of the fast acceleration condition, it appears that controllers can compensate in their projections for acceleration somewhat. Higher error in the slow acceleration condition indicates that controllers may be having difficulty either perceiving the acceleration or integrating an accurate estimate into the projection, possibly using a constant velocity prediction. The sign bias of the error indicates that controllers tend to underestimate velocity, which is consistent with the constant velocity prediction for the acceleration cases, but not for the deceleration case. But here (and only here) at short intervals there was an overestimation (positive error) which *would* be consistent with the constant velocity extrapolation hypothesis. The magnitude of the mean projection error results indicates that in a display setting representative of the TRACON environment in which 1 in=3 nm, the projection error can be as much as 1.5 nm. This projection error magnitude can be operationally significant, depending on the situation, in an environment in which aircraft are required to be horizontally separated by 3 nm.
- **Error tolerance hypothesis:** The results show a trend that error tolerance may influence the quality of the state mental model that the controller creates for the task at hand. Further experimentation increasing cognitive load during projection may strengthen this effect.
- **Impact of projection timespan:** The analysis of the projection error difference between the three projection times suggested that the projection timespan did not affect projection error, contrary to previous findings that an increase in error results from an increase in projection timespan. This could be due to the baseline measurement error being large enough to obscure any effect of projection timespan in this experiment. However, Figure 5.6 and Figure 5.7 indicate that projection timespan does affect the amount of projection error. Thus, the lack of difference in the projection time analysis could be due to other manipulated factors affecting the error, such as initial velocity of Aircraft 1.

- **Impact of velocity:** In addition to the original assumptions, the results of the probe also suggest that velocity of the display evolution is also a significant influence on projection error. Analyzing the error means of each velocity condition, an increase in aircraft velocity resulted in an overall improvement in projection accuracy, consistent with Gottsdanker (1954). However, faster velocities does not necessarily result in a better projection. There was a significant interaction between initial velocity and dynamics such that for the conditions in which velocity was changing, the fast initial velocity condition resulted in the projection using a higher velocity than other initial velocity conditions. This improved the projection accuracy of the acceleration conditions, reducing the underestimation of velocity bias and is consistent with the "representational momentum" bias of Freyd (1983), even though Freyd found that update rates greater than 1000 msec did not exhibit apparent motion biases. However, in the deceleration case, the faster initial velocity kept the magnitude of the projection error, only shifted the bias from underestimation of velocity to overestimation of velocity. The deceleration condition results were opposite to the "representational momentum" hypothesis, but consistent with other research supporting overestimation of velocity for targets at low speeds (Gottsdanker, 1954; Castet, 1995; Xu et al., 2004). As indicated in Figure 5.7, it appears that in the fast initial velocity condition, the controllers' projections closely matched the constant velocity extrapolation, indicating that controllers were less likely to incorporate the higher level dynamics in the fast velocity cases possibly due to the less time available to do so. This is consistent with the concept of "satisficing" on the projection mental model quality due to less time available.
- **Impact of update rate:** There did not appear to be an effect of update rate on projection accuracy. In addition, the results from the experiment suggested mixed support whether the update rates representative of the ATC system prevent the influence of apparent motion biases on projection.

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CHAPTER 6: Supporting Projection in the Future ATC Environment

In this chapter, supporting the future projection process in the ATC environment is addressed. The first section applies the General Projection Process Model and the Projection Error Concept to the case study of the TRACON's Continous Descent Approach procedure. The second section applies them to the transition to a mixed spatial/temporal oceanic separation environment.

TRACON case study: Continuous Descent Approach Procedure Implementation

In a conventional final approach, aircraft follow a set lateral and vertical procedure that will allow interception of the ILS localizer and glide slope for a precision approach to the runway. The controller provides airspeed commands and sometimes heading and altitude commands to ensure that the goal of efficiency is met.

In the conventional approach procedures depicted in Figure 6.1, the aircraft descends and slows in a series of altitude and airspeed steps according to procedure and/or controller commands. Maintaining airspeed and altitude at the constant portions of these steps requires a certain amount of thrust produced by the aircraft. At low altitudes, this engine thrust is a major source of aircraft noise for communities surrounding an airport. In an effort to reduce this thrust noise, an approach procedure was proposed that would keep the aircraft at higher altitudes longer, then allow for a 3 degree continuous descent approach to the glide slope, ideally using an idle thrust producing a change in deceleration profile. Figure 6.1 depicts the vertical and airspeed profiles of the conventional ILS approach procedure compared to the proposed Continuous Descent Approach (CDA) procedure. In a study simulating engine thrust noise effect on communities surrounding Boston's Logan International Airport, Figure 6.2 depicts the standard ILS noise footprint as compared to the improved CDA noise footprint.

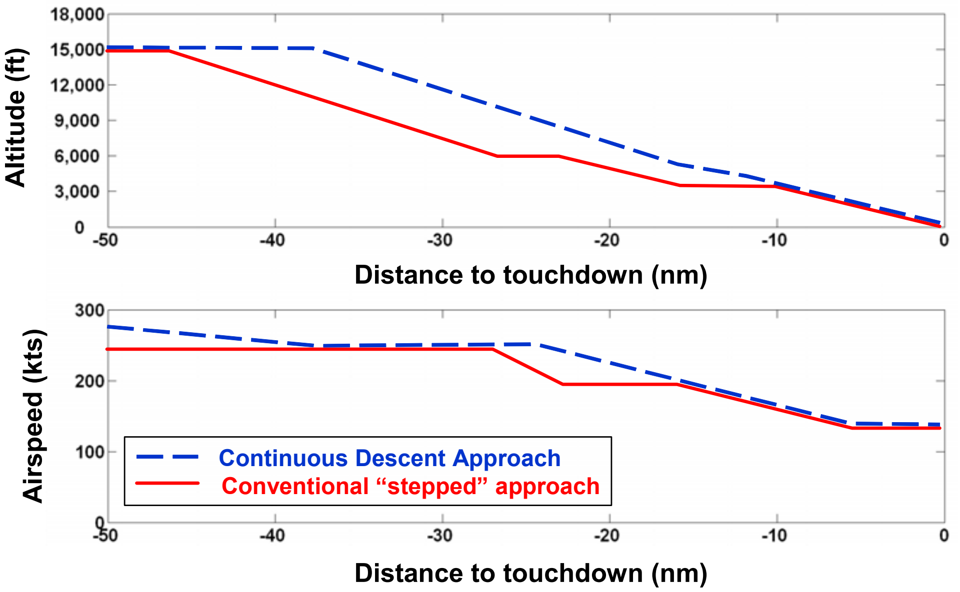

Figure 6.1: Altitude & airspeed profiles of traditional descent approach as compared to a continuous descent approach.

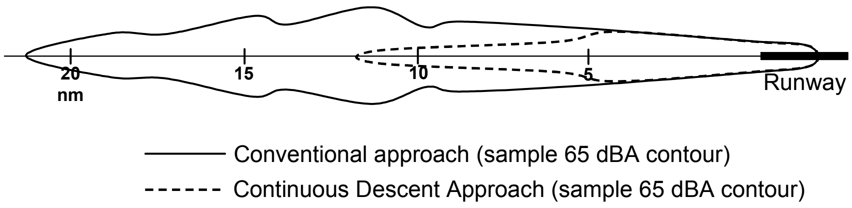

Figure 6.2: Single Event Noise Contours

While this CDA procedure is desirable from a noise perspective, subjective inquiries after the field trials found them to be difficult to use by controllers. Clarke, Ho, & Ren (2004) cited the problem of predictability of the aircraft performing the CDA procedure as the major impediment to the success of CDA procedure implementation. In the conventional procedure, the aircraft's speed and altitude were controlled by the final approach controller and there were only short periods of transience between commanded values. Addressing the problems facing ATC projection during this procedure may mean the difference between the implementation of the procedure, leading to lower noise levels and better quality of life for communities surrounding airports, and abandoning the procedure due to problems of ensuring safety & throughput at high levels of traffic.

In this section, the CDA procedure will be described and the specific impacts of this procedure on the controller's projection will be illustrated using the Projection Model and Error Concept from Chapter 4.

The CDA procedure is a general term for noise abatement procedures that eliminates level altitude segments during approach procedures, which keeps aircraft higher and at lower thrust to reduce noise compared to the typical step-down procedure. Not only does the CDA affect the altitude profile, it may also affect the way that the lateral and speed profiles are executed during the approach.

Lateral trajectory and speed profile impact:

One category of the CDA procedure is the Area Navigation (RNAV) CDA procedure. The RNAV CDA defines the vertical and lateral profile and is flown by the Flight Management System (FMS) to optimize the descent rates, maximizing the noise benefits. The lateral trajectory is a series of waypoints that can be programmed into the aircraft's FMS as shown in Figure 6.3. The specified lateral trajectory can be designed to avoid populated areas, reducing the noise impacts further.

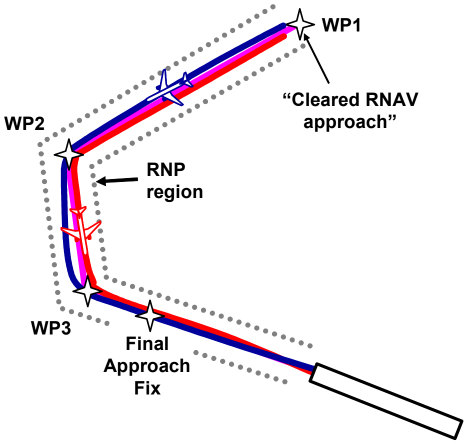

Figure 6.3: Example lateral trajectory of an RNAV CDA procedure.

The speed profile may be specified in an RNAV CDA procedure through the use of speed gates at waypoints, which define a range of speeds for which the aircraft must target. Because of the loose constraints the speed gates place on the speed profile of the aircraft, there is little standardization of speed profiles between aircraft flying the CDA. In addition, the flown speed profiles differ between aircraft depending on the aircraft type's dynamics and the logic of the FMS. These factors combine to result in a large variance of behavior in the speed profile during the RNAV CDA procedure.

Control availability impact:

Because of the nature of the CDA, the controller relinquishes control over the vertical profile to the pilot (and possibly the FMS). In the RNAV CDA, after the controller has cleared the CDA procedure, vertical, speed, and lateral profile is all determined by the FMS.

Even with FMS-assisted path definition, aircraft can exhibit different behaviors due to environmental conditions (e.g., winds) and aircraft type. Therefore, it remains important for the controller to be able to monitor separation even in cases with FMS-specified trajectories. In cases in which it becomes difficult to predict if the separation will be maintained, controllers may increase separation at the beginning of the procedure, reducing throughput and system efficiency and nullifying the benefits that the CDA brings. It is for this reason that it is critical to ensure that the controller's projection process is supported during the implementation of the CDA procedure.

Controller's task during CDA execution

During the approach, the TRACON final approach controller's task can be to vector the aircraft to the CDA entry point, clear the CDA procedure, and then monitor the aircraft's progress on the approach until interception of the ILS, when it is handed off to the Tower controllers. In addition, if there are other aircraft on the approach, the controller must monitor separation between the aircraft as well. If we consider the separation task during an RNAV CDA, because of the FMS-determined lateral and vertical trajectories, the controller is responsible for longitudinal separation between aircraft. Therefore, the primary state that the controller is required to project is the relative longitudinal separation between aircraft.

In Figure 6.4, the change in the relative longitudinal separation behavior is shown graphically between the conventional approach procedure and the RNAV CDA procedure. In each of the diagrams, the value of relative longitudinal separation is shown over time. Two critical times are depicted for each of the procedures, the "top of descent" or beginning of the approach and the time of interception of the ILS. In the conventional approach, the first aircraft is given a clearance to reduce speed to a particular value at the top of descent. Some time afterwards, the second aircraft is given the same clearance. Depending on when the aircraft execute these commands and how quickly the deceleration performs, the change in relative longitudinal separation will reduce with a particular behavior until both are at a lower constant speed. This uncertainty in the relative longitudinal separation between the time of the issuance of the first speed command and the time that both aircraft are again at the same constant speed is represented by a gray parallelogram in the diagram. The conventional approach is structured such that it is a series of these short periods of change in relative longitudinal separation behavior with long periods of constant separation.

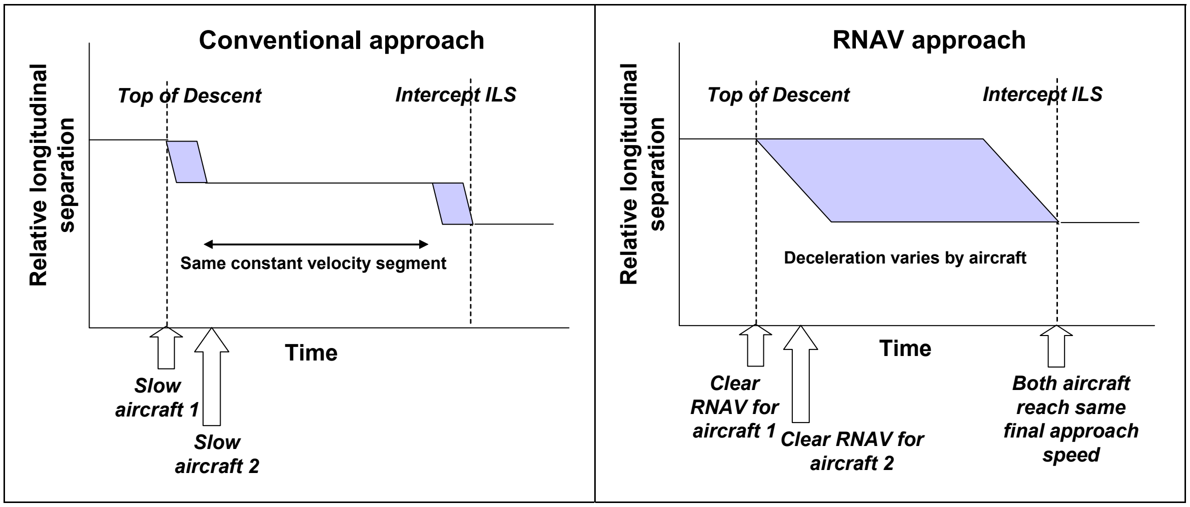

Figure 6.4: Relative longitudinal separation behavior during a Conventional approach and an RNAV CDA procedure.

In the RNAV CDA procedure, once the aircraft is cleared on the RNAV procedure, its speed profile is uncertain throughout the approach until it intercepts the ILS and achieves the final approach speed. This results in a long period of relative longitudinal separation uncertainty between when the first aircraft is cleared on the RNAV CDA until the second aircraft achieves its final approach speed. The impact that this changing relative longitudinal separation behavior has on the controller will be analyzed further in the next section.

Impact of RNAV CDA Procedure on Projection

In this section, the impact that the RNAV CDA procedure has on the controller's projection process will be discussed, using the Projection Process Model and the Projection Error Concept as a means to analyze it. The three areas in which projection is affected are Intent, Command Availability/Projection Timespan, and Abstractions.

Intent impact:

Intent of the aircraft originates from a combination of a specified state/procedure/constraint with a controller-issued clearance, as depicted in the Projection Process Model in Figure 6.5. In a conventional approach, the controller issues speed commands in addition to heading and altitude clearances which, when readback by the pilot, become the aircraft's intent. In the RNAV procedure, the intent is well-defined in the lateral and vertical profiles, however the speed profile is unconstrained except for any speed gates designed into the procedure.

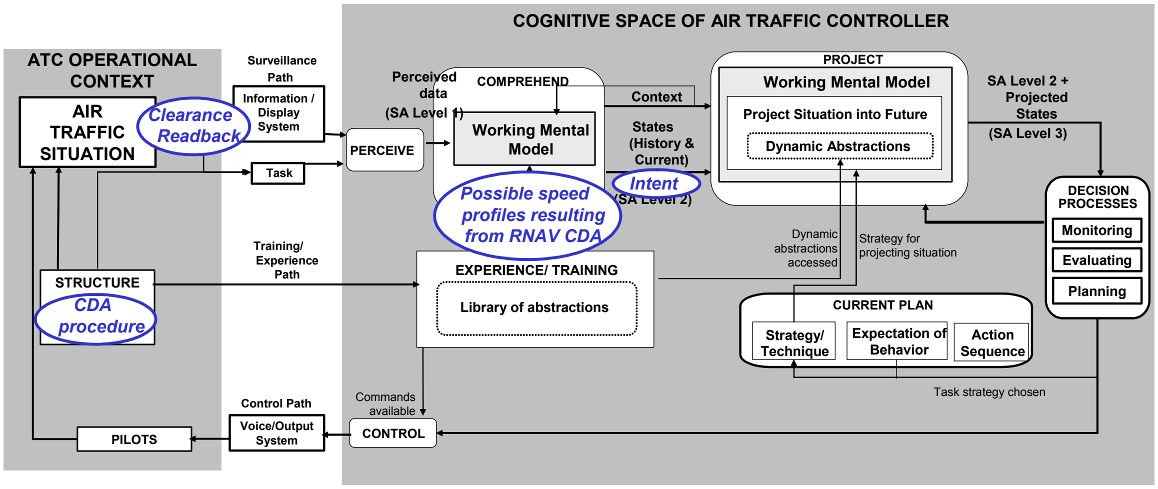

Figure 6.5: Sources of Intent in the Projection Process Model.

Figure 6.6 depicts the impact that varying intent with the RNAV CDA procedure has on the relative longitudinal projection uncertainty. In the conventional approach, when the deceleration clearance is given for the first aircraft, the projection uncertainty grows for a short period until the aircraft conforms to the clearance. Further into the future, the controller will clear the second aircraft to decelerate, adding more uncertainty to the projection. As the aircraft are both at the same constant velocity, the projection uncertainty remains the same until a second deceleration command is issued to the first aircraft. Consistent with Figure 4.13, the projection uncertainty grows the further into the future the controller is required to project.

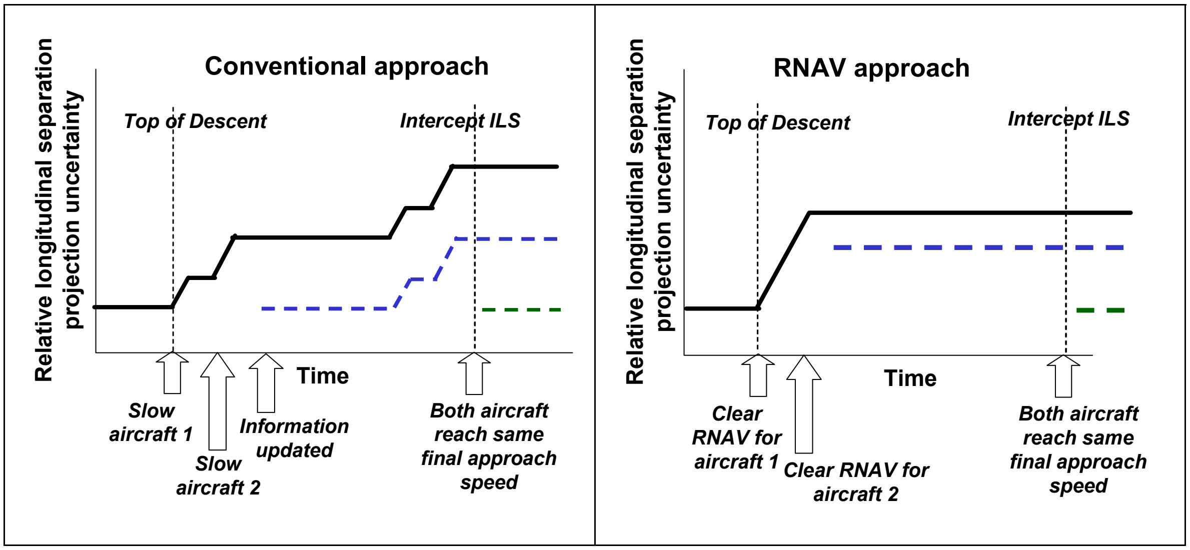

Figure 6.6: Intent impacts of the final approach procedures.

The primary way to reduce this projection uncertainty is by receiving an information update on the new current state of the system. The level of projection uncertainty after an information update returns to the baseline uncertainty as shown in the hashed line at the left of Figure 6.6, because the aircraft are not expected to change their behaviors until another speed command is issued.

In the RNAV CDA, once the first aircraft is cleared for the RNAV approach, the projection uncertainty grows quickly due to the uncertainty in the speed profile for that particular aircraft on the approach combined with the behavior of the second aircraft on the approach. However the projection uncertainty remains constant throughout the approach. When the controller receives an information update, the projection uncertainty at that time is reduced somewhat. However, due to the fact that the relative longitudinal separation is uncertain throughout the RNAV approach, the projection uncertainty is not reduced to the baseline like it was in the conventional approach until both aircraft reach the same final approach speed.

Command availability/Projection Timespan Impact:

Another area of impact that the CDA has is the command availability, which in turn affects projection timespan requirements, as depicted in Figure 6.7. In the conventional approach, position-based and velocity-based vectors are available to the controller throughout the approach. This allows the controller the ability to correct the future behavior of the aircraft quickly once the controller has determined that the future aircraft behavior is not acceptable within the constraints of the task. This tactical control availability combines with a short communication relay time available through VHF communications in the TRACON to result in a short projection timespan requirement (Ttask), as indicated on the left of Figure 6.8.

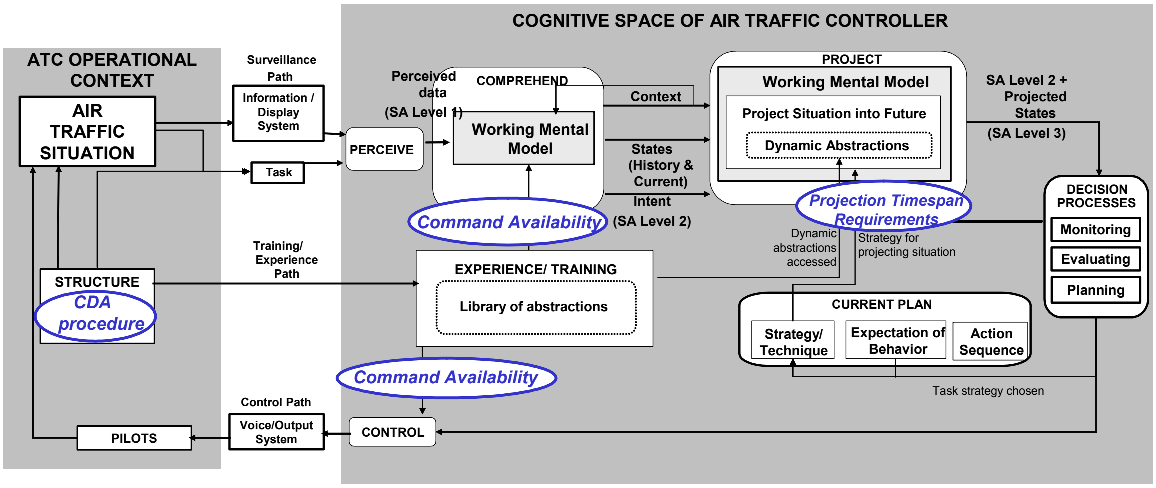

Figure 6.7: Command availability within the Projection Process Model.

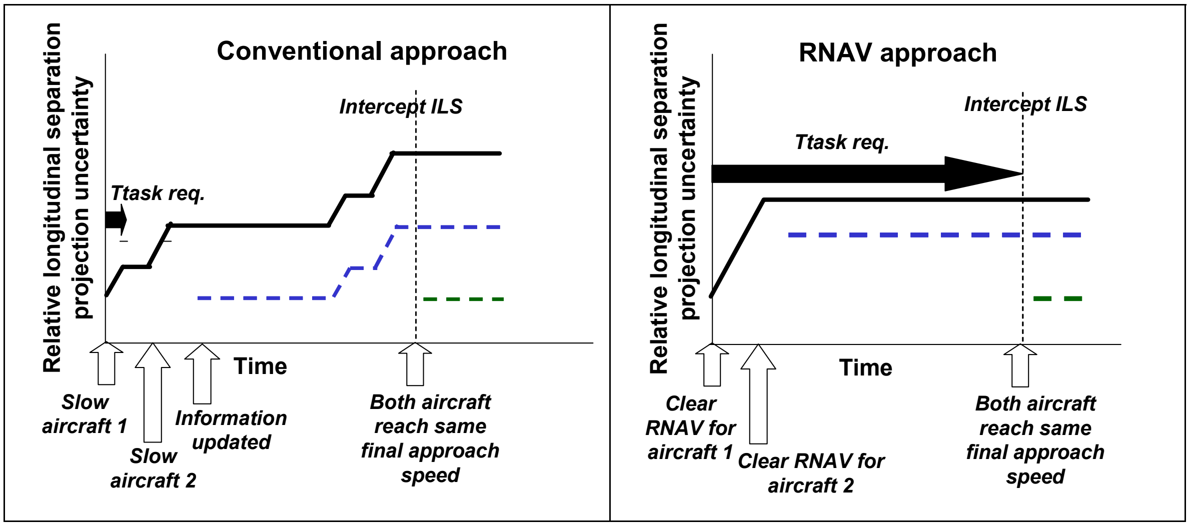

Figure 6.8: Control availability impact on projection timespan requirement.

The RNAV CDA procedure removes tactical control availability from the speed, lateral, and vertical profiles. This requires the controller to have projected the aircraft's lateral and vertical behavior from the time of clearance to the point at which the ILS localizer and glide slope has been captured, increasing the projection timespan requirement over the conventional procedure, as depicted in Figure 6.8. The difficulty that this produces for projection depends on the knowledge of intent that the controller has of the RNAV procedure. As shown in Figure 6.8, though the conventional approach projection uncertainty grows larger than the RNAV procedure throughout the approach, the controller only is required to project as long as the Ttask requirement. Therefore the projection uncertainty for the conventional approach is low compared to the uncertainty that accumulates over the projection timespan required for the RNAV approach.

Impact on controllers' abstractions:

The CDA procedure also has an effect on the abstractions that the controllers use to project the aircraft into the future. Figure 6.9 depicts the abstractions used for relative longitudinal separation projection in an approach within the Projection Process Model. In the conventional procedure, two key abstractions that the controllers incorporate into their mental models for projecting the relative longitudinal separation include the controller-pilot contract abstraction and the constant velocity abstraction. As discussed in Chapter 4, the controller-pilot contract abstraction states that if a controller issues a command and it is readback by the pilot, then the controller can assume conformance to the command within a reasonable period of time.

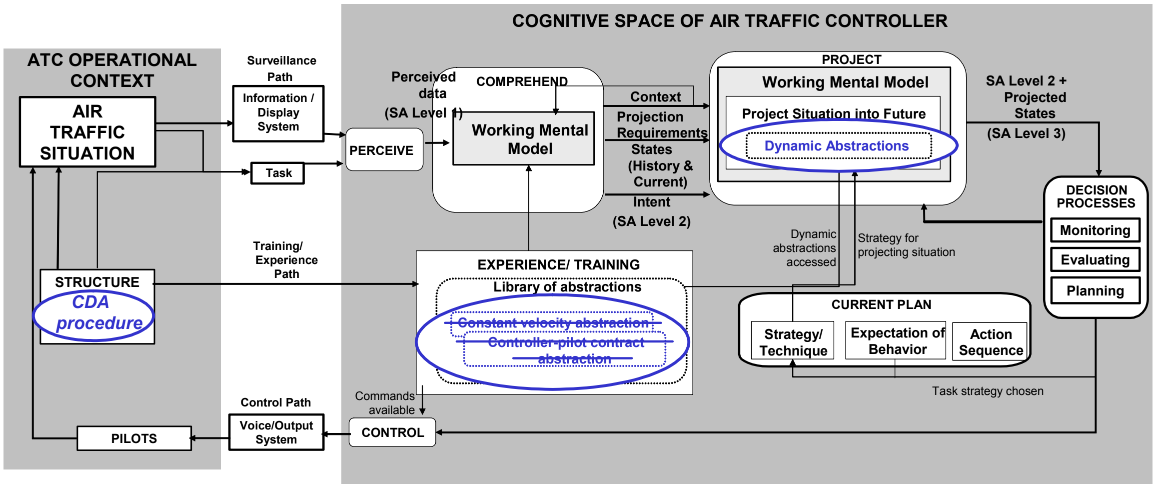

Figure 6.9: Abstractions on which the CDA has an impact.

The other abstraction used is the constant velocity abstraction. The constant velocity abstraction states that aircraft will fly at a constant velocity with only short periods of transience between speeds. When projecting an individual aircraft, the controller can use a pattern matching mechanism to extrapolate past distance intervals between radar updates to future positions. As found in both the past research (Rosenbaum, 1975) and the experiment in Chapter 5, controllers are quite good at maintaining high projection accuracy when the aircraft is proceeding at constant velocity. Due to the nature of the Standard Operating Procedures, aircraft in close proximity tend to have the same speed. The constant velocity abstraction also makes projecting the difference between aircraft easier as well. If aircraft are proceeding at the same constant velocity, then once the aircraft are separated, this distance will remain constant until one of the aircraft changes velocity, simplifying the controller's Monitoring and Evaluation processes.

In the RNAV procedure, the constant velocity and the controller-pilot contract abstractions are removed. While the controller still clears the pilot to conduct the approach, the behavior resulting from the procedure may vary from aircraft to aircraft and in different wind conditions, reducing the utility of the controller-pilot contract abstraction.

Summary:

The impacts of the RNAV CDA on projection is significant. The following summarizes this impact:

Intent: Non-standardized speed profiles resulting from the RNAV CDA procedures reduce the intent knowledge of the speed trajectory available to the controller. This prevents accurate dynamic estimates of aircraft behavior to be made, increasing projection uncertainty.

Command availability: Tactical control over speed, altitude, and heading is removed from the controller in the RNAV CDA procedure. By removing tactical control, the projection timespan requirement increases due to inability to correct aircraft behavior after procedure clearance. Increasing projection timespan requirement puts more importance on creating accurate dynamic estimates of behavior to keep the error within the controller's projection error tolerance.

Abstractions: The abstractions of controller-pilot contract and constant velocity are removed to in the RNAV CDA procedure. The removal of these abstractions requires the controller to develop new and reliable abstractions to maintain a low projection error.

Supporting Projection during CDA Procedure Implementation

To maintain the projection accuracy when implementing the CDA procedure, consideration needs to be given to the ways that the procedures impact the projection process. The two main effects that the RNAV CDA procedure has on projection are an increase in projection timespan and a reduction in speed intent knowledge. This results in a steeper increase in relative longitudinal separation projection uncertainty slope and a longer time over which this uncertainty grows. There appear to be at least two alternatives to ensure that projection capability remains accurate: providing tactical controllability and/or clarifying the aircraft's speed intent during the procedure.

Tactical controllability:

Providing tactical controllability allows the projection timespan requirement to be decreased. Even if the aircraft intent remains unclear, the controller has the chance to correct the future aircraft behavior within a short period of time, similar to the conventional ILS approach.

Clarifying aircraft intent:

Another option is to improve the controller's knowledge of the aircraft intent. This would allow the controller's dynamic estimates to be good enough such that the lengthy projection timespan is not enough time to allow the projection uncertainty to accumulate beyond the controller's error tolerance.

Since the CDA procedures involve innately different dynamic behavior than the conventional ILS procedure, the abstractions of controller-pilot contract and constant velocity cannot be used. Alternate abstractions to predict behavior during the CDA procedure are required. One question is whether the controller can develop an equally reliable abstraction involving an acceleration component as was the constant velocity abstraction.

This ability to create alternative velocity abstractions in the CDA is tested in an experiment described in detail in Davison Reynolds, Reynolds & Hansman (2005) (Appendix B). In this experiment, the controllers were asked to predict the relative longitudinal separation between two aircraft at several points along a final approach course. The variables manipulated were the velocity profiles of the two aircraft and the relative velocity of the aircraft. The aircraft could either both be proceeding at constant speed, one decelerating and one at constant speed, or both decelerating at the same rate. The velocity variable resulted in scenarios in which the aircraft could be proceeding at the same speed, the aircraft separation could be increasing ("opening") or the separation could be decreasing ("closing"). The accuracy of projecting the separation of the aircraft at the end of the final approach was measured. Figure 6.10 depicts results from the experiment that the projection accuracy of relative longitudinal separation for aircraft in the same constant rate of deceleration was equal to that of aircraft proceeding at constant velocity.

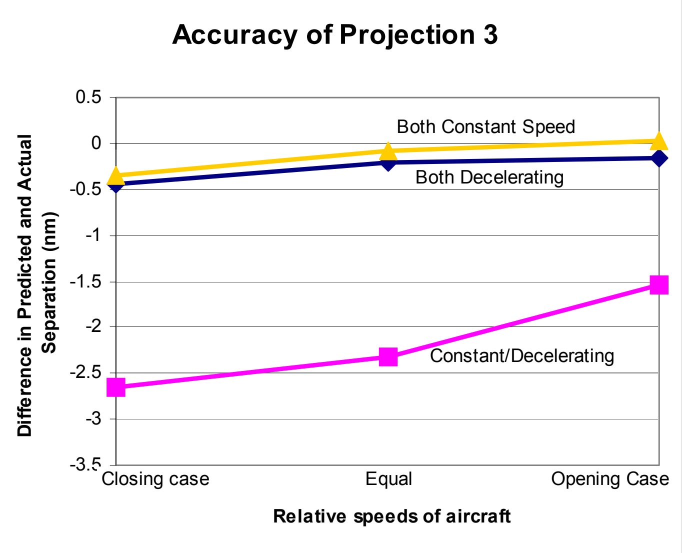

Figure 6.10: Projection accuracy results across relative speeds of the aircraft for each velocity profile.

This experiment seems to suggest that in cases in which the RNAV procedure is implemented to result in consistent vertical and lateral behavior, the controller may be able to develop alternative velocity abstractions that are quite reliable. However, in the experimental probe in Chapter 5, it was found that controller's appear to have some difficulty projecting decelerating aircraft. Thus, the ability of controllers to develop alternative abstractions to aid projection in the RNAV CDA should be further explored in the context of a particular procedure and the aircraft flying that procedure.

CDA Case Study Summary

The Projection Process Model and Projection Error Concept provided a framework in which to consider the projection impact of the Continous Descent Approach procedures. These impacts included differences in intent knowledge, control availability, and abstractions. The projection models also allowed support for procedure implementation to be suggested, including providing tactical controllability and intent clarification. Experimental findings presented in Appendix B also support the possibility of developing a reliable abstraction of a constant standardized deceleration, but accuracy suffers when requiring the controller to develop and apply multiple reliable estimates of acceleration for a task. Some difficulties of predicting decelerating aircraft were presented in Chapter 5, which should be considered in CDA implementation.

Oceanic case study: Mixed Spatial/Temporal Separation Environment

Oceanic ATC is in the midst of a major update, incorporating new surveillance and communication technologies into the former antiquated system and updating the workstation to take advantage of these new technologies and allow greater flexibility in future oceanic operations. The U.S. oceanic ATC update program is titled the Advanced Technologies and Oceanic Procedures (ATOP) program. ATOP was deployed in the New York Air Route Traffic Control Center (ARTCC) in June 2005 and in Oakland later that year. Anchorage facility is scheduled to deploy ATOP in mid-2006. In the former system, the U.S. oceanic facilities used paper flight strips to record surveillance information provided to the controller, as seen in Figure 6.11. Figure 6.12 shows the new system, in which the paper flight strips were (or soon will be) replaced with electronic versions. In addition, a situation display provides the aircraft positions on a graphical map display similar to what a domestic radar controller would see. Procedural changes will eventually allow the controllers to use the situation display as a primary means of separation, and the electronic flight strips will be phased out of the workstation in future builds. The position reports provided by the pilots will be replaced with automatic position reporting by the aircraft, utilizing Automatic Dependent Surveillance-Address (ADS-A) satellite technology. Using ADS-A, the aircraft will send information such as position, velocity, altitude, and heading information through a satellite to a specific addressee at a pre-determined frequency established by the contract.

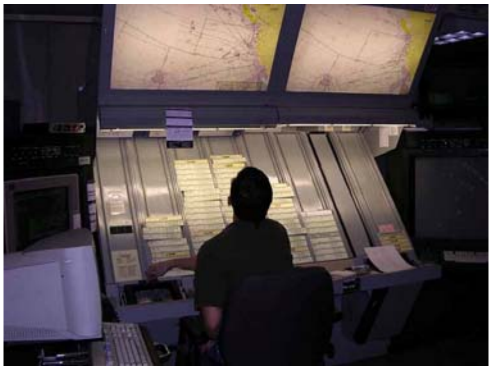

Figure 6.11: Oceanic workstation in Oakland facility before the ATOP upgrade.

Figure 6.12: ATOP oceanic workstation currently being deployed in U.S. oceanic facilities.

Communication is also expected to improve in the new system. In the current system, the pilot communicates the aircraft position through low-quality High Frequency (HF) radio to a relay operator who then transfers this information electronically to the controller. In the future oceanic ATC system, the relay operator will be eliminated and communication will occur through Satellite Communication

(SATCOM) radio or more likely through electronic datalink from pilot through a satellite to the controller.

It has generally been considered desirable to incorporate situation display functionality into a future workstation, because domestic controllers use them effectively. However, the oceanic controllers are required to perform a significantly different task than domestic controllers. Separation over the oceans is often controlled longitudinally through velocity commands, and therefore oceanic controllers are interested in estimated time of arrival at particular waypoints. Temporal information support is available through the estimated time of arrival (ETA) information on the flight strips, but not the situation display. As future workstation designs are considered, the controller's current conflict projection task should be understood and supported. Failing to understand and design for the projection process may result in new interfaces that do not support the controller's task, thereby rendering the interface unsafe, or may result in rejection of the new design by the users.

In this case study, each of these system improvements introduced above will be analyzed from a perspective of the projection process, using the model & concept from Chapter 4. The sections below directly compare the oceanic ATC trend or advancement with its older ATC system counterpart.

Surveillance improvements: Automatic Dependent Surveillance (ADS) allows improved surveillance of the aircraft outside of radar coverage in comparison with the pilot position reports. ADS is as accurate as the position report, because the position report also originates from the aircraft, however it may also include the report of additional aircraft states such as intent, depending on the implementation of the technology. It also reports these states more frequently, possibly as frequent as once every 5 minutes, as opposed to the position reports, which have an update frequency of approximately 30 minutes.

Communication improvements: Chapter 3 introduced the difficulties in communication with which the oceanic controller contends. By expanding the availability of electronic datalink and SATCOM, the communications over the oceans may not require HF communications and the relay operators in the future. This would reduce the communication relay time between pilot and controller from approximately 5 minutes to nearly instant.

ATOP and advanced oceanic workstation improvements: The U.S. oceanic facilities are transitioning from a paper-based flight strip ATC control environment to an electronic flight strip and situation display control environment as part of the FAA's Advanced Technologies and Oceanic Procedures (ATOP) program. Electronic flight strips allow automatic information updates to reduce the controller's information management tasks. Due to expanded surveillance availability and improved aircraft position estimation algorithms and conflict alerts, the situation display is becoming more important as a separation tool. Approval of U.S. procedures by oceanic controllers will likely lead to use of the situation display as the primary tool for separation over the flight strips in the future. Iceland's CAA is also in the process of integrating radar data with position report data into an integrated situation display.

Enhanced flexibility: As part of the ATC authorities' drive to enhance system performance, the oceanic environment is identifying ways to enhance flexibility of flight routes without sacrificing the traffic throughput the oceanic tracks affords it. This may lead to increasing numbers of non-standard routings (e.g., lateral crossing of oceanic tracks) or alternative, dynamic traffic structures.

These improvements are important to ensure that the oceanic ATC environment meets future service and traffic demand needs. However, as in the TRACON case study, if technological and procedural improvements negatively impact controller projection, improvements in system efficiency and safety could be reduced. In the next section, the impact on oceanic controller projection is addressed for these advancements.

Impact of Future Oceanic Environment on Projection

The future oceanic environment has a significant impact on the projection process, both positive and potentially negative. Analyzing the future technologies and procedures using the Projection Process Model and Projection Error Concept, the major impact areas appear to be: States to be projected, Intent, Projection timespan, and Human/Automation projection responsibility.

States to be projected:

In the future oceanic environment, the states available to be projected have increased due to ADS and the situation display presentation format. Figure 6.13 depicts in the Projection Process Model how enhanced aircraft intent states and lateral position information are two of the states that may be available for use in projecting separation. This allows the controller to observe these states directly rather than inferring them from other information, possibly introducing additional error into the estimates.

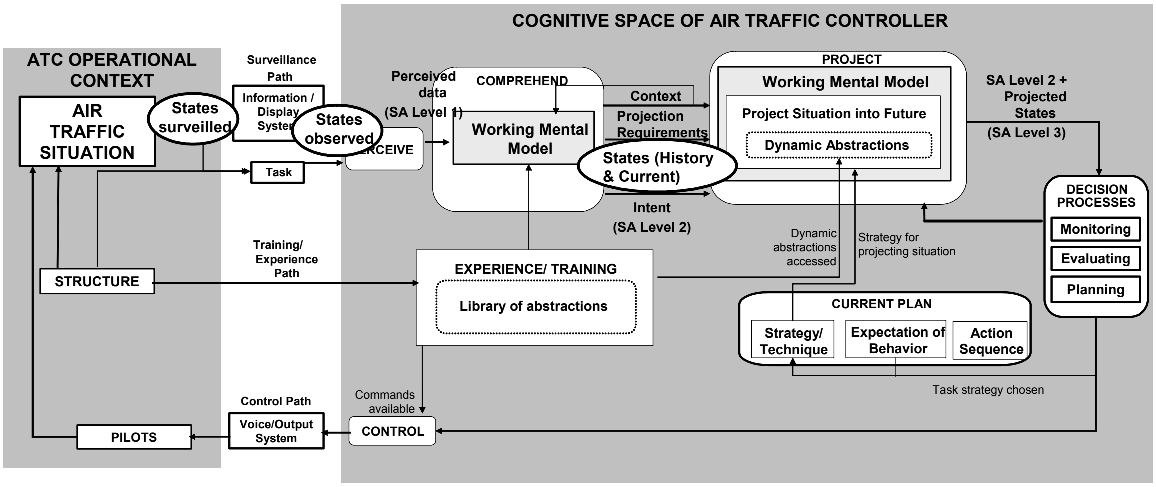

Figure 6.13: ADS may increase states surveilled improving state observability.

Besides state availability, situations dictating the need for task requirements that determine what states should be projected are changing as well. As flight operators are increasingly allowed to file routings that bypass the rigid oceanic structure improving fuel efficiency and reducing emissions, oceanic operations will become more of a lateral separation task rather than a longitudinal separation task, and this situation is depicted in Figure 6.14. As discussed in Chapter 3 and Appendix A, lateral separation requirements for the oceans are spatial, while the majority are longitudinal requirements, which are temporal. This presents, at least in the near future, a spatial/temporal mismatch between the information/display system and the separation minima.

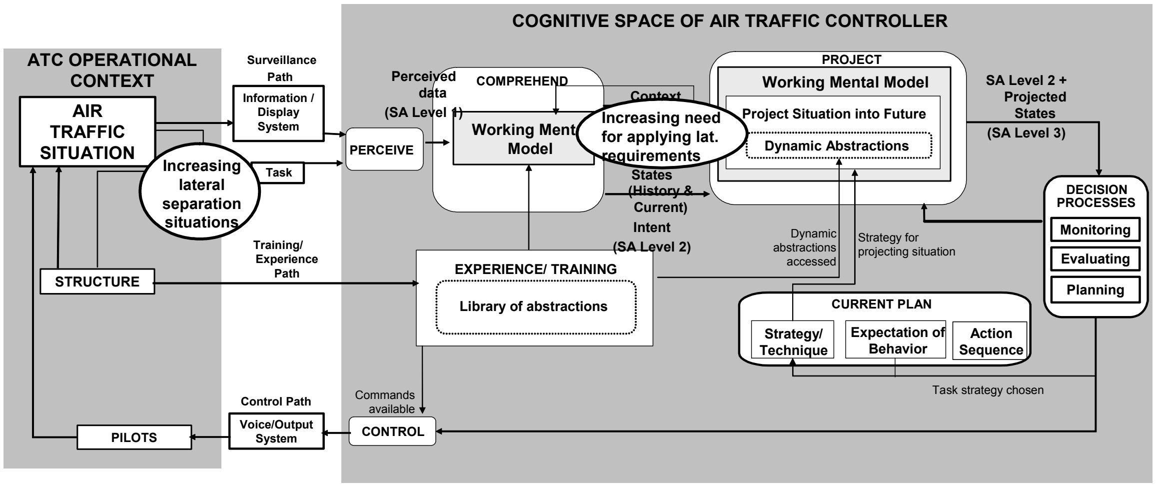

Figure 6.14: Increasing need for application of lateral separation minima in future oceanic environment.

Until the situation display is able to be legally used to separate aircraft, the controllers must use temporal flight strip information to separate lateral crossings. Once the situation display is approved as a means of separation, then there will continue to be a mismatch in the opposite way. There will still be a majority of the North Atlantic traffic using the jet stream routes as their optimal routing, and the traffic on these desired routings will be separated longitudinally with temporal restrictions. While the electronic flight strips will continue to be available for a time as a transition tool, future builds will likely eliminate this information source.

As discussed in the context of the information transform concept, the spatial/temporal mismatch problem cognitively complicates the Display to Problem Space Transform, leading the controllers to develop heuristics to transform either the presentation of the data or the restriction. By using a heuristic to transform the data, additional error is being introduced into the projection task, either through increasing the projection uncertainty of the state estimation or through reducing the error tolerance of the task.

It appears that the future oceanic projection process will require the controller to project separation against both temporal and spatial restrictions. Therefore, the future information/display system should support both temporal and spatial separation projection tasks.

Intent:

The departure from the rigid oceanic structure affects the intent knowledge that the controller can use for the projection. By allowing the flights to fly more direct routes, some routes will naturally deviate from the set routes, such as the oceanic tracks structure. The routings may also change mid-flight due to changing winds or environmental conditions. Due to this route uncertainty, the intent of the aircraft that is available to the controller is less than if they remained on the standard routings. Having less reliable intent information reduces the accuracy of the dynamic estimates used for projection, increasing the slope of the projection error growth. This reduction in intent information by standard route deviation could be offset by additional information provided by the aircraft through ADS or some other means.

Projection Timespan:

The communication and surveillance advances in the oceanic area reduce the time taken to issue commands and subsequently receive feedback about the effect of the command on the aircraft. This reduction in control relay time and surveillance time positively affects projection by reducing the projection timespan required from the controller. In the past, the controller must have projected long enough into the future to ensure that they had on the order of 5 minutes to issue a control command, give time for the pilot and aircraft to respond, and then observe the response of the aircraft through surveillance on the order of 30 minutes (or possibly by requesting special position reports with a time of 5 minutes). This 10-40 minutes of control/surveillance is reduced to on the order of 5-10 minutes, resulting in a 50-75% reduction in time. By reducing the projection timespan requirement, the requirements on dynamic estimates (and aircraft intent) are not quite as stringent to maintain an equivalent level of projection error as the previous system.

Human/Automation projection responsibility:

Projection responsibility is somewhat altered in the future oceanic ATC environment due to advanced position estimation algorithms and conflict probes. The situation display provides a current estimate of aircraft position based on interpolation between the report time at the last waypoint and the estimated time at the next waypoint. While the computer interpolation will likely contain less projection error than if a controller interpolated based on a rule-of-thumb, the automated could still be in error due to the stochastic nature of the environment. In this case, the position would "jump" on the display when a new report arrives. The error will likely be less with the incorporation of ADS due to increased reporting frequency, but minor errors are still a possibility. Thus, in this situation, the controller would have to understand how the situation display processor is estimating the position and account for the automation's projection uncertainty in addition to his or her own.

A similar situation is in effect for the conflict probe portion of the decision support technologies. The ATOP conflict probe is a heavily tested conflict probe algorithm, and designers have enough confidence in its accuracy to divert responsibility from the controller if the controller has used this probe in a separation task and there is a separation penetration due to the probe's estimation. Because the controller still performs separation tasks and will likely continue to double-check the ATOP conflict probe at least until trust is built, the controller must integrate an estimate of the probe's error into their own projection error estimate.

Another future information situation involves the integration of data with various update frequencies on a single situation display. Iceland's airspace involves a combination of radar and procedural airspace. For information integration purposes, it is probable that these different sources of data (and possible future data sources from ADS or other surveillance) will be presented on the same display. Section 4.2.2 discussed the impact of information update rate on the growth of projection error. The projection process of the controller would be complicated if the controller had not only to account for different frequencies of data presentation, but also asynchronous information updates. Major & Hansman (2004) addressed how the controllers' strategies would be affected by two differently updated flows of aircraft in a sector. One finding was that controllers were more likely to maneuver frequently updated aircraft than infrequently updated aircraft. This indicates that controllers would rather control aircraft with shorter control/surveillance loops, possibly because of less projection uncertainty that is accumulated during the shorter projection timespan requirement.

Summary:

The projection impact of future oceanic ATC technologies and procedures is both positive and potentially negative, and these impacts are summarized below:

- **States to be projected:** ADS, datalink, and the situation display may provide additional states that can be used in task projections that were not available before. Heuristics transforms caused by information/display system and task restriction mismatches can introduce additional error into the projection process.
- **Intent:** Traffic may be allowed to deviate from the structured oceanic routings reducing intent knowledge and negatively affecting controllers' ability to develop accurate dynamic estimates. This intent deficiency may be offset by increased intent information available through ADS or datalink.
- **Projection timespan:** Surveillance and communication improvements allow the projection timespan requirement to be reduced. Because of this, the requirement to minimize error growth through accurate dynamic estimates is also reduced.
- **Human/Automation projection responsibility:** Computer projection algorithms automate parts of the projection task creating systematic estimations of current states. These estimations can be erroneous, causing the controller to need to incorporate this possibility of automation error into their overall certainty of projection.

Supporting Future Oceanic Projection

The future oceanic system contains advances that provide a significant amount of support for the projection task, however there are areas in which additional support could be provided, including supporting mixed spatial/temporal operations and providing Real System to Display Space Transform transparency.

Supporting mixed spatial & temporal operations:

In the future oceanic environment, it is likely that a combination of temporal and spatial restrictions will need to be met to ensure separation in several dimensions. Spatial restrictions are optimal for ensuring separation in flexible crossing situations, but temporal restrictions are optimal for system performance and sequencing aircraft over busy fixes. Failing to provide matching information/display system and task restrictions can cause projection accuracy to suffer due to error introduction through rule-of-thumb heuristics that controllers use to cope with the mismatch. Providing both temporal support through flight strips and spatial support through the situation display appears to be only a transitory solution. One solution could be to integrate temporal information in a timeline format (e.g., NASA's Traffic Management Advisor) into the situation display to support both spatial and temporal awareness in an integrated tool.

Real System to Display Space Transform transparency:

Since the future oceanic ATC system will afford controllers the ability to rely on automated projection tools and state estimation tools, then it is important for controllers to adequately understand how the systems are performing the task. Flight data processors access multiple dynamic states to estimate the current aircraft position and conflict probability with higher accuracy than controller interpolation could estimate. However, due to stochastic nature of the environment, the automatic algorithms could produce a different estimate than occurs. Controllers must incorporate an understanding of the possible errors introduced by the algorithm into their overall projection error. To adequately incorporate the "automation error," a clear understanding of the Real System to Display Space Transform is required. Therefore, it is important to ensure that the functionality and assumptions of the estimation automation is clearly presented to the controller to ensure an appropriate Real System to Display Space Transform is created.

Oceanic Case Study Summary

In this case study, projection impacts from future oceanic technologies and procedures were considered using the Projection Process Model and Projection Error Concept framework. It was determined that the primary impacts occur in the areas of states to be projected, intent, projection timespan, and human/automation projection responsibility. Suggestions for improving projection in the future environment included supporting mixed spatial/temporal operations and clarifying the Real System to Display Space Transform in future projection and decision support tools used in aiding the cognitive projection process.

CHAPTER 7: Thesis Summary & Conclusions

Thesis Summary

The projection process is a critical cognitive process in supervisory control systems such as air traffic control because it enables a prediction of future system behavior to be created on which to base decisions about if and how to control the system. In the ATC system, system performance-enhancing procedures and technologies are being implemented that may affect the projection process of the controller. Chapter 1 discussed the role of projection in general supervisory control systems and in ATC as a specific example of a supervisory control system.

In Chapter 2 a literature review about what is known of the projection process was conducted. It was found that while there were general projection issues and biases that may apply to the air traffic controller's projection process, little projection research existed on the ATC domain or on a complex, applied and discretely updated system such as air traffic control.

Chapter 3 presented an introduction to the domains of TRACON and oceanic ATC. The tasks of the controllers on which this projection research focused were the separation & sequencing tasks. The remainder of this chapter discussed these tasks and the information/display system, task requirements, and control availability that applied in each of the domains for the projection task.

A General Projection Process Model was proposed in Chapter 4 that provided an information-processing description of the ATC projection process as observed in the site visits and inferred from training materials. This model describes the controller's role in the overall ATC system and how the contextual elements of the system interact to produce a task-relevant projection. An alternative means of analyzing the influence of the context on the projection process is through the Projection Error Concept. This concept was proposed as a means to describe the influence of projection timespan requirements and the task restrictions in the form of "error tolerance" on the quality required of the state mental model. The Information/Display System and the Task-based Projection Requirements were then described as primary influences on projection. Key aspects of the information/display system include observability of the state information and the update rate of the state information. What state to project and the error tolerance of that state are determined by the task-based projection requirements.

The ATC projection process itself was then described through the components of the State Mental Model and the Time into the Future. From the site visits, it was determined that the primary abstractions used in controller mental models included models based on observed history (e.g., constant velocity & constant acceleration models), models based on experience (e.g,. environmental wind models or pilot models), and models based on controller-pilot contracts (e.g., procedure or state clearances). The projection time into the future was based on system constraints such as control relay time, system dynamic behavior, and surveillance update time.

Several assumptions from the Projection Process Model and the Projection Error Concept were then probed in an experiment described in Chapter 5. The key hypotheses included: projection error growth slope would vary depending on the mental model of the aircraft and varying error tolerance would influence the quality of the state mental model used, affecting the growth in projection error. Using an ATC task of projecting the separation between two aircraft on an intersecting course, these hypotheses were tested. It was found that controllers appear to be able to incorporate higher level dynamics to accurately predict different aircraft dynamic behaviors, though they may still use a constant velocity prediction in some situations. There was a trend indicating that it is possible that error tolerance affects the quality of state mental model used in projecting the aircraft. It also appeared that increasing aircraft velocity changed the controller's velocity bias, reducing the underestimation. Thus, some key hypotheses of the Projection Process Model and Projection Error Concept were confirmed.

Chapter 6 then used the framework of the projection model and concept to analyze the implementation of the Continuous Descent Approach Procedure in the TRACON and the improvements in surveillance, communications and workstation through the ATOP program in the oceanic domain. Impacts on intent, projection timespan, and abstractions were identified in the TRACON case study, and model-based suggestions were made to increase tactical controllability and intent to increase the acceptability and efficiency of the procedure. In the oceanic domain, impacts on states to be projected, intent, projection timespan, and human/automation projection responsibility were identified. Suggestions for improved projection included support for mixed spatial/temporal operations and improved real system to display space transform transparency.

Conclusions

In this thesis a framework of complementary models of the projection process was proposed, based on site visits to various ATC facilities. This framework uniquely presents the influence of changing procedures, information/display systems, and communication systems on the ability of the controller to project the state of the system into the future. Even as the controller's role in ATC evolves, the requirement to project the system state will continue to exist into the future. By better understanding the projection process and its influences, better information support systems can be designed and procedures can be implemented more smoothly.

Projection is dependent on the controller's working mental model and time into the future. Controller's mental models are formed of dynamic abstractions based on observed history, controller-pilot contracts, and controller experience. Experimental data provided in this thesis suggests that controllers are able to incorporate a level of acceleration information into their projections, however with some difficulty. Constant velocity projections are also used in some situations. The minimum projection timespan requirement is based on information update rate, control relay time, and the system's dynamics.

The information/display system is important to projection because the lack of observability of states reduces the mental model quality due to the error introduced by inferred state estimates. Information updates provide an opportunity to reduce the projection error to the baseline measurement error.

The task is important to the projection, because it determines the states to be projected and it can determine how far into the future the projection is required.

The proposed Information Transform Concept provides a framework in which to understand how minimizing the transformation between display, problem space, and control space can simplify the controller's cognitive processing.

Application of the Projection Process Model and the Projection Error Concept to two ATC example cases illustrated the intent/controllability tradeoff in system and procedure design to maintain projection accuracy.

Projection is a critical process to the supervisory control system due to the need of the operator to predict future system behavior, allowing the controller adequate time and ability to control the system. From this analysis of the projection process, it appears that the information provided to the operator and the requirements on the projection are critical to determining how the projection is accomplished. The identification of the contextual information used in the projection process and the identification of key dynamic abstractions used in a task enable new procedures and technologies to be designed that take into consideration the operator's projection process.

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APPENDIX A: SEPARATION MINIMA

TRACON Lateral Separation Minima

Type of Minima	**Minima**	**Conditions**	**FAA 7110.65**
Basic TRACON lateral separation standards			
Broadband Radar or Full Digital Term Radar System	3 mi	Less than 40 mi from antenna	5-5-4
Wake turbulence separation (directly behind + less than 1000 ft below OR following IFR approach)	4 mi	Heavy behind heavy	5-5-4
	4 mi	Large/Heavy behind B757	5-5-4
	5 mi	Small behind B757	5-5-4
	5 mi	Small/Large behind Heavy	5-5-4
Wake turbulence sep. (when landing)	4 mi	Small behind Large	5-5-4
	6 mi	Small behind Heavy	5-5-4
	5 mi	Small behind B757	5-5-4
	2.5 nm	Final within 10 nm of landing on runway using a single sensor slant range mode, a/c w/in 40 mi of antenna, and: -lead a/c weight class = or < trailing a/c -H & B757 participate as trailing only -Rwy occupancy time < 50 sec -CTRDs operational & used for quick glance reference -turnoff pts visible from Tower	
Other TRACON separation standards			
From formation flights	Add 1 mi to separation minima		5-5-8
From obstructions	3 mi	Less than 40 mi from antenna	5-5-9
TRACON approach standards			
Approach	2 minutes or 5	All aircraft except Small behind Heavy;	6-7-5

interval minima	mi	Increase interval based upon: -relative speeds of a/c -distance between approach fix & airport -type of approach -weather conditions	
Exception	3 minutes or 6 mi	Small behind heavy	6-7-5
Parallel dependent approach	3 mi radar sep.		5-9-6
	1.5 mi radar diagonally	Aircraft on adjacent localizer/azimuth courses, and the runways are between 2500-4300 ft apart	5-9-6
	2 mi radar diagonally	Aircraft on adjacent localizer/azimuth courses, and the runways are between 4300-9000 ft apart	5-9-6
Parallel independent approach	3 mi radar		

Oceanic Separation Minima

Type of Minima	Minima	Conditions	CAA Ops. Manual
Oceanic Lateral Separation Minima			
	60 nm	Between aircraft certified MNPS; Within, above, or below MNPS airspace	961.1 A
	90 nm	Between aircraft operating outside MNPS airspace and at least 1 aircraft NOT MNPS certified	961.1 B
	120 nm	All other aircraft	961.1 C
Oceanic Vertical Separation Minima			
	1000 ft	Below FL 290	951.1 A
	1000 ft	From FL 290 to FL 410 inclusive within MNPS airspace at RVSM-designated flight levels	951.1 B
	2000 ft	At or above FL 290 outside RVSM-designated flight levels	951.1 C
Exception	4000 ft	At or above FL 450 between supersonic aircraft and between supersonic aircraft and any other aircraft	951.1 C
Oceanic Longitudinal Separation Minima			
Mach Number Technique			
Same direction when following aircraft is faster	For each 600 nm in distance between the entry and exit points of the area where the Mach number technique is used, add one minute for each 0.01 difference in Mach number for the two aircraft concerned		988.4
Automated conflict prediction	10 min	At oceanic exit point, where tracks diverge, or to mutually agreed limit	972.2
No automated conflict prediction	+1 min for each 0.01 difference in Mach number for each 600 nm segment in flight	At the common point between aircraft concerned	972.3
Supersonic Transport			
Same direction	10 min	Both aircraft in level flight at same Mach number or same type operating in cruise climb AND aircraft both reported over a common point and follow same track or diverging tracks until other sep. provided OR if not reported, it is possible to ensure	976.1 A

		appropriate time interval exists by radar or other approved means	
	15 min	Not covered in 976.1 A	976.1 B
Opposite direction (both reported over point)	10 min	Vertical separation maintained until 10 min prior & after aircraft estimated to have passed to have passed	976.2 A
(not reported)	15 min	Vertical separation maintained until 15 min prior & after aircraft estimated to have passed	976.2 B
Intersecting tracks (both reported over point	10 min	Vertical separation maintained until 10 min prior & after aircraft estimated to have passed	976.3 A
(not reported)	15 min	Vertical separation maintained until 15 min prior & after aircraft estimated to have passed	976.3 B
Turbojet Aircraft Operations (MNPS)			
Same direction	10 min	MNPS airspace; application of Mach Number Technique, where tracks diverge and 60 nm lateral sep achieved at or before reporting point or within 90 min of the time the 2nd aircraft passes the common point or within 600 nm of the common point (or whichever occurs first)	977.1 A
	9-5 min inclusive	Possible to ensure by radar or other means that interval exists & will exist at common point, provided aircraft following same or continuously diverging tracks until other sep. provided and preceding aircraft maintaining greater Mach number than following aircraft: -9 min if preceding aircraft is Mach 0.02 faster than the following aircraft -8 min if preceding aircraft is Mach 0.03 faster than the following aircraft -7 min if preceding aircraft is Mach 0.04 faster than the following aircraft -6 min if preceding aircraft is Mach 0.05 faster than the following aircraft -5 min if preceding aircraft is Mach 0.06 faster than the following aircraft	977.1 B
	15 min	MNPS certified and in MNPS airspace but not covered in 977.1 A or B	977.1 C
Opposite direction (both	10 min	Vertical separation maintained until 10 min prior & after aircraft estimated to	977.2 A

reported)		have passed	
(not reported)	15 min	Vertical separation maintained until 15 min prior & after aircraft estimated to have passed	977.2 B
Intersecting tracks (both reported)	10 min	Vertical separation maintained until 10 min prior & after aircraft estimated to have passed	977.3 A
(not reported)	15 min	Vertical separation maintained until 15 min prior & after aircraft estimated to have passed	977.3 B
Turbojet Aircraft Operations (Non-MNPS)			
Same Direction	15 min	Mach Number Technique applied; both reported & continuing along same or diverging track until other sep. applied or if not reported interval verified by other means	978.1A
	10 min	Ensure by radar or other means that time interval exists & will exit at common point, provided preceding aircraft is at least Mach 0.03 faster than following aircraft	978.1 B
	5 min	Ensure by radar or other means that time interval exists & will exit at common point, provided preceding aircraft is at least Mach 0.06 faster than following aircraft	978.1 B
	20 min	Turbojet aircraft not covered by 978.1 A or B	978.1 C
	30 min	Non-turbojet aircraft	978.1 D
Opposite Direction	15 min	Vertical separation maintained until 15 min prior & after aircraft estimated to have passed	978.2 A
	20 min	Vertical separation maintained until 20 min prior & after aircraft estimated to have passed	978.2 B
Intersecting Tracks (both reported)	15 min	Vertical separation maintained until 15 min prior & after aircraft estimated to have passed	978.3 A
(not reported)	20 min	Vertical separation maintained until 20 min prior & after aircraft estimated to have passed	978.3 B
Sub-sonic Aircraft other than Turbojet Aircraft			
	30 min	Operating wholly or partly in or outside MNPS airspace	979.1

Table 7.1: Oceanic separation minima (CAA Operations Manual).

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APPENDIX B

HUMAN FACTORS IMPLICATIONS OF CONTINUOUS DESCENT APPROACH PROCEDURES FOR NOISE ABATEMENT

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Abstract

Continuous Descent Approach (CDA) procedures can be effective at reducing aircraft noise in the vicinity of airports. The air traffic control human factors implications of transitioning from conventional to CDA procedures are addressed in this paper. A cognitive difference analysis revealed the impacts on intent, controllability and structure-based abstractions in the lateral, vertical and speed domains. An experiment is presented that probes the cognitive implications of changing speed profiles during the approach, which was one of the key differences between the procedures identified in the cognitive difference analysis. Based on the results, recommendations were made for CDA procedure designers to standardize deceleration profiles, design procedures to be non-interacting and to consider allocating separation authority to the pilot with a view to easing transition and controller acceptance.

Introduction

Growth in the number of air transportation operations is likely to be restricted unless the number of people significantly affected by aircraft noise is limited (US DOT, 2000; UK DETR, 2003). Although technological advances have made today's aircraft significantly quieter than older generations, modified operating procedures are likely to be required in order to achieve noise targets in the future. One of the most promising operational techniques for noise abatement during approach flight phases involves Continuous Descent Approach (CDA) procedures that keep aircraft higher and at lower thrust levels for longer than conventional techniques. This can reduce noise impacts by a noticeable amount in some locations. For example, flight trials in the US have demonstrated that peak noise from a Boeing 767 at a location 14 nmi from the airport was 67 dBA with a CDA compared to 73 dBA with a conventional approach procedure (Clarke et al., 2004).

However, the use of CDAs can modify the way aircraft behave during approach operations which in turn can affect how they are to be managed by air traffic controllers. This paper, therefore, focuses on the human factors implications of the introduction of CDA noise abatement procedures.

Continuous Descent Approaches

CDA Concept

Conventional approach procedures typically employ periods of constant altitude and speed. These constant segments simplify the air traffic control (ATC) tasks of spacing and sequencing traffic because they provide periods of well-defined vertical and speed (i.e. longitudinal axis) behavior during approach operations. When coupled to the use of tactical heading vectors to control an aircraft's lateral path, the air traffic controller can the optimize traffic flow onto the final approach path in order to make best use of the runway capacity. However, the steps in the altitude profile lead to aircraft spending periods of time flying level at low altitude near the airport and requires significant thrust input at each of the transitions to level altitude in order to arrest the descent. The combination of low altitude and frequent thrust transients leads to significant noise impacts on the ground. By contrast, a Continuous Descent Approach aims to eliminate the level altitude segments and their associated thrust transients at low altitude. The aircraft are kept higher and at lower thrust for longer prior to the final approach segment (such as defined by the instrument landing system (ILS) guidance path), thereby reducing noise exposure on the ground. A comparison of altitude profiles during a typical conventional procedure and a sample CDA is illustrated in Figure 1.1.

In addition to the changes in the altitude profile, the use of CDAs can also affect the way aircraft behave in the lateral and speed axes relative to the conventional procedure. This depends on the type of CDA being flown, which can be broadly classified into two types: Vectored CDAs and RNAV (Area Navigation) CDAs, each of which are discussed in the following sections.

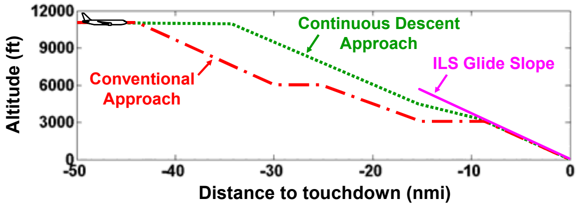

Figure 1.1: Sample Conventional vs. Continuous Descent Approach Procedures.

Vectored CDAs

A Vectored CDA (also sometimes referred to as a "Basic" or B-CDA) is illustrated in Figure 1.2. The air traffic controllers retain the lateral control flexibility associated with conventional heading vectors. But unlike conventional step-down approaches, the controller also estimates the track distance to be flown by an aircraft given the chosen vectored path and issues these estimates to flight crew at various points during the approach (typically 30 nmi and 20 nmi to touchdown). Flight crew use the track distance estimates to determine the appropriate descent rate for their aircraft in order to achieve a CDA, either with rules of thumb or flight manual charts. Tactical speed commands are still issued by the controller as in a conventional procedure, but the resulting aircraft speed behaviors could be different from a conventional procedure because a CDA is being flown.

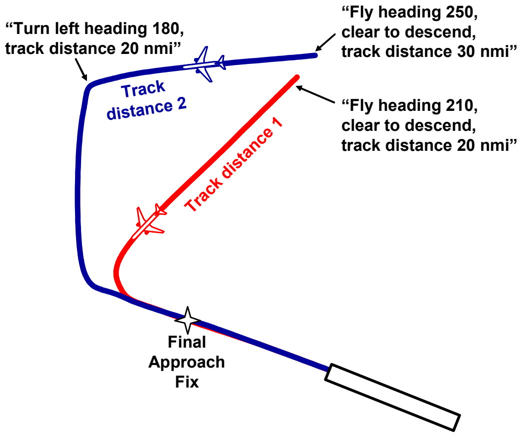

Figure 1.2: Lateral View of Vectored CDA Concept.

The Vectored CDA can be used by most aircraft types at many airports, so has found widespread use. For example, they have been used during night-time operations at London airports for many years and can reduce noise by up to 5 dBA at 10-25 nmi from touchdown (UK DETR, 2000). However, experience has suggested that track distance estimates can be difficult to determine accurately (Kershaw, et al., 2000), especially in highly dynamic situations. This can result in aircraft needing to level off if the track distance is under-estimated (making it similar to a conventional procedure) or needing more rapid descent rates than expected towards the end of procedure if the distance is over-estimated (leading to a rushed approach or need for a go-around). In either case, the noise benefits of the Vectored CDA are reduced unless track distances can be determined accurately.

RNAV CDAs

A more advanced type of CDA involves a pre-defined trajectory of a series of waypoints with altitude and/or speed targets to define a specific lateral, vertical and speed profile throughout the approach. These can be programmed into an aircraft's area navigation (RNAV) equipment such as the Flight Management System (FMS). This type of RNAV CDA is illustrated in Figure 1.3.

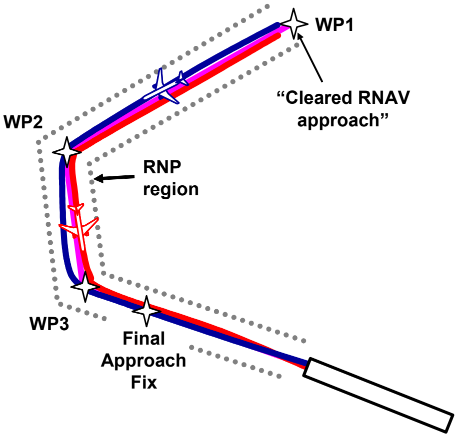

Figure 1.3: Lateral View of RNAV CDA Concept.

In this type of approach, track distances can be determined accurately because the waypoint locations are known. Descent rates can then be optimized in the procedure design or by the FMS such that level segments can often be eliminated entirely, improving CDA compliance and maximizing the associated environmental benefits. Additionally, since the lateral path is predetermined, all the aircraft flying the procedure can be constrained to a narrow path whose width is determined by the Required Navigation

Performance (RNP) requirement level of the procedure. This enables noise exposure to be limited to these lateral regions, potentially avoiding highly populated or sensitive regions. However, because of the pre-determined nature of the trajectories, the procedure must be designed to be robust to a wide range of aircraft performance and environmental conditions (especially wind).

Control Implications of CDAs

Conventional, Vectored CDA and RNAV CDA procedures have different implications for the way the aircraft are controlled in the lateral, vertical and speed domains, as summarized in Table 2.

Table 2: Control Implications of Procedures.

Procedure	**Lateral Path Definition**	**Vertical Path Definition**	**Speed Definition**
Conven-tional	ATC heading vectors	ATC altitude clearances	ATC speed clearances
Vectored CDA*	ATC heading vectors	Pilot calculation or chart in flight manual *(after ATC descent clearance)*	ATC speed clearances
RNAV CDA*	FMS waypoint locations *(after ATC procedure clearance)*	FMS vertical targets *(after ATC procedure clearance)*	FMS speed targets *(after ATC procedure clearance)*

*Note: ATC can choose to abort a CDA at any time and revert to a conventional procedure.

In a conventional procedure, ATC has full path flexibility in all domains for each aircraft. In the Vectored CDA, the controller has tactical flexibility all axes is defined by the procedure after clearance to fly it has been issued by ATC.over the lateral and speed domains while the specific vertical path is determined by the flight crew after the descent has been cleared and track distance estimates given by ATC. In the RNAV CDA, path definition in

In all types, differences in behavior between aircraft can result from varying environmental conditions. However, additional differences can be introduced with CDAs due to different aircraft dynamics during the descent and, in the case of the RNAV CDA, differing FMS logics. These differences can lead to ATC using larger separations between aircraft flying CDA procedures compared to conventional approaches, affecting runway throughput and therefore limiting the use of the procedures during peak demand periods. The human factors implications of the differences outlined above must be carefully considered so that the environmental benefits associated with the use of CDA procedures can be gained whenever possible without unduly affecting controller workload and performance.

Controller Tasks During Approach Operations

A CDA approach can involve en route, terminal radar approach control (TRACON) and tower controllers depending on the altitude at which the procedure starts. For the purposes of this paper, only the TRACON approach controller will be considered, because they are most directly affected by CDA procedure transitions. To better understand controller tasks on approach, operations were observed during site visits to approach facilities at Boston, New York, & Manchester, NH in the US and Reykjavik in Iceland.

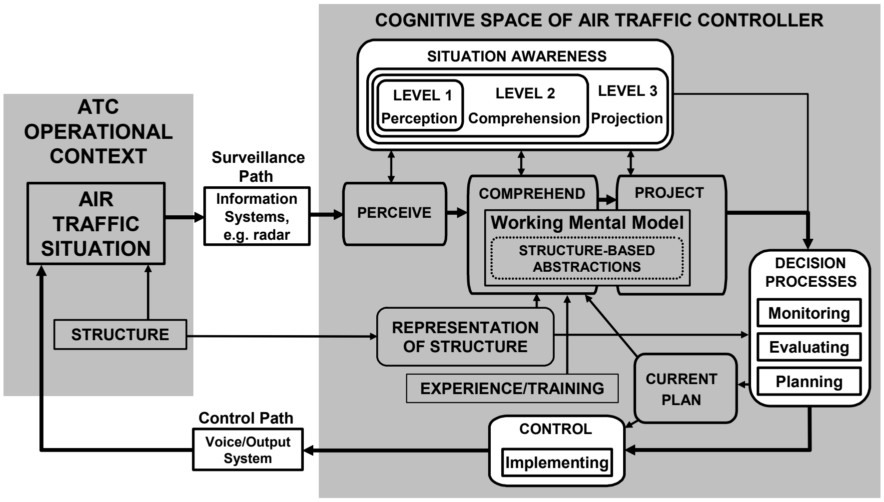

Figure 1.5: ATC Process Model.

An ATC Process Model was used to represent the controller's cognitive processes and their interaction with the environment, as shown in Figure 1.5. This model integrates Endsley's (1995) Situation Awareness model, Pawlak's (1996) Decision Process model and Histon & Hansman's (2002) concept of "structure." Reynolds, Histon, Davison & Hansman (2001) provide a discussion of the model development and validation in more detail. The following subsections discuss the primary system elements of the model with respect to the final approach controller.

Information System

The approach controller has several sources of information available to him or her. These include the radar display, which provides aircraft state data, and Very High Frequency (VHF) radio communications, providing pilot-sourced information.

Another key input to the approach controller's information processing is the "structure" of the approach environment. Structure is defined as a set of constraints (either physical or human-imposed) that limits the evolution of the dynamics of the system. Examples of physical structure include runways, navigation aids, terrain or obstructions. Examples of human-imposed structure include airspace boundaries, procedures and standard flight levels. In a conventional approach, the ILS beam, Standard Terminal Arrival Route (STAR) and ATC Standard Operating Procedures (SOPs) are critical elements of structure.

Each of these examples of structure establishes constraints such that, if violated, either physical or system laws will have been broken. The structure is a pilot-controller shared information set, and therefore the controller can expect the aircraft to remain within the constraints under normal circumstances.

Situation Awareness Processes

As the approach controller observes the various inputs from the environment, these data are transformed into situation-relevant information through a set of cognitive processes that contribute to Endsley's (1995) concept of "situation awareness". Data from the information sources are first *Perceived* through auditory or visual modalities. This information is then *Comprehended* and *Projected* into the future.

Figure 1.6 depicts an expansion of the Comprehension process. In this process, information from the display is filtered and integrated with information from training and experience to develop an understanding of the current air traffic situation.

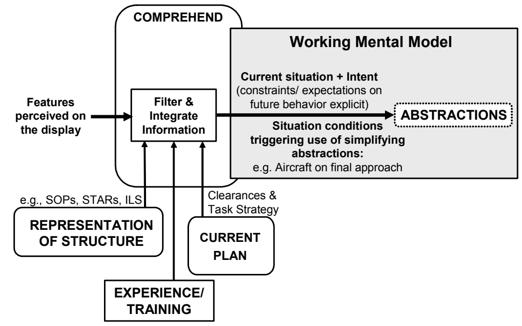

Figure 1.6: Comprehension Process.

Information about structure and clearances issued, which are indicated in the figure, contribute to this formation by partially specifying the aircraft's intent. Intent, in this context, is defined as a controller-pilot shared plan of the aircraft's trajectory into the future. Clearances are a contract between the controller and the pilot about the aircraft's future trajectory. Often, an aircraft is cleared to proceed using a particular procedure (e.g., "Cleared ILS 4R"). This clearance indicates that the controller and pilot agree on a precise lateral and vertical flight path limited by the structure imposed by the ILS localizer and glideslope. Other clearances may only specify a desired state until further commands are issued (e.g., "Reduce speed to 240 kts."). This allows the controller to impose control on the aircraft in situations in which intent is not defined or is unclear. Knowledge of the current situation and the limitations of evolution allow the controller to apply dynamic abstractions for use in the third situation awareness level, namely that of the projection process into the future.

The projection process is particularly important to controllers in their aircraft separation assurance role in the presence of time delays inherent in the ATC surveillance/control loop. The comprehension stage provides current situation information and accesses dynamic abstractions that form the working mental model. In the projection stage, the current situation is propagated forward in time using the abstractions in the working mental model.

In the conventional approach, lateral and vertical trajectories are based on the general flow patterns defined in the STAR & SOPs. In order to properly space and sequence traffic, the longitudinal axis is the primary control dimension and is the main dimension along which tactical projection is required. Control is imposed on the speed dimension through speed state controls (e.g., "Decelerate to 240 kts."), and therefore the speed profile is delineated into periods of constant velocity combined with short periods of speed transition. Thus, apart from these short transition periods, a constant velocity longitudinal extrapolation is an appropriate mechanism. Constant velocity extrapolation is a projection based on past position information in which the controller uses estimated distance traveled over the most recent update to propagate the aircraft position over the same distance at the next update.

The constant velocity extrapolation requirement is consistent with the controller's tendency to propagate dynamics linearly into the future. Gottsdanker (1952) reported on a task in which participants were required to project two intersecting objects. Even when the objects were accelerating or decelerating, the participants projected the objects with constant velocity. Wagenaar & Timmers (1979) confirmed this when asking participants to propagate an exponential function, and participants would underestimate the growth by substituting a linear function.

Whether the information used in extrapolation is sufficient for the separation task depends on whether an adequate rate of change estimate can be established to capture the aircraft dynamics to the precision required for the evaluation against separation standards.

As projection extends into the future, uncertainty increases, requiring different projection techniques. An adapted version of Vigeant-Langlois & Hansman's (2004) uncertainty framework is shown in Figure 1.7. Over a very short projection time (e.g. less than one update cycle), the aircraft can be assumed to be in the same location on the radar screen, which is the persistence region in the figure.

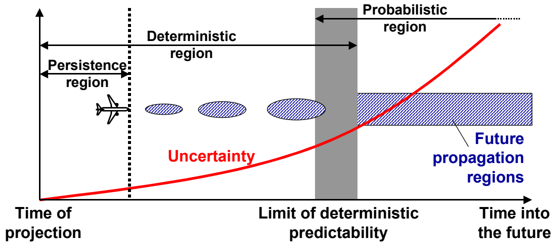

Figure 1.7: Effect of Time on Longitudinal Projection Process. (Adapted from Vigeant-Langlois & Hansman, 2004)

Over slightly longer times (e.g. a few position updates into the future), a deterministic projection can be made using cognitive models of the dynamic behavior of the elements in the situation compiled into a working mental model. The constant velocity extrapolation is an example of a simple dynamic model.

At some point in the future, deterministic models break down, and alternatively, stochastic models are used. Intent plays an important role in determining the limit of deterministic predictability. Knowledge of intent constrains the future aircraft trajectory, extending the time into the future that a deterministic projection can be made (pushing the limit of deterministic probability in Figure to the right). The periods of non-transition in the longitudinal structure in the conventional approach allow the constant velocity structure-based abstraction to be an accurate projection further into the future. In Figure , the example shows a longitudinal projection constrained by lateral intent knowledge, however different limits of deterministic predictability can be present in different axes, influenced by the intent information in that axis.

Decision Processes

Based on the controller's projection of the situation dynamics, the controller performs a conformance monitoring task to determine whether the observed state is consistent with his or her "current plan," which is an internal cognitive state. This is the controller's time-dependent schedule of events and commands to be implemented as well as the resulting situation evolution and aircraft trajectories that will ensure that the air traffic situation evolves in an efficient and conflict-free manner. If the projection of the situation does not match the plan, the controller evaluates whether the situation evolution meets the task constraints. If the projection is found to be unacceptable, the controller then plans an action or set of actions on the system that will return the situation behavior within acceptable bounds, modifying the "current plan".

Developing a plan that satisfies all of the constraints that controllers must meet can be very complicated; however structure allows the simplification of the evaluation and planning tasks. Procedures like the approach SOPs are specifically constructed to ensure that separation constraints are met between highly interacting traffic flows. If the default current plan is to follow the SOP and the STAR on approach, the sequence of descents and heading vectors is already established depending on the type of aircraft.

3.2 Control

Once the current plan has been created, the controller must then implement the actions of this plan. The primary means of ATC plan execution is through VHF radio communications to the pilot. In ATC there is a fundamental limit on the controller's ability to respond to the system in a timely fashion due to the system cycle time (e.g. imposed by surveillance and communication delays) and the controller's dependence on the pilot to execute commands quickly and accurately.

In the TRACON environment, there are several types of control actions that the controller can implement. A discrete control command signals ATC authorization to begin a standard or approved procedure, e.g. "Cleared ILS 4L". The controller can execute fine control over the aircraft by using state control clearances such as "Fly heading 270" or "Descend to 4000 ft." Approach controllers can also provide state constraints to the aircraft, such as "Descend to (altitude) by (waypoint)" or "Cross (waypoint) at (time)."

By having developed expert models of the aircraft dynamics, controllers can also achieve a desired state in one axis while controlling another axis through an indirect control command. An example of this is meeting a time-over-fix requirement through speed vector commands.

Control provides another means by which future aircraft behavior uncertainty can be reduced. If a controller is projecting future aircraft state in the probabilistic region in Figure , a state constraint or command can be issued to clarify intent of the aircraft and maximize the accuracy of the projection.

Cognitive Difference Analysis

Using the ATC Process Model as a framework for understanding the controller's task during a conventional approach, cognitive differences between the conventional approach and the Vectored and RNAV CDA approaches were identified. The three cognitive areas in which the CDA procedures most significantly differ from the conventional approach are *Intent*, *Controllability*, and *Structure-Based Abstractions*. Each of these areas of potential cognitive dissonance is discussed in the sections below.

Intent

In the conventional approach procedure, aircraft generally follow standardized flows outlined in the Standard Terminal Arrival Routes (STARs) or ATC facility Standard Operating Procedures (SOPs), although the specific trajectory followed depends on the tactical vectors and speed commands employed. These procedures describe the expected behavior of the aircraft in lateral, vertical, and speed dimensions that is shared with the controller. They provide the structural base patterns that support the controller's tasks of perceiving, comprehending, projecting, and monitoring. As in Figure 1., intent information (in the form of structure and clearances) also allows access to dynamic abstractions, simplifying the projection process. The procedures simplify the controller's tasks of evaluation and planning because they are specifically designed to separate the major traffic flows.

The Vectored CDA procedure modifies the SOP and STAR structure in at least the vertical dimension. Because the Vectored CDA procedure requires the pilots to plan the vertical trajectory based upon aircraft type and reported track distance from the runway, each individual aircraft may exhibit a different descent profile. Once vertical stable periods are removed, the aircraft's longitudinal behavior may be complicated due to vertical transition interactions, making the constant velocity abstraction unreliable. Instead, pair-wise comparisons of separation between aircraft must be projected to assure required separation, compounding ATC workload. If separation becomes a problem, the controller will also be constrained to ensuring that any trajectory modifications are conflict-free in the lateral and speed dimensions when planning due to the CDA vertical structure requirements.

The RNAV procedure is structured in all three dimensions through an FMS profile to optimize descent rate and meet altitude and airspeed constraints. Although the base procedure will be known by both ATC and the flight crew, detailed information about how the aircraft will execute the procedure (especially away from the procedure target points) is not available to the controller with the current ATC technologies. Depending on how the procedure is created, it can be consistent with the non-interacting flows of the SOPs and the STARs, allowing the controller to rely on the safety of non-interacting flows to compensate for the constant velocity abstraction unreliability. Because of the non-interacting design, the controller's evaluation and planning process is similar in difficulty to the conventional procedure. If the procedure is inconsistent with the SOPs and STARs, the cognitive difficulty would increase unless the controllers could develop an effective mental model of the new pattern.

Controllability

As previously discussed, the conventional approach allows a variety of control actions to be performed on the traffic flow including discrete control, state control and constraint-based control. The controllers have the ability to alter the aircraft's lateral, vertical, and speed trajectories.

In the Vectored CDA, the controller retains full path determination in the lateral and speed dimensions, but passes vertical path determination to the flight crew, who establish a CDA-compliant descent rate using the controller-determined track distance estimate. The controller is able to use the track distance determination to exert indirect control over the vertical dimension to compensate for the direct control lost in the CDA. This indirect control was used by the controllers to ensure a conservative (safe) altitude profile in the analyses by Kershaw, *et al.* (2000).

In the RNAV procedure, tactical controllability is almost completely removed from the controller, preventing fine control over aircraft behavior. Controllers are only given discrete control over whether an aircraft is cleared to fly the RNAV CDA before the pilot executes it on the aircraft, typically through the FMS. However, if controllers determine that action should be taken to prevent a conflict or maintain separation minima, the controller can remove the aircraft from the RNAV approach and resume a non-CDA conventional approach or command the aircraft to perform a go-around procedure.

The controller's ability to clarify aircraft intent through control commands appears to be diminished in each of the CDA procedures, as indicated in Table 2. Similar to the structure issue, controllers may be unable to effectively reduce the uncertainty of projection in the probabilistic regime.

Structure-Based Abstractions

Controllers using conventional approach procedures are able to simplify their projection processes through the use of non-transition periods, especially constant velocity, to maximize the accuracy of their extrapolations. The use of non-transition velocity periods of flight were used to establish a pattern of position change of the radar blips and project using a cognitive pattern-matching mechanism. In both CDA procedures, vertical non-transition periods are lost due to the requirement of continuous descent for noise purposes. Thus, the vertical projection process could be made more difficult by the lack of non-transitional periods. The interactions between the vertical profile and speed in the Vectored CDA, and the removal of ATC-controlled constant velocity periods in the RNAV CDA, also makes the longitudinal projection process more difficult.

Therefore, simple structure-based abstractions of constant velocity and constant altitude periods appear to be reduced or removed in the CDA procedures. It is unclear whether controllers are able to develop new structure-based abstractions of deceleration patterns to aid them in their projection at a level of accuracy appropriate to the task being undertaken. In order to better understand the ability of the controllers to develop new structure-based abstractions based upon deceleration patterns, an experiment was performed to investigate further the constant velocity structure-based abstraction.

Experimental Investigation of Benefits to Constant Velocity Structure

In the Cognitive Difference Analysis, periods of constant speed were hypothesized as being a key structure-based abstraction mechanism for improved projection performance. An experiment was performed to test this hypothesis by comparing the projection accuracy of aircraft separation tasks involving constant velocity and decelerating aircraft combinations.

Participants

Eight French student air traffic controllers with an average of 1.25 years experience participated in this experiment. Five of the controllers were two months from being certified as approach controllers and 3 were in their final stages of training to be en route controllers. Because these and most student controllers are all trained to perform a generalizable radar separation technique, one may assume that such a technique that is critical in performing the experiment has been taught to most controller populations.

Experimental Task

Participants were asked to view a low-fidelity PC-based simulation of an approach scenario with pairs of aircraft proceeding down a straight path, as depicted in Figure 1.8. Controllers were shown the position of the aircraft on the flight path as well as the current ground speed of the aircraft, which varied between 300 and 150 kts. The update rate of the position mimicked the TRACON surveillance radar rate of 4.8 sec. At three points along the path, controllers were asked to make a projection of the aircraft pair's separation at the end of the flight path by mouse-clicking the location of the trailing aircraft when the leading aircraft passed the runway threshold. The controllers were asked to view 48 scenarios. These scenarios were randomly ordered, blocked into groups of 12 and then the blocks were counterbalanced across participants.

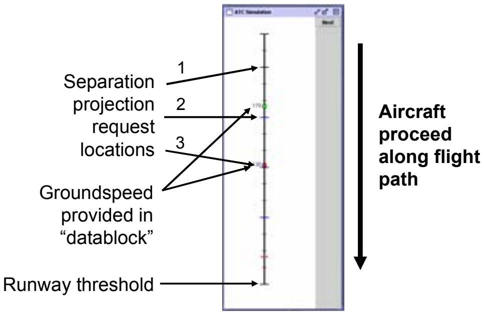

Figure 1.8: Experimental Display.

Independent & Dependent Variables

The speed profiles of the aircraft pair were varied in this experiment. The aircraft were either both decelerating, both proceeding at constant speed, or one aircraft was decelerating and the other was proceeding at constant speed. The latter scenario will be termed a "mixed" profile scenario. Deceleration profiles were all linear between a start and end speed.

The end speed of the aircraft was also varied in this experiment. Typical end speeds were 150 or 160 kts, representative of an aircraft on final approach. The exception was in the decelerating/constant case, in which in order to be able to observe the separation change of the aircraft at all three projection points, the end speeds of the trailing aircraft in this scenario were required to be slightly higher at 180-190 kts.

Depending on the relative aircraft speeds in each scenario, the separation of the aircraft pair could either be decreasing along the flight path (a "closing" case), increasing along the flight path (an "opening" case), or the speeds could be the same (in the both constant speed cases). Twenty-five percent of the scenarios involved both constant, 25% involved both decelerating, 25% involved an opening case, and 25% involved a closing case.

Final separation of the aircraft was counterbalanced across the scenarios, ranging between 1-6 nmi. The exception, again, was in the decelerating/constant scenarios in which the scenario dynamics required between 10-12 nmi separation at the threshold to allow observability during the projection periods.

Accuracy of the projection and improvement of the accuracy over time were measured in this experiment. Accuracy of the projection was defined as the projected estimate (recorded from the simulation at each projection time) minus the actual separation when the leading aircraft passed the threshold. Accuracy over time was measured by comparing the differences over the three points of projection requested in a scenario.

Questionnaires provided at the end of the experiment elicited subjective responses to the question: "What was your strategy for predicting separation in this task?"

Results

Projection accuracy analysis for the third projection was performed because controllers were given the longest time to observe the aircraft behaviors until the projection was made. Figure 1.9 depicts the projection accuracy results for this analysis. The difference between the projected and actual separation is depicted as a function of the relative speeds of the aircraft pair for each of the speed profiles. Three speed profiles were biased toward negative difference values, i.e. towards projected estimations of less separation than was actually present. This indicated that the controllers tended to be conservative (safe) in their separation projections. In the decelerating/constant profile, the "risky" behavior resulted from the fact that the final separations were significantly larger (at 10-12 nmi) than the other scenarios (at 1-6 nmi) due to the dynamics in that scenario. No data were available for the decelerating/constant "equal" and "opening" cases due to the dynamic constraints of the scenario.

There was no significant difference between the both constant and both decelerating cases, however there was a significant difference between the both decelerating case and the constant/decelerating scenario (closing case: t=2.021, p<.05, equal case: t=1.279, p<.15). The average difference between the constant/decelerating scenario was significantly more "conservative" possibly due to the controller's inability to predict the mixed scenario accurately, therefore erring the estimation on the conservative side. No significant difference was found between the closing and opening cases of the constant/decelerating scenario.

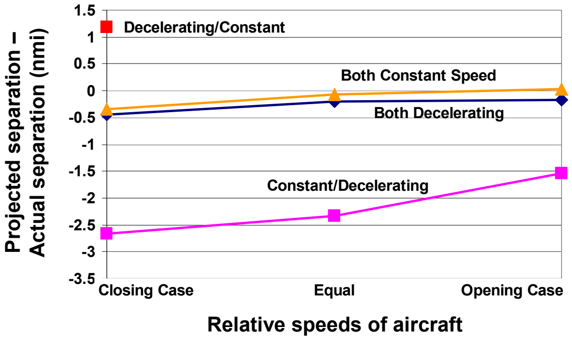

Figure 1.9: Projection Accuracy Results (3rd Projection Time).

Analyzing projection accuracy over the three projection times, as depicted in Figure 1.10, the data suggest that projection accuracy marginally improved over time in the mixed profile scenarios. Accuracy was lower in the decelerating/constant profile scenarios at projection 1 (t=3.774, p<.0005) and projection 2 (t=1.973, p<.05). No improvement was apparent in the both decelerating or both constant speed scenarios. In a similar situation as the previous analysis, the decelerating/constant case resulted in "riskier" separation projections due to the significantly larger final relative separation over the other speed profiles. No data were available for the constant/decelerating projection 1 due to the scenario dynamics.

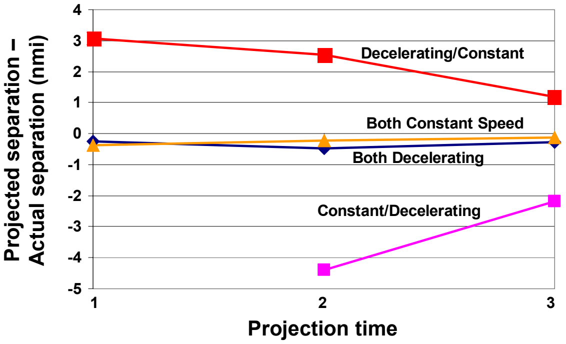

Figure 1.10: Projection Accuracy Over Time.

The subjective results from the questionnaire indicated that 6 of the 8 participants described sampling the separation at two different points, then estimating a final separation based upon the rate of change of the relative separation. One participant described imagining a speed vector, and one claimed it was a "feeling" not a strategy.

Significance of Results

Projection accuracy of the mixed profile scenarios was significantly worse than when projecting either both constant or both decelerating aircraft. There was no difference in accuracy comparing both decelerating and both constant projections. These results suggest that if there is a structure-based abstraction that allows higher extrapolation accuracy of constant speed, the same or a similar abstraction is created and used when projecting both decelerating aircraft. These results also support the findings by Gottsdanker (1952) and Wagenaar & Timmers (1979) that a constant velocity projection is made even when the system is exhibiting non-linear dynamics.

One possible explanation of the structure-based abstraction involves the key variable being projected in this experiment, namely relative separation. This is consistent with the ATC Cognitive Process Model in that the task strategy drives the state that the controller projects. Figure 1.11 shows that the relative separation of both constant speed aircraft is constant. The relative separation of both decelerating aircraft in this experiment approximates a linear function. The relative separation in the mixed profile scenario is a non-linear function. It was established from the subjective reports that the controllers' task strategy was developing a dynamic model of changing relative separation. Therefore, it appears that they were more able to internalize the constant and linearly changing relative separation over the non-linear change in relative separation.

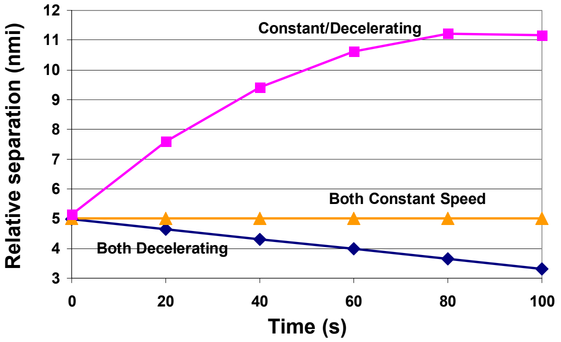

Figure 1.11: Relative Aircraft Separation.

A limitation of this experiment is that only linear deceleration profiles are used, and this hypothesis should be confirmed using non-linear deceleration profiles for purposes of realism. However, if controllers are just as easily able to internalize the dynamics of a both decelerating aircraft scenario (assuming standardized decelerating profiles) as they are a both constant aircraft scenario, then the implications for CDA procedure design are great.

CDA Design Guidance & Conclusions

Based upon the findings from the Cognitive Difference Analysis and the Experimental Investigation, recommendations and considerations for the design of CDA procedures can be provided to minimize the cognitive difficulties in transition.

A tradeoff exists between the design of CDA procedures to minimize the impact of noise on the communities and providing enough flexibility to the air traffic controller who is responsible for the safety and efficiency of the traffic being controlled. Standardization of CDA deceleration profiles may be able to take advantage of several of the adaptation mechanisms that the controllers have developed. As discovered in the experimental investigation, standardization of deceleration profiles would allow the use of structure-based cognitive abstractions. These abstractions are similar in performance to constant velocity structure-based abstractions which are currently used to simplify the working mental model used in controllers' future longitudinal state projection. This simplifies the projection because the intent is explicit, reducing the uncertainty and offsetting the reduced speed control that is currently used to manage longitudinal intent. However, further research needs to be performed using realistic deceleration profiles (as opposed to linear profiles) and to determine if, given different aircraft types and environmental factors, standardized deceleration profiles are possible.

It is also useful to simplify the controller's evaluation process by designing the standardized CDA procedures to be non-interacting across merging traffic flows. As long as the aircraft are conforming to the expected procedure laterally, vertically, and longitudinally, the controller can be assured that separation is met because the procedures were designed in that way.

Another issue to address in CDA procedure design involves the level of responsibility that is delegated to the controller. In procedures that require precise trajectories and many constraints, it may be best to delegate fine control of the trajectory and tactical separation assurance to the pilot. This delegation best suits the situation due to the surveillance and command delays inherent in the control loop and the location of precise intent knowledge in the FMS-driven procedures.

In conclusion, CDA procedures provide a near-term improvement to the problem of noise in the terminal environment. By designing the procedures to compensate for removal of critical structure-based abstractions, system performance is enhanced while minimizing transition issues with the controllers.

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Key Words

Noise abatement procedures, continuous descent approach, human factors, projection, prediction, extrapolation, situation awareness.

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