HUMAN-CENTERED SYSTEMS ANALYSIS OF MIXED EQUIPAGE IN OCEANIC AIR TRAFFIC CONTROL

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BY

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ABSTRACT

Technical capabilities for improved communication, surveillance, and navigation (CNS) over the oceans are currently available. However, all aircraft operators will not equip simultaneously because of the high costs required. Consequently, as these CNS systems are integrated into oceanic air transportation architecture, the controller will have to manage the current low frequency surveillance and communication paths in parallel with future enhanced CNS. The cognitive effects of the mixed equipage environment were studied through field studies and experimental analysis.

Field studies at New York Center, Oakland Center, and Reykjavik Center in Iceland were conducted to identify human-centered systems issues with the emerging mixed equipage environment. Findings show that the integration of varying communication latencies influences controller planning. The fusion of multiple surveillance sources and the application of varying separation standards based on equipage was found to limit the cognitive processes of the controller. These limitations may constrain the controller from providing full efficiency benefits to aircraft equipped with the highest capabilities, which would reduce the incentives for equipping.

Experimental analysis was conducted to further study the integration of high and low frequency surveillance and the use of varying separation standards. Results show that workload increases and situation awareness degrades in the mixed surveillance environment, compared to segregated operations. The results also demonstrate that efficiency benefits attained by equipped aircraft are in fact limited in the mixed equipage environment.

Implications for the design of air traffic control systems and procedures are also discussed. Strategies for the segregation of airspace based on equipage are suggested to alleviate controller cognitive limitations and ensure incentives for equipped aircraft. Options are given for the display of equipage information in the future environment.

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Contents

Chapter 1

Introduction

Over the oceans, communication, navigation, and surveillance (CNS) is limited because aircraft are beyond line-of-sight range and there are limited tools to handle them. However, the means for improved CNS through satellite-based technologies is emerging. These technologies are dependent on onboard avionics capabilities. The aircraft capabilities for the three CNS components are defined as equipage. When differences in CNS capabilities require the controller to treat the aircraft differently, the situation is termed mixed equipage.

The CNS components are critical to air traffic control (ATC). Controller intervention in an air traffic situation is enabled through surveillance and communication. Surveillance allows the ground controller to monitor the environment and communication permits him/her to modify the air traffic situation. The navigation system defines the precision of the route that can be flown by an aircraft. A mixed equipage problem arises because controller tasks for monitoring and issuing commands is significantly different for aircraft with a heterogeneity in surveillance and communication equipage. Also, differences in navigation equipment require varying separation minima, based on the uncertainty in the aircraft route.

Opportunities for improved CNS are surfacing. The ATC system is being driven forward by these opportunities, the demand for ATC improvements due to airspace congestion, a growing focus on greater fuel efficiency, and a continued demand for safety. However, there are inhibitors that limit many aircraft operators from equipping with the necessary onboard avionics equipage. The primary inhibitor is the cost for equipping the current fleet. Costs include the initial costs incurred from the purchase of the avionics equipment, the installation and the certification of the equipage, as well as the recurring costs of crew training and maintaining the equipment [1]. The other limiting factors are the time required to remove the aircraft from use and install the equipage and the anticipated benefits to the users.

A mixed equipage environment is rapidly emerging in oceanic ATC. This is caused by the recent availability of improved CNS systems and the numerous opportunities for improvement upon the current oceanic ATC operations. For example, since aircraft over the oceans are out of radar coverage, they are currently surveilled by the pilot reporting aircraft position at specific waypoints, which typically occur once per hour. These current CNS limitations require separation standards that are conservative compared with the domestic ATC environment. For example, lateral separation minima over the North Atlantic is 60 nautical miles (nm), whereas it is 5 nm within radar coverage over the United States. However, as equipage improves separation standards can be reduced based on the upgrades.

Since there is a significant gap in the difference between previous equipage and future equipage in the oceanic ATC environment, oceanic ATC was chosen as the focus for this thesis. The control of mixed equipage may increase controller workload and degrade their understanding of how the situation is evolving. To address the problem, this thesis examines the human factors and system risks of mixed equipage, specifically in the oceanic environment, through a human-centered systems approach. Possible solutions for future systems are also posed.

1.1 Motivation

There is substantial push to integrate new CNS technical capabilities into oceanic ATC due to the need for reduced separation, which is driven by increased demand and constraints on the desired routing over the oceans. These constraints result in competition for specific airspace at certain times. Optimal airspace at desired time is requested to increase fuel efficiency and reduce delays. This overcrowding limits flexibility for handling perturbations in oceanic airspace (e.g., avoid turbulent weather or emergency maneuvers).

Because of the procedural limitations, oceanic traffic was beginning to reach maximum allowable capacity within the desired airspace at peak times before the terrorist attacks on September 11, 2001. This resulted in many aircraft being forced to fly through turbulent conditions and making considerable deviations from optimal routings, which caused increases in fuel usage and delays. Since September 11, 2001 the traffic load has decreased. However, the Federal Aviation Administration (FAA) 2003 forecast predicts an annual growth rate of 4.2% for oceanic passenger traffic and 6.3% for oceanic cargo traffic for the period of 2005 to 2014. [2]

Based on history of the implementation of new CNS systems, the time required for any significant change in ATC architecture can be substantial. Therefore, full equipage cannot be assumed when designing future displays and procedures. This means that as new aircraft equipage is integrated into the ATC system, controllers will have the added responsibility of being aware of aircraft equipage and considering this new attribute in their decision making. The purpose of the present study is to better understand the controller cognitive implications of the mixed equipage environment.

1.2 Background

1.2.1 Oceanic Air Traffic Control

The oceanic environment is a unique ATC domain. While there is a considerable amount of available airspace, there is a narrow corridor of optimal airspace at desired times between major continental areas. Factors influencing the optimal routings include winds, fuel efficient altitudes, and overflight fees for air services. Oceanic winds, such as the jetstream, can significantly effect flight times. In the northern hemisphere, the jetstream is generally an easterly flowing wind pattern with speeds that sometimes exceed 250 miles per hour. Jetstream position changes everyday and

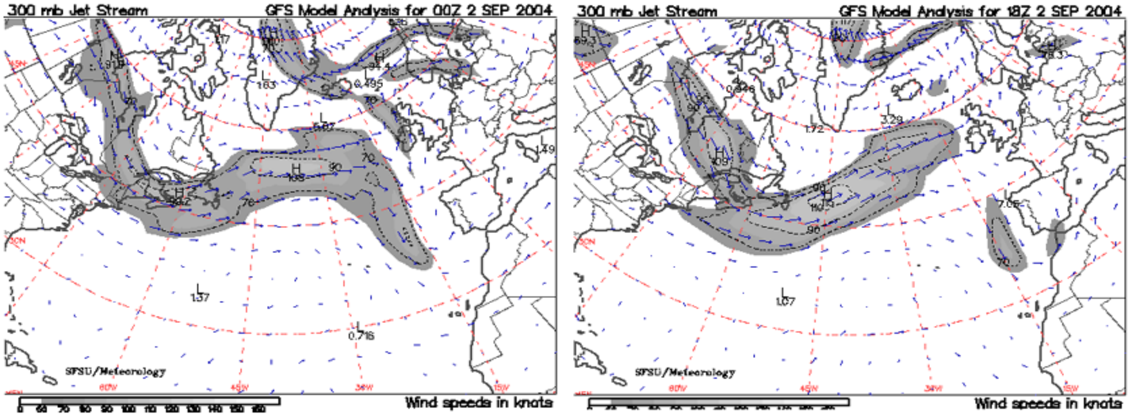
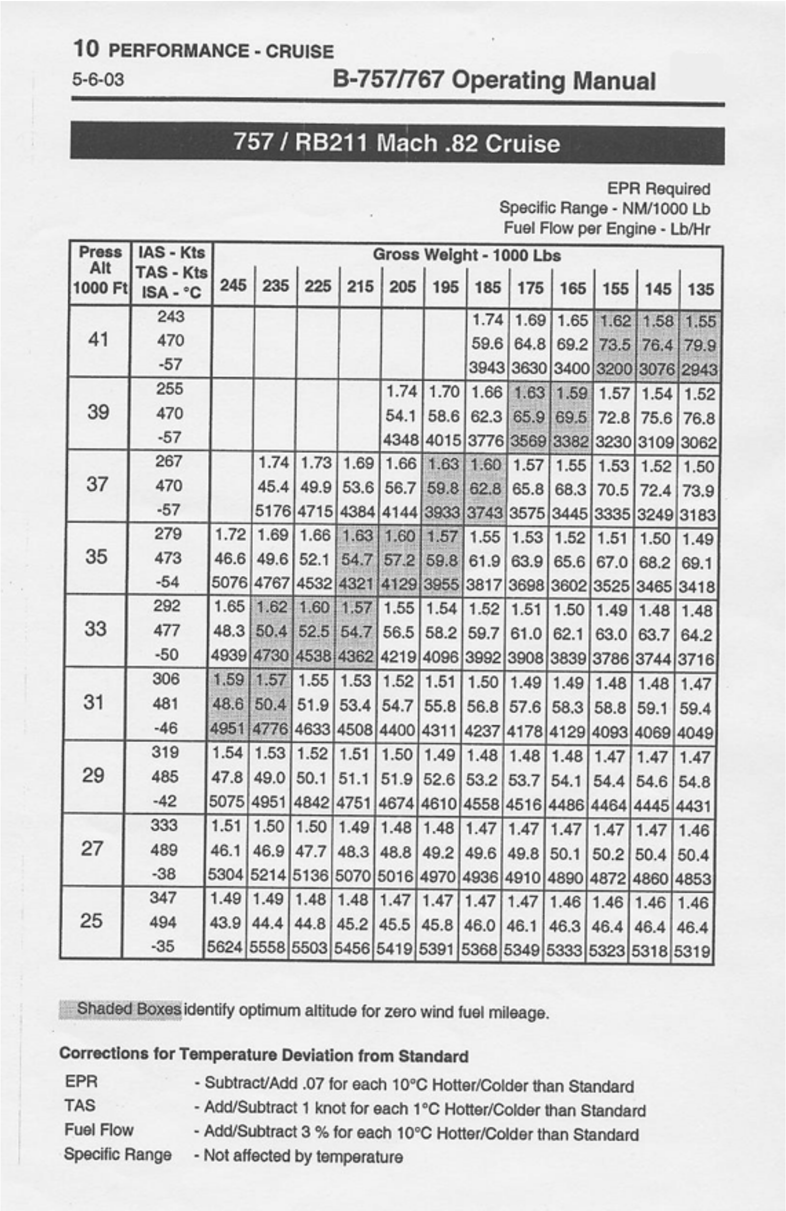


Figure 1-1: Jetstream position in the morning (*left*) and in the evening (*right*) for September 2, 2004 [4]. The shaded region represents the strongest area of the jetstream and the arrows represent the direction of the winds. The comparison shows the variability, even within a 24-hour period.

throughout the day as shown in Figure 1-1. The jetstream can decrease flight time if it is utilized when flying in the same direction as the winds and avoided when flying against the winds [3].

The most desired route is also influenced by fuel efficiency, which is dependent on the altitude flown. Depending on the type of aircraft and the weight, there is a specific optimal altitude. An example of the most fuel efficient altitudes for a Boeing 757 is shown in Figure 1-2. The optimal altitude is highlighted along the diagonal, indicating that as the weight decreases, the optimal altitude increases. During flight, aircraft weight decreases due to fuel burn, thus the optimal altitude slightly increases. However, this is not accommodated by the current oceanic procedures. Consequently oceanic flights currently try to attain a flight level that corresponds to their average weight during the flight.

Overflight fees also effect the optimal routing. Routing optimization tries to minimize flight time in airspace with expensive overflight fees. These fees vary depending on the country responsible for the airspace. The United States is one of a few countries that does not charge for overflight. An example of overflight fees are those charged by Canada. In October, 2004 the fee for the provision of navigation services over the North Atlantic was $97.12 per flight and their fee for international air to ground communication was $52.33 for position reporting using voice and $26.44 for using



10 PERFORMANCE - CRUISE

5-6-03 **B-757/767 Operating Manual**

757 / RB211 Mach .82 Cruise

EPR Required
Specific Range - NM/1000 Lb
Fuel Flow per Engine - Lb/Hr

Press Alt 1000 Ft	IAS - Kts TAS - Kts ISA - °C	Gross Weight - 1000 Lbs											
		245	235	225	215	205	195	185	175	165	155	145	135
41	243 470 -57							1.74 59.6 3943	1.69 64.8 3630	1.65 69.2 3400	1.62 73.5 3200	1.58 76.4 3076	1.55 79.9 2943
39	255 470 -57					1.74 54.1 4348	1.70 58.6 4015	1.66 62.3 3776	1.63 65.9 3569	1.59 69.5 3382	1.57 72.8 3230	1.54 75.6 3109	1.52 76.8 3062
37	267 470 -57		1.74 45.4 5176	1.73 49.9 4715	1.69 53.6 4384	1.66 56.7 4144	1.63 59.8 3933	1.60 62.8 3743	1.57 65.8 3575	1.55 68.3 3445	1.53 70.5 3335	1.52 72.4 3249	1.50 73.9 3183
35	279 473 -54	1.72 46.6 5076	1.69 49.6 4767	1.66 52.1 4532	1.63 54.7 4321	1.60 57.2 4129	1.57 59.8 3955	1.55 61.9 3817	1.53 63.9 3698	1.52 65.6 3602	1.51 67.0 3525	1.50 68.2 3465	1.49 69.1 3418
33	292 477 -50	1.65 48.3 4939	1.62 50.4 4730	1.60 52.5 4538	1.57 54.7 4362	1.55 56.5 4219	1.54 58.2 4096	1.52 59.7 3992	1.51 61.0 3908	1.50 62.1 3839	1.49 63.0 3786	1.48 63.7 3744	1.48 64.2 3716
31	306 481 -46	1.59 48.6 4951	1.57 50.4 4776	1.55 51.9 4633	1.53 53.4 4508	1.52 54.7 4400	1.51 55.8 4311	1.50 56.8 4237	1.49 57.6 4178	1.49 58.3 4129	1.48 58.8 4093	1.48 59.1 4069	1.47 59.4 4049
29	319 485 -42	1.54 47.8 5075	1.53 49.0 4951	1.52 50.1 4842	1.51 51.1 4751	1.50 51.9 4674	1.49 52.6 4610	1.48 53.2 4558	1.48 53.7 4516	1.48 54.1 4486	1.47 54.4 4464	1.47 54.6 4445	1.47 54.8 4431
27	333 489 -38	1.51 46.1 5304	1.50 46.9 5214	1.50 47.7 5136	1.49 48.3 5070	1.48 48.8 5016	1.48 49.2 4970	1.47 49.6 4936	1.47 49.8 4910	1.47 50.1 4890	1.47 50.2 4872	1.47 50.4 4860	1.46 50.4 4853
25	347 494 -35	1.49 43.9 5624	1.49 44.4 5558	1.48 44.8 5503	1.48 45.2 5456	1.47 45.5 5419	1.47 45.8 5391	1.47 46.0 5368	1.47 46.1 5349	1.46 46.3 5333	1.46 46.4 5323	1.46 46.4 5318	1.46 46.4 5319

Shaded Boxes identify optimum altitude for zero wind fuel mileage.

Corrections for Temperature Deviation from Standard

EPR	- Subtract/Add .07 for each 10°C Hotter/Colder than Standard
TAS	- Add/Subtract 1 knot for each 1°C Hotter/Colder than Standard
Fuel Flow	- Add/Subtract 3 % for each 10°C Hotter/Colder than Standard
Specific Range	- Not affected by temperature

Figure 1-2: Fuel burn table shows the optimal altitude, which is shaded, based on aircraft weight. [4].

Datalink, per flight [5]. These constraints define a specific route that the majority of oceanic traffic compete to fly along, and currently only few aircraft receive. As CNS enhancements are introduced, separation standards can be reduced and aircraft can be more tightly packed on the optimal trajectory. Added available airspace in the optimal region would provide for increased flexibility, which would allow more flight plan changes during flight.

1.3 Methodology

An integrated human centered systems approach (IHCSA) was applied to gather a better understanding of the controllers' cognitive activities, identify information exchanged, and determine how mixed and variable equipage will change the oceanic ATC environment. The IHCSA combines traditional human factors techniques with those used in systems engineering [6] . This approach is a practical technique for evaluating ATC systems, in which the human is considered a functional component of the closed-loop information system. The first two steps of IHCSA are to model the system and operator as a closed-loop feedback process and determine the information requirements the operator needs to perform their tasks. Field studies at North Atlantic and Pacific Oceanic ATC facilities were conducted to accomplish these steps. The findings are discussed in Chapter 3. Key human factors issues were identified from these models and system level trends emerged.

A controller cognitive model, based on human-centered systems literature is discussed in chapter 4. The impact of mixed aircraft equipage on the controller cognitive processes is also included in this chapter. The risks of the mixed equipage environment identified through the field studies and modeling were further examined through experimental studies, which are discussed in chapter 5. Implications for ATC were developed based on the results. These can be found in chapter 6.

Before getting into the results from the IHCSA, a background of the current and future technology trends in oceanic ATC is provided in chapter 2.

Chapter 2

Technology Trends

The challenges in oceanic CNS methods arise because aircraft are beyond the horizon. The current methods used are described below. Satellites are providing the opportunity for improved CNS over the oceans. While these changes alleviate the problems with the current methods, they also introduce a mixed equipage environment, which may create new problems. These satellite-based technologies will also be discussed.

2.1 Current Technology Trends

2.1.1 Communication

Very high frequency (VHF) radio is commonly used for air to ground communication over land. But VHF is limited to line-of-sight range, which precludes its use for oceanic traffic beyond the horizon. Currently, most oceanic communication is done over high frequency (HF) radio. The HF radio signal propagates by reflecting between the ionosphere and the earth's surface, therefore it can be transmitted over long distances. This capability also creates a significant amount of background noise on HF frequencies, since signals from around the globe can be received.

Originally HF radio had to be continuously monitored to retrieve incoming messages. The controller was not able to handle the role of monitoring HF radio, while also performing the control task. Therefore, the functions were split and the role

Figure 2-1: Current Controller-Centered Control Loop for oceanic ATC. Communication is conducted over HF radio through a third party communication relay service. Surveillance is conducted by pilot position reports, which are reported approximately every hour.

of monitoring HF radio was delegated to a third party communication relay service. The communication relay service transmitted all messages between ground controller and the flight deck. Despite improvements in HF radio, this process is still performed today. The current control loop is shown in Figure 2-1. The controller and the communication relay service communicate through electronic messaging or by phone. This indirect method of communication has not basically changed since the 1940's. The most major change to this communication process has been a switch from Morse code to voice communication [2].

The detailed current communication process is illustrated through a process diagram in Figure 2-2. When a pilot wishes to communicate with ground control they must first give this command over HF radio. Since HF radio is unreliable, it can take a considerable amount of time for the pilot to get through to the communication relay service radio operator (RO). Once this step is completed the RO must confirm the received command and transcribe it into electronic format. The message is then sent to the ground controller. Once received, the controller reviews the message and determines a response. The time it takes the controller to determine a response to the message varies depending on the situation. For example, if a nominal position report is received, only a few seconds to review are typically required. If a complex pilot request is received, the controller will need more time to determine if the request is possible. The increase in time is due to the time it takes the controller to project the

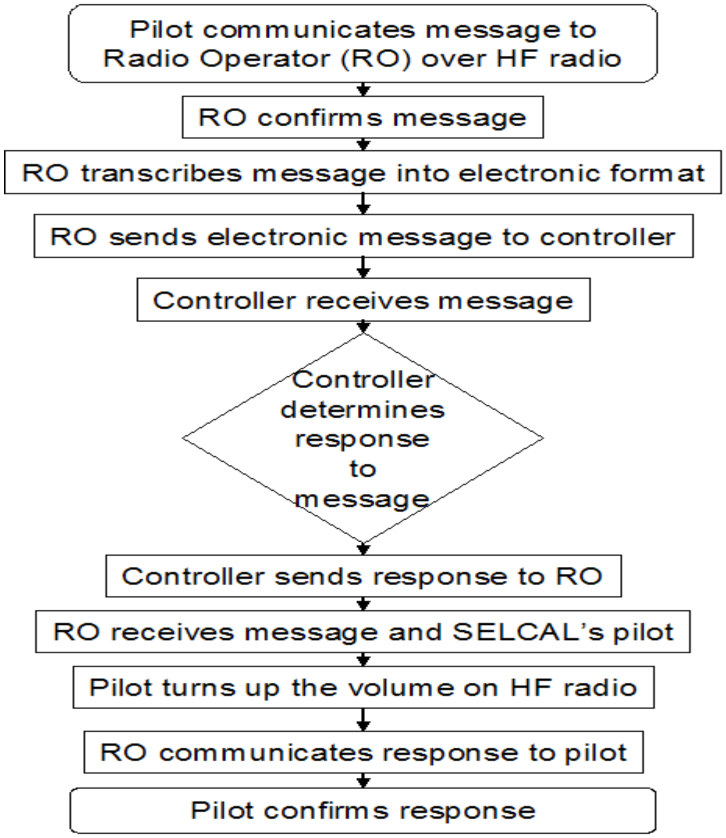


Figure 2-2: The current communication process reveals the unnecessary tasks.

new situation and also the time required for communication and coordination with other pilots or controllers of adjacent facilities if necessary.

Once a response is determined the controller nominally sends an electronic message with their response to the RO. To contact the pilot, the RO first SELCAL's (selective call system) the cockpit. SELCAL sends a signal through an HF link. The signal is decoded and a chime is activated in the cockpit to alert the pilot to begin monitoring their HF radio. When the chime is received the pilot turns up the volume on their HF radio and the message is delivered. The pilot must then confirm the message to ensure it was accurately received.

The communication process reveals the numerous unnecessary administrative tasks that must be completed for each communicated message. The future communication process shown in Figure 2-4 shows how these steps are eliminated through the use of Datalink. This process is discussed further in section 2.2.

The time it takes between when the pilot or controller wants to communicate a message to the other and when the message is received is defined communication latency. The communication latency varies using the current communication process. Nominally it takes three to five minutes, however it can take up to thirty minutes. The nominal latency is mostly due to the numerous steps required to deliver each message. Longer latency can be due to difficulty getting through over HF radio, increased controller or pilot workload, which may limit when they can address the message, or difficulty in determining a response to the message.

2.1.2 Surveillance

Radar is used for most ATC surveillance over land. There are two types of radar used: primary and secondary. Primary radar works by sending out an electromagnetic signal. The presence of an aircraft is determined by receiving an echo of the signal off of the aircraft. Distance is determined by the elapsed time between transmission of the signal and reception of the echo. Directive antenna patterns are used to determine direction. Secondary radars use an amplified return of the signal by the transponder and can include other coded information such as aircraft ID, altitude, etc.

Since oceanic traffic is beyond line-of-sight range, the radar signal will not reach the aircraft. Consequently, surveillance is currently dependent on communication and navigation. Pilots determine their position using onboard navigation systems and report this position at specific position reporting points to the ground controller, using the above communication process. For example, over the North Atlantic, position reports are required every ten degrees longitude, or approximately once an hour [7]. Currently, surveillance is limited by both the communication latency issue described above and the accuracy of the navigation system.

Pilots have the responsibility of reporting their position at predetermined points. If an aircraft does not report its position within three minutes of the expectation, the position report is considered late and the controller must try to make contact with the pilot to resolve the late report.

2.1.3 Navigation

Traditionally, aircraft navigation over land has been reliant on ground-based radio navigation systems. The most common is very high frequency omni-directional radio range, or VOR, which transmits two signals. The signals are received by the aircraft systems and used to determine position relative to the VOR. This position is then displayed in the cockpit. While there is a movement towards GPS based navigation, the current systems and procedures for ATC over land is based on radio navigation systems.

Radio-based navigation cannot be used for oceanic traffic since it is out of line-of-sight range. Historically inertial navigation system (INS) has been used. INS determines current position based on a detection of movement relative to the given starting position. Satellites present the opportunity for more accurate navigation through global positioning system (GPS). Presently onboard navigation typically consists of either INS and/or GPS. GPS is more accurate than INS at detecting aircraft position. Over the oceans, GPS coverage is fairly consistent because there are no structures such as buildings or trees to disrupt the GPS signal. GPS is not as reliable in the Polar regions because was designed for moderate to low level altitudes.

Vertical navigation is based on the sensing of Barometric pressure. At low altitude a unit increase in pressure corresponds to a small change in altitude. Due to the exponential relationship between altitude and pressure, at high altitudes the same unit change in pressure corresponds to a much greater change in altitude. Therefore at high altitudes more precise pressure measurements are needed to reduce the error in measured altitude.

2.2 Emerging Technology Trends

There are many oceanic ATC technologies surfacing to provide higher frequency communication and surveillance and more accurate navigation. Many of these advancements are based on the application of satellite-based technologies. The emerging controller-centered control loop is shown in Figure 2-3. Ground systems are also

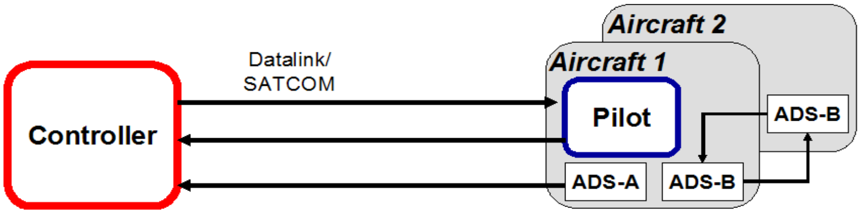


Figure 2-3: Future Controller-Centered Control Loop will consist of direct communication and surveillance through satellite communication and ADS-A. Surveillance information about surrounding aircraft will also be available to the flight crew via ADS-B.

adapting to receive and display the information provided by these technologies. Since there will be a significant shift in oceanic ATC operations, there is a unique opportunity to make substantial changes in the ATC systems.

2.2.1 Communication

Future communication will consist of a direct link between the ground controller and the flight deck. Satellites are providing the opportunity for direct voice and data communications. Datalink, also referred to as CPDLC (controller pilot Datalink), provides the means for data transmission between the ground and the flight deck. CPDLC has emerged as the primary means of oceanic communication for equipped aircraft since its introduction at Oakland Center in 1995 and New York Center in 2003 [2]. Figure 2-4 illustrates the reduction in the number of tasks required to communicate a message using Datalink, as compared to HF radio. This reduction in tasks results in fewer opportunities for human error. The use of data communication also eliminates language barriers that can occur at oceanic facilities. The improvements in the communication process using Datalink was demonstrated in a study of current Datalink and HF radio operations. As expected, the results revealed that it takes less time for Datalink transactions than transactions over HF voice [8].

Voice communication is also available through SATCOM. The use of SATCOM is reserved for critical communication messages because there is a high cost associated with each minute of communication. The cost of SATCOM is typically based on the use of geosynchronized satellites. As other satellite systems are available this cost is

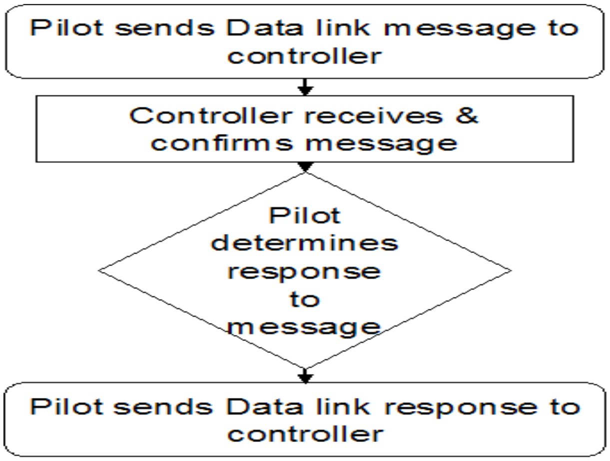


Figure 2-4: The future communication process using Datalink shows the reduction in the unnecessary tasks.

expected to go down. HF voice usually serves as a back-up to the satellite capabilities.

In a survey on future means of oceanic communication, 235 oceanic pilots were asked to rank their preferred mode of communication (HF radio, CPDLC, or SATCOM) in various situations. Most of the pilots selected CPDLC for frequent communications that can be done with standardized messages, such as reporting position, requesting clearances, and receiving clearances. For emergency situations and dialog or negotiation discussions, SATCOM was chosen most frequently. [9] This study reveals that there is a need for voice communication. In fact, as separation minima are reduced, the need for negotiation discussions will likely increase, making the need for voice communication more critical.

Inter-facility communication is also evolving to incorporate electronic messaging through air traffic services inter-facility data communications (AIDC). AIDC will reduce the problems associated with language barriers between international facilities. It is currently available on a limited basis and there are plans for including more facilities in the near future.

2.2.2 Surveillance

Future oceanic surveillance will continue to be dependent on the aircraft's onboard navigation and communication equipage. The communication advancements described above are providing the opportunity for more frequent and reliable position reports, through enhanced communication. Automatic dependent surveillance (ADS) will introduce a more revolutionary oceanic surveillance concept. ADS allows for automatic reporting of flight information such as position, velocity, altitude, heading and identification. The reports are based on the onboard GPS navigation system. ADS comes in two forms: ADS-A (address) and ADS-B (broadcast).

2.2.3 ADS-A

ADS-A[1] automatically sends flight information through a satellite communication link to specified addressees (typically ATC ground stations) at specified intervals, determined by contracts. This reduces unnecessary pilot workload by taking the pilot out of the surveillance loop. It also reduces controller administrative tasks by displaying this information to the controller directly. The controller will no longer need to process each report individually.

ADS-A reports are limited by economics because there is a significant cost associated with each report obtained. The current operations manual for the South Pacific specifies that reporting frequency should not exceed once per five minutes [10]. ADS-A is currently not available as stand-alone equipment; it is sold as a part of the FANS-1/A package, which includes CPDLC. The nonrecurring average avionics cost to equip an aircraft with FANS-1/A is estimated to be $560-620K in 1998 dollars [11]. The cost includes the FANS-1/A package with CPDLC, but excludes GPS. A major portion of this cost comes from the pilot interface and integrating the communication system with the aircraft's current navigation and flight control systems.

2.2.4 ADS-B

ADS-B automatically broadcasts flight information at specified intervals and surrounding "listeners" within a certain range (typically 200 nm) can pick up the information. The "listeners" in the oceanic environment refer to surrounding aircraft, but

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[1] ADS-A is referred to as ADS-C (contract) in Europe.

in domestic ATC ground receivers can also pick up the broadcasted flight information. ADS-B provides the flight crew with information about surrounding aircraft, increasing their situation awareness. This introduces the opportunity for some level of self separation by the flight deck. However, future operations utilizing ADS-B are still being debated. A brief review of previous human factors studies of ADS-B operations is included in Appendix A. An example of the nonrecurring cost of equipping an aircraft with ADS-B in 1998 dollars is estimated to be $25-35K in the high range and $5-7K in the low range [11]. This is only a preliminary estimate since there are still many unknowns.

2.2.5 Navigation

While most aircraft are currently equipped with GPS and have back-up INS capabilities, it is predicted that all aircraft will be equipped with GPS/Galileo navigation systems within 15 years [2]. Currently there are issues with the integrity of GPS. However, as more satellite systems are introduced, integrity issues will be reduced.

There have been improvements in vertical navigation due to requirements for reduced vertical separation minima (RVSM). The objective of the requirements is to reduce the total error in measured altitude. This includes improvements in the accuracy of barometric pressure sensing in the air data computer and calibration of the pressure measurement system. RVSM will be discussed further in the following section.

2.2.6 Performance-Based Separation Standards

ATC improvements are dependent on CNS upgrades. However these upgrades cannot occur without industry investment in avionics equipage. Investment decisions are made based on benefits to the user, which are obtained through improved ATC operations. This challenge cannot be alleviated without providing benefits to equipped aircraft immediately. In the oceanic environment, in order to provide flexibility and optimal routings to equipped aircraft, the minimum allowable separation needs to be reduced. To do this, separation minima must be based on aircraft equipage.

One of the first programs to introduce the concept of differential separation standards based on CNS equipage is RVSM over the oceans. Vertical separation is reduced for aircraft with improved navigation systems from 2000 feet to 1000 feet, between 29,000 feet and 41,000 feet, or flight levels (FL) 290 and 410. More specifically, RVSM aircraft must be equipped with redundant altitude measurement systems, altitude reporting transponder, altitude alerting system, and automatic altitude control system [12]. RVSM was first implemented in the North Atlantic in 1997 and in WATRS and the Pacific in 2000. Approximately 98% of aircraft that fly over the oceans are equipped for RVSM.

Prior to RVSM, minimum navigation performance (MNPS) was integrated into the North Atlantic airspace. MNPS is defined for airspace between FL 285 and 410. Within this airspace, all aircraft must be equipped with two long-range navigation systems (LRNSs) which must continuously display an indication of the aircraft position relative to the desired track [13]. The LRNSs may be any two of the following: INS, GPS, or another navigation system that complies with the MNPS requirements.

A shift in the criteria for separation assurance has occurred since the introduction of improved altimetry systems was introduced. The criteria metrics have transitioned from specific equipage to aircraft performance. Under this concept, regulatory agencies can give aircraft operators the freedom to choose their preferred avionics equipage that meets the performance requirement. These performance criteria can be applied to any airspace region and be used to define separation standards. This is captured in a model known as required total system performance (RTSP), which establishes a standard set of performance component metrics [14]. The performance metrics represent each of the CNS components. The three metrics are defined as required communication performance (RCP), required navigation performance (RNP), and required surveillance performance (RSP). Every aircraft's total system performance can be defined on this 3D Cartesian coordinate system, which is illustrated in Figure 2-5.

The RNP concept is presently used in the Pacific airspace. The RNP specification

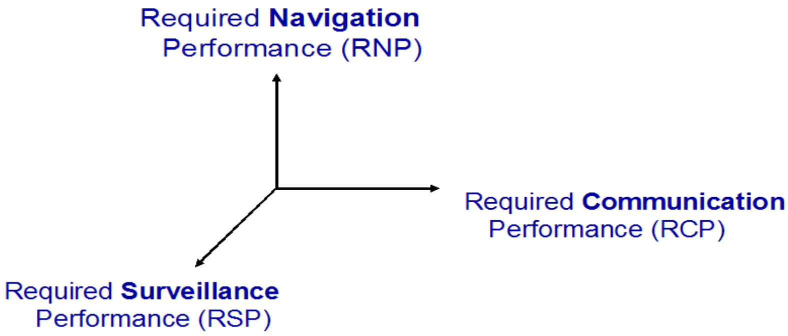


Figure 2-5: Required Total System Performance Model defines 3 axes by which aircraft performance can be measured.

Figure 2-6: Currently RVSM is active in the North Atlantic and Pacific and RHSM for RNP-10 certified aircraft is active in the North Pacific.

requires aircraft maintain a cross-track and along-track navigational accuracy error within the defined bounds, 95% of the time [15]. Under RNP rules aircraft must also be equipped with an onboard system to automatically alert the crew if the navigation system is no longer capable of maintaining the specified accuracy. RNP-10 is currently implemented in the Pacific airspace. Reduced horizontal separation minima (RHSM) from 100 nm to 50 nm is active for aircraft that are RNP-10 certified.

The current state of improved procedures based on performance is shown in Figure 2-6. RVSM is active in most oceanic airspace and RHSM is active in the Pacific, in certain airspace regions.

Future FAA plans follow the trend for performance-based separation standards. According to the FAA oceanic Strategic Plans for reduced separation, the require-

Separation Minima	**RCP**	**RNP**	**RSP**
50 nm lat.	HF voice, enhanced comm in some areas	RNP-10	60 min. position reports
50 nm long. (limited)	Direct voice or Datalink	RNP-10	30 min. position reports
50 nm long. (extended)	Direct voice or Datalink	RNP-10	ADS-A with distance verification at 30 min. intervals
30 nm lat.	Direct voice or Datalink	RNP-4	ADS-A with conformance monitoring/detection
30 nm long.	Direct voice or Datalink	RNP-4	ADS-A with conformance monitoring & 21.5 min. automated distance verif.

Table 2.1: Future FAA oceanic plans to reduce separation match the RTSP concept. The aircraft requirements can be separated into CNS performance categories [12]. As RTSP requirements increase the separation minima decrease.

ments for reduced separation can be categorized into one of the three RTSP components [12]. Currently the communication and surveillance criteria specify required equipage instead of performance, although this may change in the future as more avionics equipage options become available. The FAA plans are fit to the RTSP model in Table 2.1.

Long term plans are illustrated in Figure 2-7. The first step, included in the above Table is to move towards 30 nm lateral and longitudinal separation in the North Atlantic by 2006 and in the Pacific in proceeding years. Then horizontal separation in the North Atlantic is planned to be reduced further to 15 nm. There are also plans to implement a new oceanic ATC ground system in the U.S. facilities. The new system was integrated into the facilities on a limited basis for testing and training at Oakland Center in June, 2004. This new system will be discussed in the next chapter.

2.3 Conclusions

Significant CNS improvements are currently available. Direct communication is available by Datalink and SATCOM. ADS-A introduces high frequency automatic position reporting. And navigation improvements are available based on GPS. These improvements provide the opportunity to bring the aircraft closer together. Separa-

Figure 2-7: Future state of oceanic procedures, based on the FAA plans. The improvements from the current state, which are bold faced, are expected beyond 2007.

tion reductions are possible because the controller will have a significantly improved ability to intervene in the air traffic situation. Also, navigation improvements allow the pilot to more precisely specify their route or trajectory. Reduced separation is needed in oceanic ATC because currently aircraft are required to fly non-optimal routes, which increases fuel usage and delays. Also, flexibility is severely limited, which compromises safety by forcing aircraft to fly through turbulent conditions.

Aircraft operators must be incentivized to attain the equipage to drive the ATC system forward. In order to incentivize aircraft operators to purchase the improved equipage, there must be an immediate return on investment. This is challenging to offer since the aircraft with limited CNS must also be serviced. Mixed equipage problems experienced today, with limited variations in equipage, will be discussed in the following chapter. Then in chapter 4 and 5, the issues associated with integrating future equipage will be discussed.

Chapter 3

Field Studies

Field studies were conducted to understand the current oceanic ATC system and identify emerging mixed equipage issues. This contextual study was required because of the complexities of the mixed equipage problem. Key issues can be identified only through observation of the controller within the control environment. Once identified, issues were studied further through modeling and controller experimental studies.

3.1 Objectives

In order to gather a better understanding of oceanic ATC operations and the impact mixed equipage will have on this environment, field studies were conducted at various facilities that control air traffic over both the Atlantic and Pacific Oceans. These included Reykjavik Center in Iceland, New York Center, and Oakland Center. The observations were focused on gathering operational data on key human-centered systems issues with the current and future mixed equipage environments and gathering controller insight.

3.2 Methodology

Prior to the site visits, an observation plan was developed, shown in Table 3.1. The plan consists of the following categories: goals, process analysis, plan, situation aware-

Probe Type	Probe Objective
Processes	Process for handling nominal, abnormal, and
	emergency situations
Goals	Controller's actual goals, means for achieving goals, goal to situation matching
Situation Awareness	Method for gaining awareness, use of flight strips, other useful tools, cognitive view of the world vs. actual
	view
Workload	Workload constraints, method in which the controller stay within their workload capacity, assistance of other controllers to remain in their capacity
Plan	Formulation of plans, plan flexibility for pilot requests
Communication	Effectiveness of the current communication system between the controller and pilot/comm. relay service and between controllers, suggestions for fixing breakdowns
Information	Most useful pieces of information, suggestions information that could be useful

Table 3.1: Observation plan developed to guide the site visit observations.

ness, workload, communication, and information. Within each of these categories specific probes were developed based on the controller cognitive model to guide the observations and conversations with the controllers.

3.3 Current General ATC Operations

There are significant commonalities between the oceanic facilities observed, which were identified through the field studies. Most oceanic ATC follows a procedural process. Aircraft are procedurally designated a flight plan, that provides a path from entry into oceanic airspace to exit, which does not interact with other aircraft or reserved airspace regions.

The primary task of the controller is to monitor these procedurally planned flight paths at each position reporting point, or waypoint, and at the sector entry and exit points. Controllers are mainly concerned with ensuring adequate longitudinal and vertical separation. Lateral separation is provided by the oceanic track structure, to which most of the North Atlantic and part of the Pacific traffic conforms. The tracks are spaced according to the minimum allowable lateral separation and have minimal

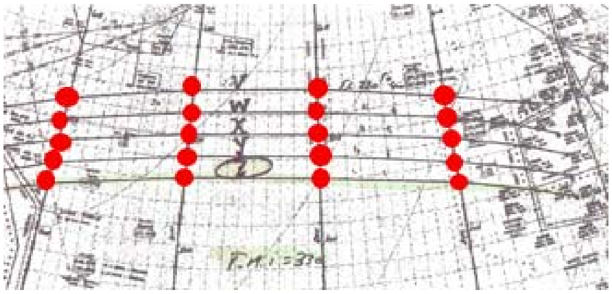


Figure 3-1: Eastbound North Atlantic track structure, the circles represent the position reporting points along each track.

crossings to reduce the four-dimensional problem space to two-dimensions, time at waypoint and vertical separation. The tracks are negotiated by the Centers daily based on wind information and forecasted traffic. An example of eastbound tracks across the North Atlantic is shown in Figure 3-1. The position reporting points are shown as triangles along the tracks, every 10° of longitude. The airspace structure ensures safety despite the high frequency of communication failures, which also result in a lack of surveillance.

Flight strips, in paper or electronic form, are used to monitor progression along the track structure. The flight strip organization corresponds to the track structure. The controllers are provided with a flight strip or marking on the strip for each position reporting point, which allows them to monitor longitudinal and vertical position at each of the reporting points. Longitudinal separation is currently given as a temporal restriction (e.g., 10 minutes in trail). In order to ensure adequate longitudinal separation the controllers manually compare an aircraft's time at each waypoint with other aircraft that also pass through these points.

3.4 Generic Information Flow

Based on the field studies, a general information flow diagram, shown in Figure 3-2, was developed to identify the agents in the control loop and information requirements for the controller. The agents, shown in bold, rounded rectangles, include Controllers both within and outside of the facility, Pilot, Radio Operator at the Communication

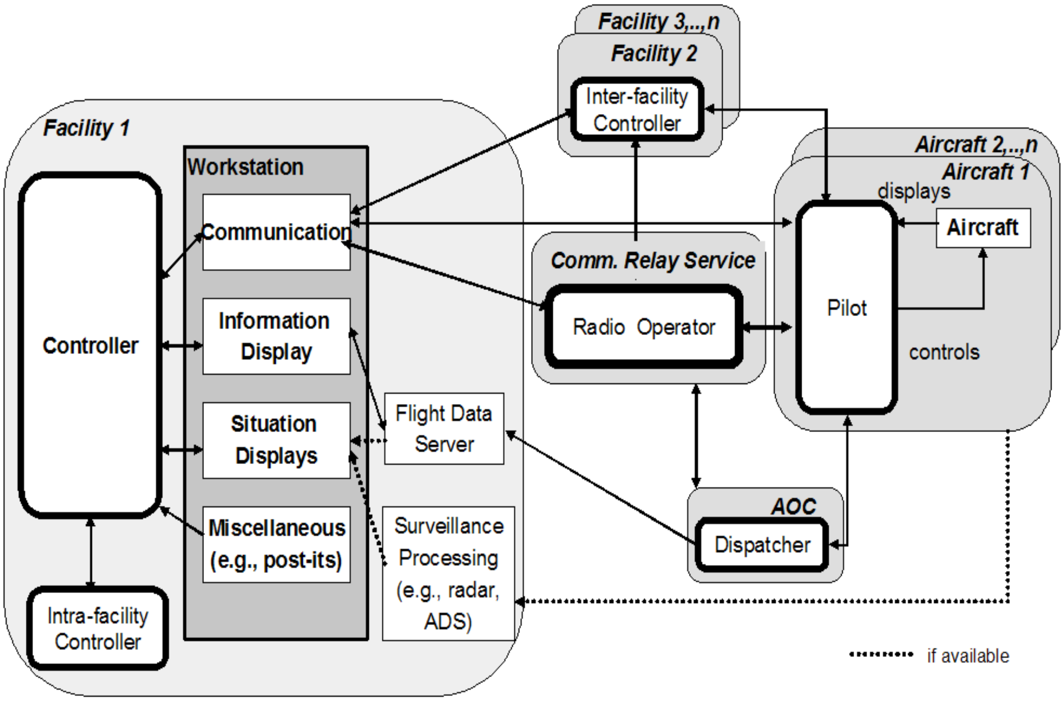


Figure 3-2: General information flow for current oceanic facilities (based on New York Center, Oakland Center, and Reykjavik Center)

Relay Service, and the Dispatcher at the Airline Operations Center (AOC). The observed oceanic workstations varied across the facilities. However, they all contain the following elements: Communication, which may usually includes voice and Datalink communications, Information Display (e.g., flight strips), Situation Display, and other Miscellaneous information (e.g., maps, notes from supervisor, etc).

3.4.1 Flight Data Server

The Flight Data Server is the central database for all electronic flight information. Flight plans for all aircraft that enter the airspace region controlled by the facility are originally put into the flight data server by the Dispatcher at the AOC. This flight plan is then updated by position reports that are received electronically, through Datalink, radar, ADS-A, or electronic messages from the Radio Operator. Controllers also update the Flight Data Server based on Voice Communication with the Pilot, Radio Operator, Dispatcher, or other Controllers. The information on the spatial Situation Display and flight strips is retrieved from the Flight Data Server.

3.4.2 Interface and Conflict Alerts

The controller interface consists of the spatial Situation Display, a display of electronic messages (from both the radio operator and pilots), and flight strips. If radar information is available, another spatial display of this information may also be included. At each facility, there are conflict probes. These probes search for conflicts based on the constraints identified by the facility and alert the controller when they are identified. The constraints may include deviations from expected position, anticipated violation of separation standards or other procedures, missed position reports, etc. The alerts may appear on the spatial situation display, electronic flight strips, or display of electronic messages.

3.4.3 Information Exchanged Between Agents

A controller communicates with pilots through a third party communication relay service. Position report information is currently the primary information exchanged between pilots and controllers. Position report information consists of a current position (lat./long. point and flight level), Mach number, and time at the next two reporting points.

A position report that is greater than three minutes past the expected arrival time is considered late and must be resolved. First the controller attempts to make contact through the radio operator. If the radio operator is unable to reach the pilot through HF radio, then the controller will attempt to call the cockpit using SATCOM, if the aircraft is equipped. If a position report cannot be resolved within thirty minutes then the supervisor is alerted and further action is taken. This may include asking other nearby aircraft to contact the "missing" aircraft over VHF.

Pilots make requests for changes to their flight plan or additional information through the communication relay service. Oceanic controllers reported that the most frequent requests are for flight level changes, typically to a higher altitude. Another common request that was observed was slight off-track deviations to avoid turbulent situations. Additional information requested from the controller may include information on winds, delays, and restrictions at adjacent Centers.

Communication between controllers within the facility is exchanged either over phone or face-to-face. Information between facilities is exchanged through either phone or electronic messages (when available). Controllers answer the phone and look at the messages in the order that they receive them, which allows for urgent messages to get lost in the pile. Typically, phone calls are attended to more rapidly than electronic messages.

Currently, most communication with other controllers both inside and outside the Center occurs during hand-offs. Information exchanged during hand-offs includes aircraft time at sector boundary, Mach number, cruise altitude, and cleared route. Typically, oceanic controllers need to contact the controller responsible for the adjacent sector that an aircraft will be entering approximately thirty minutes prior to the hand-off, to alert them of the entering aircraft. After this information is exchanged, the controller may need to amend the hand-off information if the pilot asks for changes before crossing the sector boundary. The controller then contacts the adjacent sector or facility again when the aircraft has exited the airspace that he/she is responsible for. Other communication is typically for clarification on an aircraft route, speed, or altitude for an aircraft in an adjacent sector or sector restrictions, such as the number of aircraft they will accept.

Communication between the ATC Center and the airlines is done through the AOC dispatcher. Initially the airline files a flight plan through an integrated network, such as the North American data integrated network (NADIN). The dispatcher sends the flight plan to necessary facilities, which gets entered into the Flight Data Server. Once the flight plan is in the Flight Data Server it will automatically be shown on flight strips and on the situation display.

3.4.4 Direct Surveillance Information

Other surveillance information is available on a limited basis. Radar coverage is available in oceanic transition areas as well as near islands, such as Iceland and Greenland in the North Atlantic, and Hawaii and Guam in the Pacific. Aircraft equipped with

FANS-1/A have the capability of sending automatic surveillance updates. Currently most workstations, including those in the U.S. and Iceland, are not capable of receiving this information. The next generation workstation in most regions will be able to accept ADS-A information.

The individual elements of the information flow vary across facilities. The specifics at Reykjavik Center in Iceland, New York Center, and Oakland Center and observations at these facilities will now be discussed.

3.5 Reykjavik Center Observations

The Reykjavik site visit consisted of four hour observations on four separate days. During the visit, thirteen controllers (five in non-radar sectors and eight in sectors with partial radar coverage), a chief controller, a supervisor, and a training instructor were observed and interviewed.

3.5.1 Overview of Facility

The airspace controlled by Reykjavik Center is illustrated in Figure 3-3. The NAT tracks occasionally pass through the Reykjavik airspace. Reykjavik Center also handles a portion of the Polar tracks. The majority of the Reykjavik Center's southeast airspace is covered by radar, as shown in Figure 3-4. This section of airspace is also mostly covered by VHF communication, which provides more reliable, direct controller to pilot voice communication. This provides a good case for looking at the issues that will be faced in the future non-radar sectors as enhanced communication and surveillance become more prevalent.

In April 2002, Reykjavik Center switched from the use of paper flight strips to a flight data processing system (FDPS). A non-radar workstation is shown in Figure 3-5. FDPS consists of electronic flight strips and a spatial situation display. This system provides the opportunity for decision support and other display features to be integrated into the controller workstation. The electronic flight strips, shown in Figure 3-6, are grouped by altitude. An expected time at every position reporting

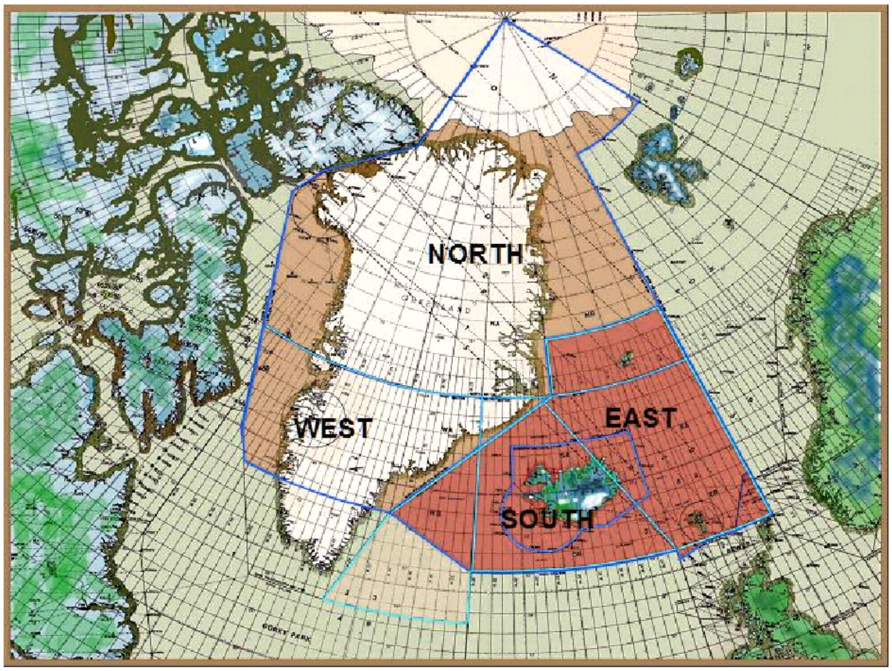


Figure 3-3: Airspace controlled by Reykjavik Center handles some traffic on the North Atlantic tracks and a portion of the Polar tracks [16].

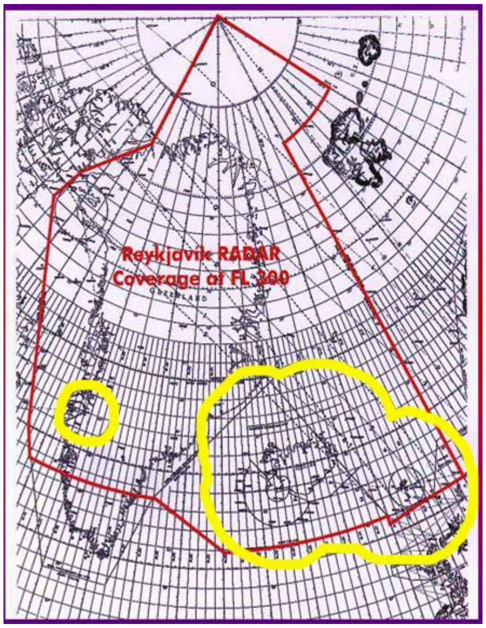


Figure 3-4: Radar coverage in Reykjavik Center airspace is circled. Some oceanic traffic passes through this airspace, in which the separation is reduced from 60 nm to 5 nm [16].

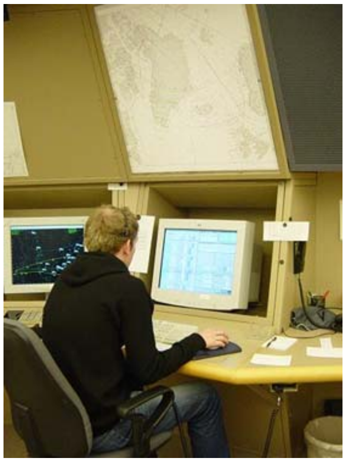


Figure 3-5: The Reykjavik controller workstation consists of electronic flight strips, in front of the controller and a situation display, to the left of the controller.

point is included on each strip. The left to right order of the time at position reports matches the actual west to east location of the waypoints. This organization enables quick comparison of strips to determine if there is adequate time between aircraft at each waypoint, within each altitude.

3.5.2 Detailed Observations

Facility Technologies

Reykjavik controllers reported that the electronic strips are much easier to use than the paper strips. All of the tasks associated with manually inserting and removing the paper strips into the proper location is eliminated with the electronic format. They also reported that the Situation Display provides the means for a quick reference check on the air traffic situation, which makes understanding the state of the air traffic situation when first beginning a shift is easier.

While FDPS was generally accepted by the controllers, there were a considerable amount of false alarms created by the conflict probes. During the observations more than three false alarms were issued to each controller observed. Most of the warnings were conflict warnings on the situation display. There were also coordination warnings. The controllers reported that many of these warnings occur because the conflict probe does not take the reduced separation due to radar coverage into

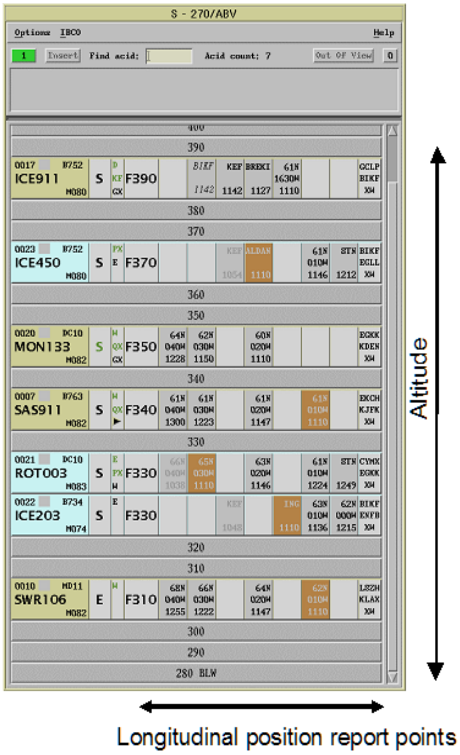


Figure 3-6: Electronic flight strips used at Reykjavik Center are grouped by flight level and ordered left to right by position reporting points.

Figure 3-7: Equipage information is located on the flight strip. This aircraft is equipped for MNPS ("X") and RVSM ("W").

account. Future versions of the FDPS are planned to improve on conflict detection.

Mixed Equipage Issues

In order to inform the controller of RVSM and MNPS status, the navigation equipage information is located on the flight strip. In Reykjavik Center there is a letter designator for each equipage type, which is shown in Figure 3-7. There is an "X" if an aircraft is equipped for MNPS and a "W" if an aircraft is equipped for RVSM.

An analogy to mixed equipage was observed at Reykjavik Center in the sectors that had partial radar coverage. Rather than CNS improvements due to onboard

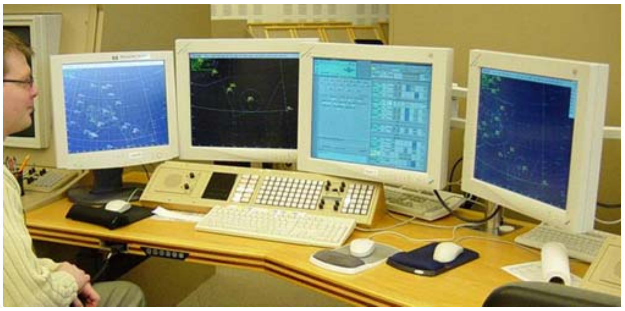


Figure 3-8: Reykjavik Center workstation in a sector with limited radar coverage. The screen on the left is the situation display. The second screen from the left and the screen on the far right display radar information, two screens are provided so that the controller can see an overview of the traffic and zoom in on a conflict at the same time.

avionics equipage, radar and VHF availability based on geographic location provides significantly enhanced ATC operations. The current workstations for these sectors consists of three spatial displays of the traffic, two of them are radar displays (one shows a global view and one is used to zoom in on a situation) and the other is the situation display described above. One of these workstations is shown in Figure 3-8. This workstation configuration requires the controller to manually integrate the nearly continuously updated radar information with the projected information shown on the situation display. This process constrains the tasks of the controller.

The limited radar coverage also provided an opportunity to observe the impact of transitioning boundaries from an area of increased separation to an area of reduced separation. Within the area of radar coverage the longitudinal separation is reduced from 10 minutes to 3 minutes, as illustrated in Figure 3-9. Since oceanic traffic entered the radar coverage separated by 10 minutes and needed to leave the radar coverage with this conservative non-radar separation, the controllers did not utilize the reduced radar separation for the majority of the traffic. There were a few situation during which the controllers applied separation reduced below the oceanic standards. The commonality between the situations where separation was reduced was that the aircraft regained oceanic separation before leaving the radar coverage without controller intervention. In one observed instance, an aircraft on the NAT tracks and another that crossed the NAT tracks on a Polar track were allowed to come within 5

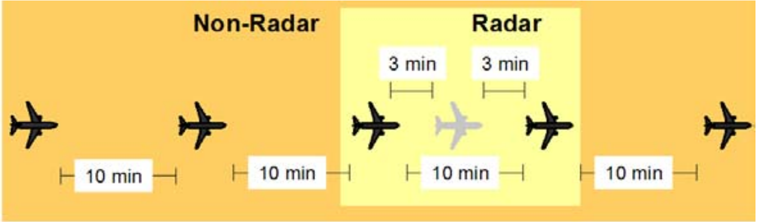


Figure 3-9: Example of the issue of transitioning boundaries from Reykjavik Center. Radar coverage allows longitudinal separation to be reduced from 10 minutes to 3 minutes, however the track traffic does not benefit from this reduction.

minutes of each other within the radar region. The two aircraft resumed 10 minute separation soon after crossing.

Other Observations

Several communication and surveillance problems were observed at Reykjavik. There were several missed or late position reports. A position report 3 minutes past the expected time or more is considered late. Also, an aircraft lost HF radio communication during the site visit. The controller reported that the protocol for problems with HF radio is to issue the oceanic clearance while the aircraft is still within VHF coverage and then assume that the aircraft will stay on its path, according to the flight plan.

3.6 New York Center Observations

During the site visit at New York Center three observations were performed for four hours each. Two of the observations were during the day and one was during the night. Of the eleven controllers observed, three were in North Atlantic radar sectors, nine were in North Atlantic non-radar sectors, and eight were in WATRS non-radar sectors. Three supervisors were observed. In addition an ATOP specialist gave a tour of the ATOP simulators.

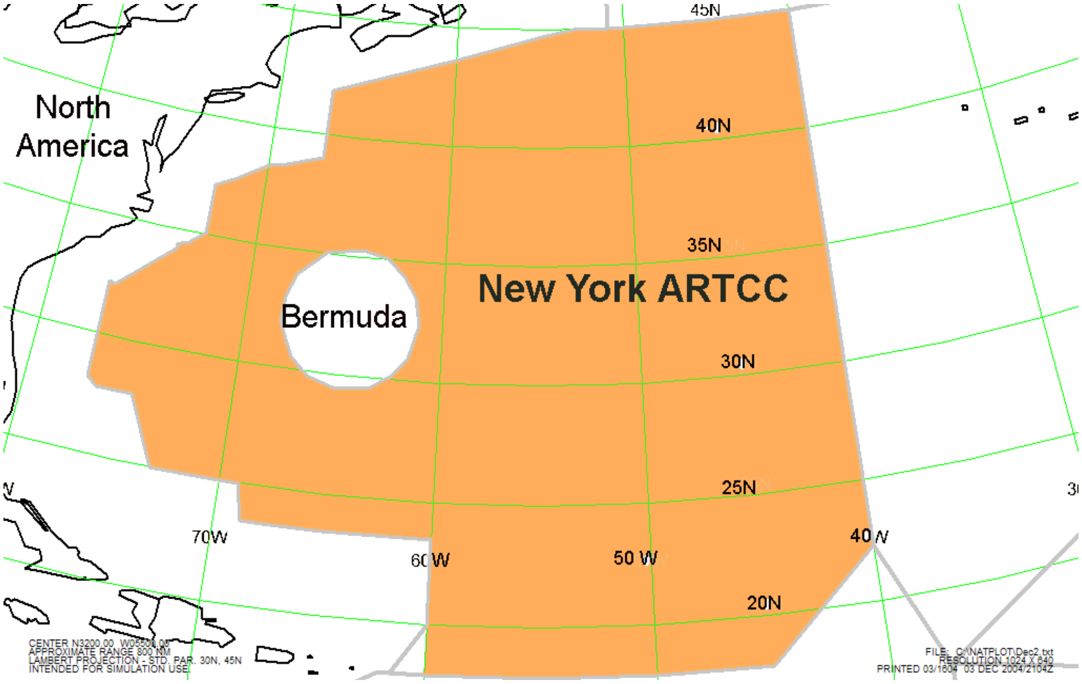


Figure 3-10: New York Center is responsible for North Atlantic traffic from the U.S. coast to 40W, which consists of the NAT tracks and WATRS routes [17].

3.6.1 Overview of Facility

Oceanic airspace controlled by New York Center is shaded in Figure 3-10. The northern part of the airspace consists of the southwestern half of the north Atlantic track system (NAT) and the southwestern part of the airspace consists of the northern portion of the west Atlantic route system (WATRS). NAT traffic is comprised mainly of traffic between Europe and the U.S. WATRS airspace is a unique non-radar environment that consists of a complex web of crossing fixed routes, primarily between the east coast of the U.S. and the Caribbean islands. The WATRS routes are shown in Figure 3-11.

The workstations used in the U.S. oceanic sectors consist of paper flight strips and the oceanic display and planning system (ODAPS). The controllers primarily use the flight strips for their separation tasks. ODAPS is composed of electronic messages, both Datalink and messages from the third party communication relay service (ARINC), and a spatial situation display.

The organization of the U.S. paper flight strips provides the temporal display

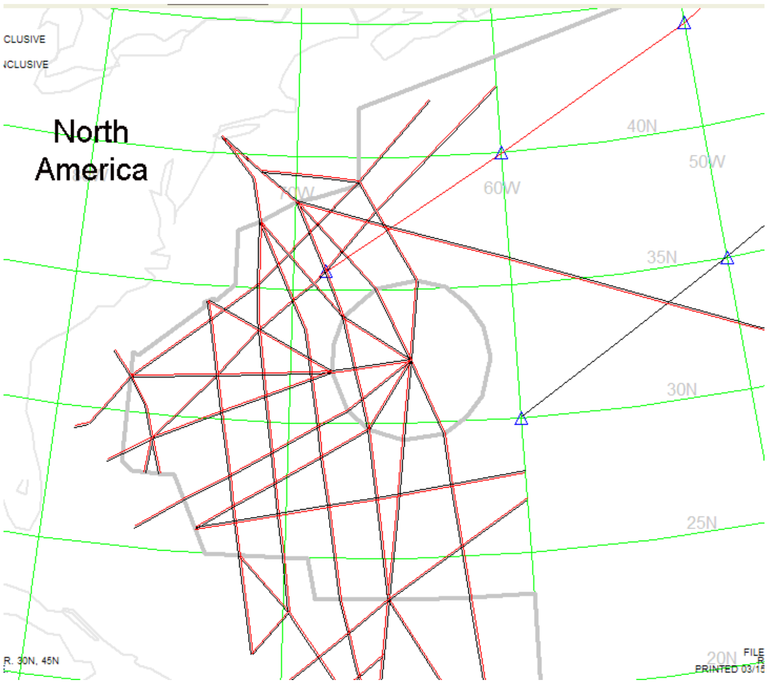


Figure 3-11: The dense, crossing routes flown in WATRS [17].

Figure 3-12: The primary means of control for the New York and Oakland Center controllers is paper flight strips (*right*). A situation display is also available for reference (*left*).

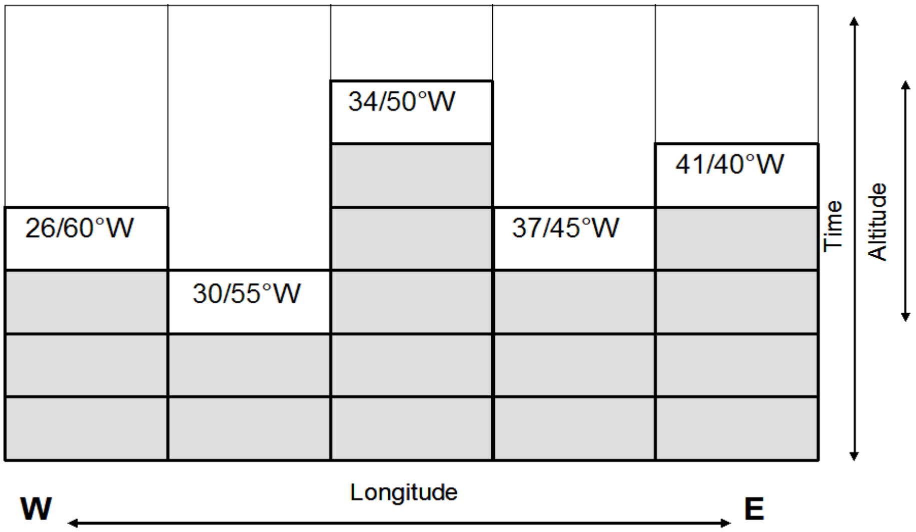


Figure 3-13: Paper flight strips at New York Center are first organized vertically by time and then by altitude. Horizontally there is a copy of each strip in each longitudinal position it passes through.

that is needed for meeting the longitudinal separation. As shown in Figure 3-13, the columns represent the position reporting points or other critical points, such as crossing traffic. Within these columns the strips are arranged by time, with the next strip at that waypoint on the bottom. This allows the controller to ensure that multiple aircraft will not arrive at the same point at the same time (or within the designated separation minima).

The future U.S. workstation, the advanced technologies and oceanic procedures (ATOP), shown in Figure 3-14, is being developed and planned for implementation in 2005. ATOP consists of electronic flight strips and an improved situation display. The plans for this workstation include using the spatial display as the primary means of separation. All available radar information, ADS-A, and position report information will be integrated and displayed on the situation display. Further decision support tools for identifying and resolving conflicts are also planned for future workstations. ATOP is currently used at Oakland Center on a limited basis and simulators for training are installed at New York Center.

Figure 3-14: ATOP is the future oceanic ATC workstation scheduled to replace ODAPS in the U.S. facilities in 2004 and 2005.

3.6.2 Detailed Observations

Facility Technologies

ODAPS is fully integrated into all NAT sector workstations. The Situation Display provides the controller with a spatial representation of the traffic situation display.

ODAPS was not however fully integrated into the WATRS sectors because of controller resistance. The sector controllers use paper flight strips, sector maps, and print-outs of ARINC messages only. There is an additional workstation added to the WATRS area to monitor ODAPS for conflict alerts and electronic messages and ensure that they are being attended to by the sector controllers. Without the situation display, sector controllers have to plot out close crossing or merging traffic on the sector map with a grease pencil to determine if there is adequate separation. Figure 3-15 shows a picture of one of the erasable maps used at Oakland Center, pictures of the map were not allowed at New York Center. The ruler used to draw the routing and measure the spatial separation is shown in the bottom right corner. This process is imprecise. For example, the controllers reported that the grease pencil line is approximately 8 nm in width on their sector map.

The controllers reported that ODAPS does not account for RVSM. Therefore a

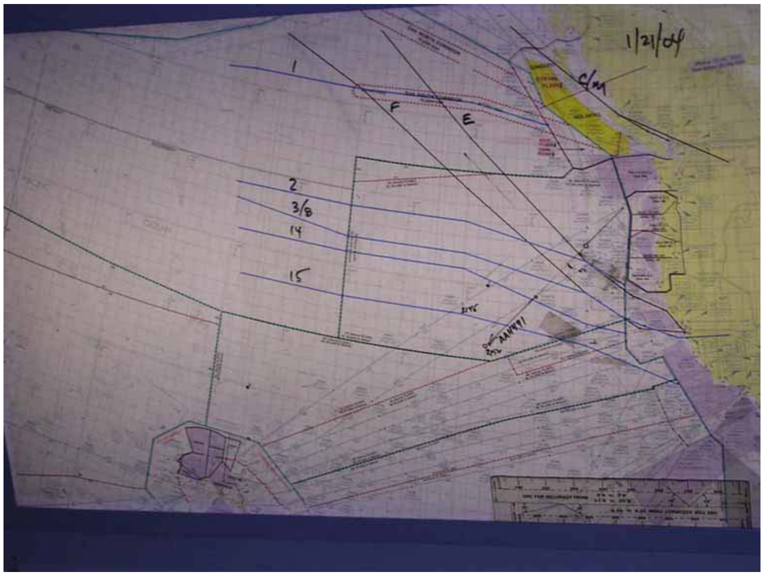
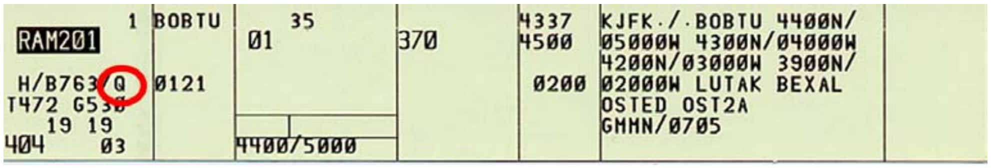


Figure 3-15: Erasable map used to plot out routings to determine separation for crossing or merging traffic.



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         1 BOBTU        35           4337 KJFK./.BOBTU 4400N/
RAM201          01          370      4500 05000W 4300N/04000W
                                          4200N/03000W 3900N/
 H/B763/Q  0121                      0200 02000W LUTAK BEXAL
T472 G530                                 OSTED OST2A
   19 19                                  GMMN/0705
404     03      4400/5000
```

Figure 3-16: Equipage information is shown using a one-letter designator on the flight strip in the U.S. facilities. This aircraft is equipped for RVSM and RNP-10 (“Q”).

false alarm is produced by the conflict probe for RVSM aircraft that are separated by less than 2000 feet.

Mixed Equipage Issues

Since RVSM is applied to NAT and WATRS traffic navigation equipage information is displayed on the paper flight strips, illustrated in Figure 3-16. There is a one-letter designator for the equipage; “W” represents RVSM certification, “R” represents RNP-10, and “Q” represents RVSM and RNP-10.

Datalink capability is indicated on the display that contains electronic messaging. This will be discussed further during the observations at Oakland Center.

Other Observations

The New York controllers reported that their job consists mostly of reactive tasks. They spend a significant amount of time waiting for new information, such as pilot position reports or pilot requests. Also, since they primarily use paper flight strips, there is no means of alerting them to overdue position reports, so they must manually monitor for them.

The controllers were observed to spend a considerable amount of time updating their flight strip bays. This included removing outdated strips, adding in new strips, and assuring that current strips were in the correct position. The electronic flight strips provided by ATOP will remove these tedious tasks.

3.7 Oakland Center Observations

At Oakland Center, three days of observations were conducted. During the visit nine sector controllers were observed. Four of the controllers were controlling in South Pacific non-radar sectors and five were controlling in the North Pacific non-radar sectors. A controller in the traffic management unit (TMU) was also observed in order to understand the planning tools.

3.7.1 Overview of Facility

Oakland Center controls most of the non-radar airspace in the Pacific, which is demonstrated in Figure 3-17. Traffic in the Pacific is much less dense, but the flights are usually longer, which makes receiving optimal routing critical. For this reason, ATC initiatives such as RHSM based on aircraft navigation performance (RNP) and implementation of conflict probes have emerged first in the Pacific airspace.

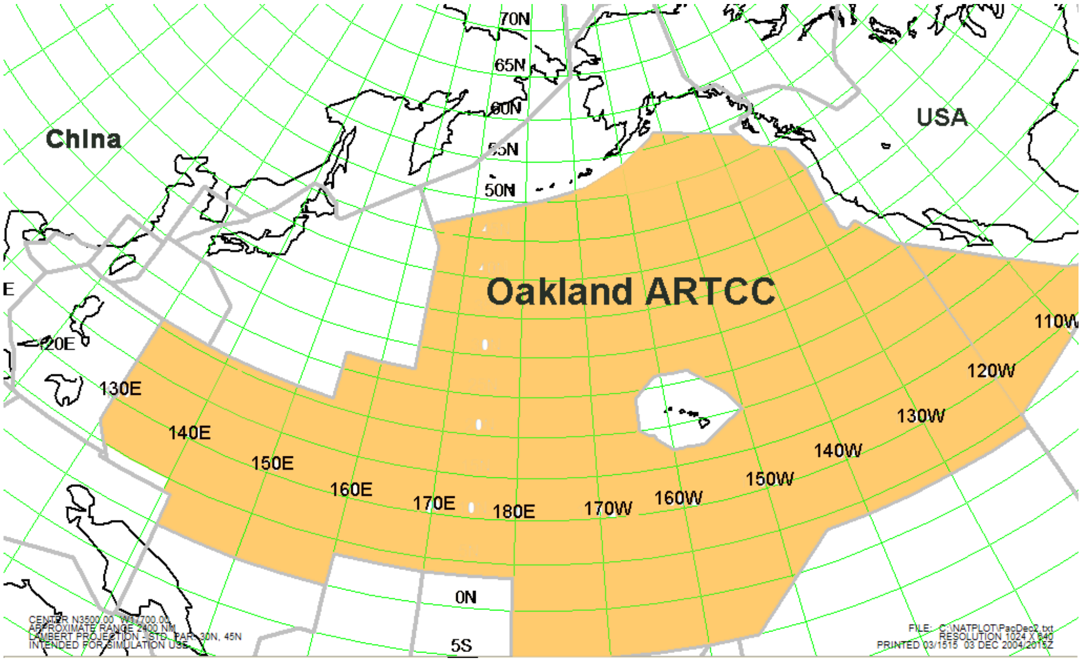


Figure 3-17: Oakland airspace extends over most of the Pacific Ocean. [17]

3.7.2 Detailed Observations

Facility Technologies

ODAPS was fully accepted by the controllers at Oakland Center. The situation display is particularly helpful in the Pacific airspace because the routes flown are not always parallel like the NAT tracks. The spatial display allows the controllers to more easily determine lateral separation.

Several inconsistency alerts generated by ODAPS were observed at Oakland Center. These inconsistencies occured during data input because ODAPS cannot receive different forms of the same message. One of the alerts observed occurred because position information for an aircraft with an ID of XX081 was entered by the radio operator as XX81. ODAPS generated an error and did not update the flight information on the situation display. This created an inconsistency in the traffic situation displayed on ODAPS and the information on the flight strips. The controller manually notates changes directly on the strips. Therefore information on the strips is more accurate since the controller is flexible and can adapt the received messages to the form he/she needs them in. The observed poor data quality of the situation display

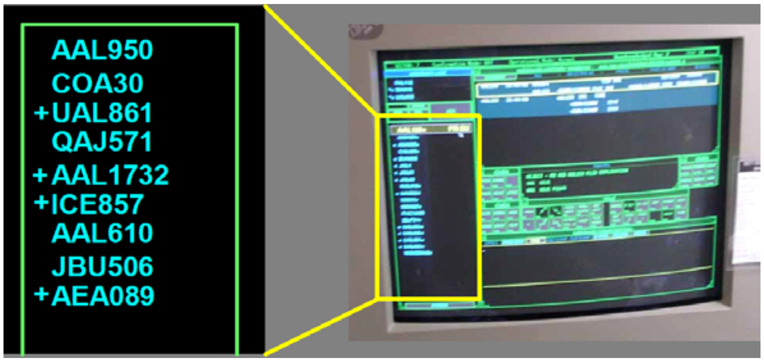

AAL950
COA30
+UAL861
QAJ571
+AAL1732
+ICE857
AAL610
JBU506
+AEA089

Figure 3-18: Communication window contains a list of aircraft within the sector. Aircraft equipped with Datalink have a “+” next to their aircraft ID. Controllers click on any aircraft ID to send an electronic message.

resulted in very little trust by the controllers in the system. They were observed to only refer to the situation display when workload was low, to relieve boredom. Once improvements are made to the data input quality for ATOP, controller trust in the situation display is expected to increase.

Mixed Equipage Issues

At Oakland, there was a higher percentage of traffic equipped with Datalink. The controllers were shown a list of all the aircraft in their sector. To send an electronic message they clicked on that aircraft’s ID. An illustration of this list is shown in Figure 3-18. However, not all of these electronic messages were delivered at the same rate. The “+” next to some aircraft IDs represents Datalink equipage. The messages sent to aircraft equipped with Datalink were observed to be received and confirmed within approximately thirty seconds, whereas the latency of the messages sent to aircraft without Datalink varies, as described in chapter 2. The controllers were observed to have different thresholds for the different communication frequencies. One example of this was observed when an aircraft without Datalink made a flight level change request near the border of the controller’s sector. The controller refused the request and explained that when there are temporal constraints, such as approaching the border of their sector, they will not make any unnecessary changes to aircraft without Datalink.

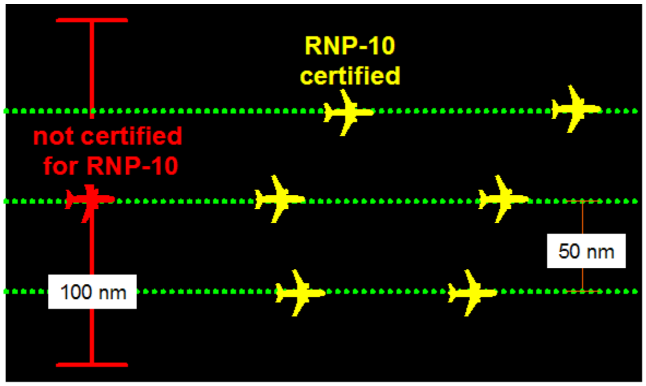


Figure 3-19: When an aircraft that is not certified for RNP-10 enters the Pacific tracks dedicated to RNP-10 aircraft, the controller must spend all their time ensuring separation on the surrounding tracks.

Another unique aspect of operations over the Pacific is that many of the tracks are dedicated to aircraft certified for RNP-10. During observations, mixing separation standards based on aircraft equipage within an airspace region was found to negate some of the advantages of equipping. This was observed when aircraft without RNP-10 used the dedicated tracks. RNP-10 aircraft have a reduced lateral separation of 50 nm, from 100 nm for aircraft that are not certified. To gain the efficiency benefits of the reduced separation, most tracks dedicated to RNP-10 were separated by 50 nm. An aircraft that was not certified for RNP-10 requested to enter one of the RNP-10 tracks during the observations. The controller approved this request. The controller then had to manually ensure separation on the surrounding tracks, as is illustrated in Figure 3-19. Consequently, the controller was not able to address any pilot requests or other non-critical situations, which decreased the quality of the service provided to aircraft equipped with RNP-10.

3.8 Conclusions

Even though the aircraft in today's oceanic environment mostly meet the current equipage requirements the overall findings from the field studies suggest that the mixed equipage environment is limiting the control task. Variable communication latencies were observed to have a significant effect on controller planning. Findings show that workload increases when mixed equipage and performance-based separation standards must be managed by the controller. Also, equipped aircraft may not achieve the full advantages of equipping in a mixed equipage environment. As future equipage is introduced, these problems will be exacerbated.

The current method of displaying equipage information on the flight strip will not be adaptable to the expected future technologies and there is not a clear way to display an equipment failure, which may also become a problem in the future. Also, the discrete flight strip information and procedural control are not currently capable of handling the nearly continuous information that ADS, or other high frequency surveillance provides. Therefore high frequency surveillance information needs to be displayed on a spatial situation display. As the observations show, there are issues of trust and controller acceptance with the current situation display. Integrating high frequency surveillance with pilot position reports needs to be addressed further before implementation. This issues will be further studied through experimental analysis in the following chapter.

Chapter 4

Cognitive Effect of Mixed Equipage

4.1 Cognitive Model

A controller-centered cognitive model was developed based on a literature review and field observations. Previous human factors literature on situation awareness, decision processes, and structure-based abstractions [18] provided the framework for the model. The cognitive model is partly based on work by Endsley [19] and Pawlak [20]. A job task analysis [21] and field observations were used to gather a better understanding of the tasks of oceanic controllers.

The air traffic controller cognitive model, shown in Figure 4-1, consists of three states: Situation Awareness, Decision Processes, and Performance of Actions [18], [22]. During Situation Awareness, a concept developed by Endsley [19], the controller develops an understanding of the air traffic situation. First the incoming information is physically perceived, usually by visual or aural means. The controller's attention limits which elements of the environment are perceived. Then, during comprehension, the perceived data elements are integrated with the controllers goals. This is when the controller begins to understand what has been perceived. This information is fed into the controller mental model, which generates a projection of the current and future states of the air traffic situation. Structure imposed on the ATC environment (e.g., standard routes) create structure-based abstractions within the controller mental model. These abstractions provide context for the situations, which makes them

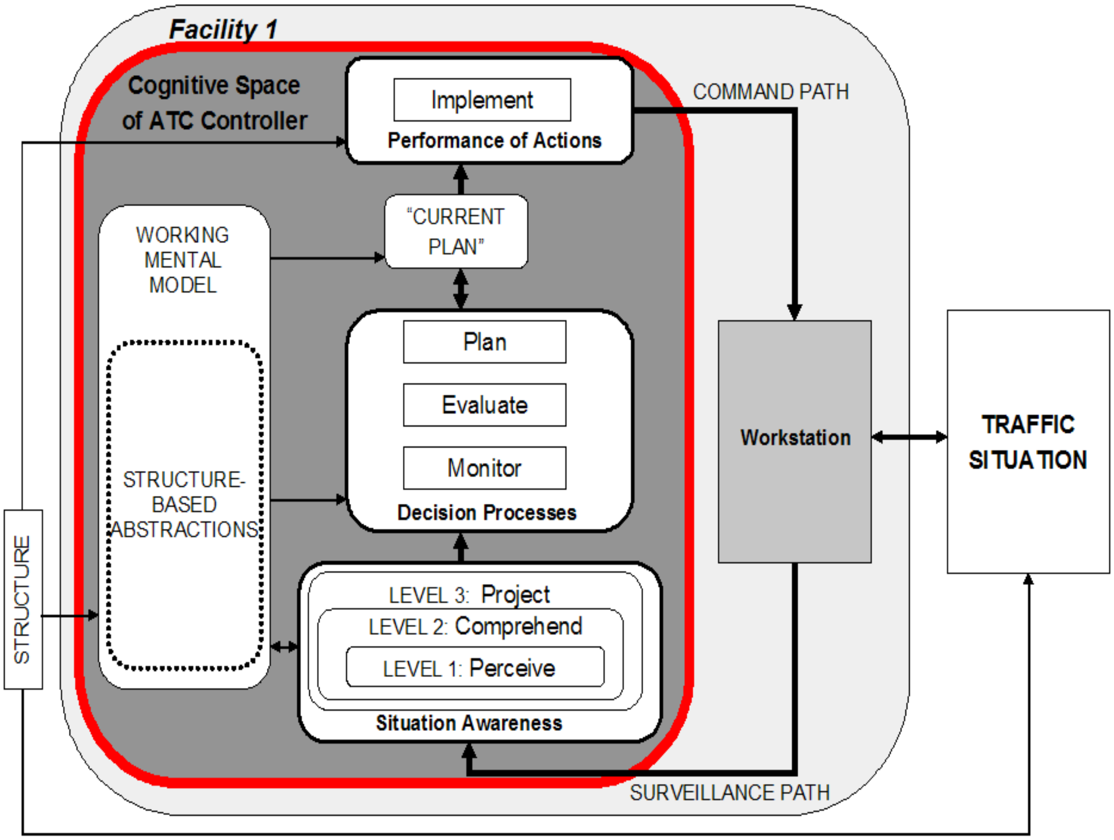


Figure 4-1: General cognitive model for air traffic controllers, partly based on work by Endsley [19] and Pawlak [20].

easier to understand.

Situation Awareness serves as the basis for the Decision Process. If the controller does not develop adequate Situation Awareness, then he/she will not be equipped to make the best decisions. During the Decision Process the controller first monitors the situation. To do this he/she compares the current and future state of the air traffic situation to the expected states to see if there are any deviations. If there are not any deviations, the controller continues to develop his/her Situation Awareness. If there are deviations then the controller evaluates the situation to determine if the deviations are within their threshold of acceptability. If the deviations are outside this threshold, the controller plans an alternate solution which he/she uses to update his/her "Current Plan". The "Current Plan" is a dynamic, internal representation of scheduled events and commands that will ensure the safety of the air traffic situation. Performance of Actions is dependent on the timing established during planning. The implementation of the planned commands or events are executed through the controller's workstation, which was discussed in the previous chapter.

4.2 Impact of Mixed Equipage on the Cognitive Model

When the observed operational impact of mixing information from multiple surveillance sources and multiple communication modes and the application of various separation minima is considered in the context of the cognitive model, further understanding of the adaptation of the cognitive processes can be extracted. Since the onboard CNS equipage limits the surveillance and command paths, the controller cognitive processes are affected by aircraft equipage. Hence, the impact of introducing additional levels of equipage on controller cognitive processes needs to be addressed.

4.2.1 Control Inertia

The means for conducting surveillance and communication are two factors that contribute to an aircraft's control inertia. Control inertia is a concept that is defined as the representation of the perceived work required by the controller to modify an aircraft route or trajectory from what is planned. The work required, i.e. inertia, depends on the resistance to a change in the air traffic situation. More specifically, the term work refers to process limitations as well as cognitive requirements. High control inertia is caused by impediments in the cognitive processes of the controller to develop a plan for modifications or impediments in the physical implementation process. High control inertia results in reduced flexibility in the ATC environment and the need for increased separation to make up for the limited ability of the controller to intervene in the air traffic situation.

The type of communication and its equivalent communication latency have a significant effect on control inertia because communicating a command is the only means the controller has for modifying the aircraft route. Therefore, communication limitations result in an impediment in the implementation of a modification. Communication issues also influence control inertia for downstream changes. This uncertainty in the ability to make a modification in the situation at future time may cause a controller to be more conservative in their present decisions. In general, longer communication latency results in higher control inertia.

Surveillance and display limitations also effect control inertia. The controller uses displayed flight information, which is partly based on surveillance, to produce a picture of the current state and project the future state of the air traffic situation. Therefore, cognitive compensation is necessary where there are issues with surveillance or the display of the flight information. In particular, the development of situation awareness becomes more difficult with greater surveillance or display limitations. Slower surveillance update rates and poor algorithms for projecting flight information displayed on the situation display are two examples of factors that currently limit control inertia. These limitations effect the formulation of the plans for modifications, as well as the feedback loop for determining if the changes were correctly implemented.

Control inertia plays a role in the planning process. In oceanic ATC the planning process consists of two functions, which are included in the generic functions that are performed across a range of systems established by Endsley [23]. The first is to generate options or potential solutions, the second is to select an option or plan, which then becomes the "Current Plan." The selection process is limited by the control inertia of the aircraft involved. The controller does not always choose the most optimal option, but rather the option that seems to be the safest. This typically translates into minimizing the total control inertia.

There are many operational situations that are effected by the role of control inertia on the planning process. For example, if an aircraft has a high control inertia and makes a time critical request the controller will not consider the request, even if a change is possible. In the mixed equipage environment, this limitation on the planning process reduces the advantages achieved by highly equipped aircraft. For instance, if there is a conflict between an aircraft equipped with enhanced communication and surveillance and an unequipped aircraft, the controller will be more likely to resolve the conflict by maneuvering the equipped aircraft because it has a lower control inertia. This solution is not optimal under most circumstances because it reduces the benefits achieved for the highly equipped aircraft by requiring the equipped aircraft to deviate from the most direct route.

4.2.2 Cognitive Impact of Mixed Surveillance Equipage

Air traffic controllers determine the state of the air traffic situation through surveillance. Limitations of the surveillance path not only affect the control inertia, they also increase the amount of uncertainty the controller has in their understanding of the situation. Therefore the limitations should be minimized. Two potential limitations identified through the cognitive model are the display of position information with asynchronous update rates and inconsistency in the real update rate and the display update rate.

In oceanic ATC, the surveillance update rate is once per hour. To compensate for this slow update rate tools have been developed to assist in the controllers' projection. This is done by extrapolating the aircraft path based on the flight strip information and displaying the continuous projection on a spatial display. This provides the controller with misleading information. For example, when a new position update is received, it can often be very different from the displayed position and require a sudden jump in the position of the aircraft target on the situation display. The mismatch in the real surveillance update rate and the display update rate leads to a lack of trust in the spatial display.

Fusing improved surveillance information with information provided by pilot position reports needs to be addressed. Displaying asynchronous update rates can increase the cognitive complexity of the situation for the controller. The combined display of asynchronousisms complicate observability. The varying update rates are visually distracting to the controller and thus they cannot easily perceive how the situation is evolving. This will limit the controllers' ability to project the future state. When the controllers' ability to project is limited, they may go into a less cooperative state and prefer to not make any unnecessary changes because of the uncertainty.

The controller is hypothesized to take steps to reduce the uncertainty. Two options have been identified as possible reactions to the mixed surveillance environment. The first is to treat all aircraft as if they were equipped with the slowest surveillance update rate. This is the lowest common denominator effect. The second reaction is to establish cognitive strategies to reduce the amount of uncertainty in the situation. Both of these options may be used at various times.

4.2.3 Cognitive Impact of Mixed Navigation and Separation Standards

As navigation performance improves and pilots are able to more precisely define and monitor their routes aircraft can be brought closer together. During the transition aircraft not equipped with enhanced navigation will still require current separation minima. Also, separation minima can be reduced based on improvements in communication and surveillance, which will allow for more timely intervention by the controller. Hence, aircraft equipage is a new attribute that controllers need to be aware of during situation awareness in order to determine which separation standards to apply. This attribute must then be considered during their decision process.

In the mixed equipage environment controllers will have to apply different procedures, such as separation minima, to aircraft with different levels of equipage. In the case of equipment failures the procedures applied to a single aircraft will also be varied. When given multiple procedures, the controller is hypothesized to use the lowest common denominator strategy and apply the worst case procedures to all aircraft to ensure safety.

4.2.4 Trust

The issue of uncertainty was introduced in the discussion on control inertia. When controller uncertainty is based on the tools given, their trust in the tools will degrade. There were two specific trust issues identified. The first is a general distrust of the information. Oceanic situation displays are based on a model that uses limited input information because the position reports are infrequently updated. This causes the controllers to be generally skeptical of the situation display. Also, if the controllers observe multiple inconsistencies in the displayed information and the real world, their trust in the display degrades. As more frequently updated surveillance becomes available, the controllers' trust in this new information may be limited if high and low frequency surveillance are mixed in the same airspace region.

The second issue is a distrust of the conflict probes. Reduced separation due to RVSM and radar is not currently included in conflict detection. This creates numerous false alarms, which degrade controller trust in the conflict probes. In the mixed equipage environment, separation standards will be significantly evolving. In order to maintain controller trust, reduced separation minima must be immediately used to update the conflict probes.

4.3 Conclusions

Overall, mixed equipage will have a major effect on the controller cognitive processes. Not only does the controller have a new attribute to be aware of and consider in their decision processes, but varying surveillance frequencies and communication latencies will affect controller trust in the information displayed and aircraft performance. These cognitive issues were studied further through experimentation. The results are discussed in the following chapter.

Chapter 5

Experimental Studies

The number of surveillance updates within a given time period is defined as surveillance frequency. Fusing high frequency surveillance with low frequency surveillance and varying the minimum separation between the two levels of equipage will introduce a new oceanic ATC environment. This is currently experienced operationally on a limited basis. Mixed oceanic and radar sectors experience a variation in surveillance frequency. Also, in the South Pacific aircraft that report their position over HF radio are integrated with aircraft equipped with ADS-A. The cognitive implications for the controller and resulting operational impacts in the mixed surveillance equipage environment have not previously been studied. This experiment sought to determine how controllers handle multiple surveillance update rates and varying separation minima.

5.1 Approach

The experiment performed consisted of participants monitoring and controlling air traffic in accelerated time. The airspace and traffic flow were modeled after oceanic ATC. An example of the display used to complete these tasks is shown in Figure 5-6.

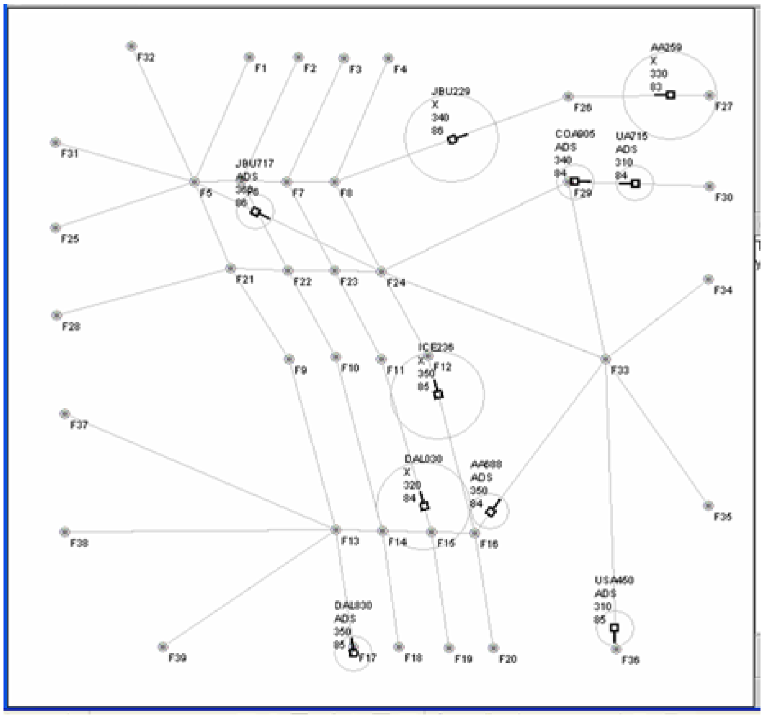


Figure 5-1: ATC display used for experiments.

5.2 Objectives

The objectives were two-fold. First the experiment was designed to gather a better understanding of the cognitive implications of the mixed equipage environment. Specifically controller workload, situation awareness, and trust were examined. The second objective was to determine whether controllers would negate the benefits achieved by the highly equipped aircraft because of the limitations of the unequipped aircraft.

5.3 Variables

The independent variables for the first experiment were the surveillance frequency and the minimum separation. These were varied between aircraft equipped with ADS (high frequency) and those that were unequipped (low frequency). The aircraft target updated once per surveillance update, representing the known information about the aircraft to the subject. The difference in the update rates was modeled after the current oceanic environment where low frequency aircraft report their po-

Scenario	**Equipage Type**	**Surveillance Frequency**	**Minimum Separation**
1	High	1:12	20 nm
2	Low	5:60	50 nm
3	Mixed	Mixed	Mixed

Table 5.1: Three scenarios used in this experiment.

sition approximately once every hour and the high frequency aircraft reporting rate is currently set at one report per five minutes [10]. The time scale was shortened proportionally due to time constraints. The minimum separation was modeled after those currently used in the Pacific and those that are planned for the future [12].

The dependent variables were participants' subjective assessment of the difficulty of each scenario, situation awareness, controller trust in the position information, and which aircraft the controller maneuvered during the mixed scenario. The controller was hypothesized to maneuver the equipped aircraft when faced with a conflict between an equipped and unequipped aircraft. In the mixed scenario, situation awareness was expected decrease and difficulty was expected to increase.

5.4 Scenarios

The subjects were presented with three, five to seven minute scenarios, shown in Table B.1. Scenario 1 consisted of only aircraft equipped with high frequency surveillance, which had a surveillance frequency of 1 update per second (1 update/0.5 minutes) and minimum separation of 20 nm. Scenario 2 consisted of only aircraft equipped with low frequency surveillance (or unequipped aircraft), which had a surveillance frequency of 1 update per 30 seconds (1 update/15 simulated minutes) and minimum separation of 50 nm. Scenario 3 was the mixed case, in which 50% of the aircraft were equipped with ADS and 50% were unequipped. The equipped and unequipped aircraft maintained the separation minima appropriate for their surveillance frequency, as described for the first two scenarios.

For each of these scenarios there was moderate traffic and the airspace geometry was varied, however the level of complexity was held constant. A primary geometry

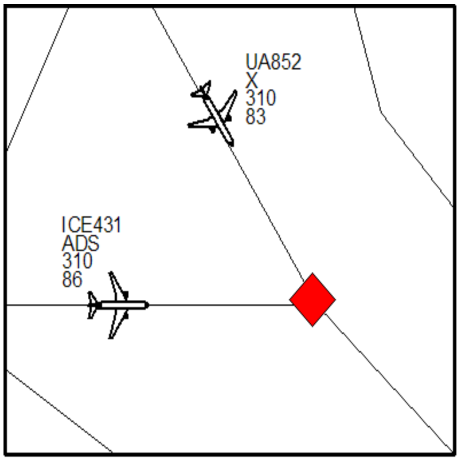


Figure 5-2: Example of the first merging conflict used in the three scenarios. The point of conflict is shown with a diamond.

was designed and then rotated or flipped for the different scenarios so that there would not be a "training effect."

Four conflicts were designed or changed in a superficial manner to maintain consistency across the scenarios. The four conflicts were built into each of the three scenarios in random order. Two merging conflicts between two aircraft, as shown in Figure 5-2 and 5-3 and a head on conflict, shown in Figure 5-4 were included in each scenario. The fourth conflict was more complex, involving four aircraft that were all merging at one point. Two of the aircraft were on the same flight level, another was one flight level above and the other was one flight level below. Figure 5-5 demonstrates this conflict. There were also three pilot requests, which were easy to medium difficulty. The responses were not used in the analysis.

5.4.1 Participants

The participants were air traffic controller trainees. The experiment took place approximately three weeks prior to their full ATC certification. A questionnaire was administered to determine the level of the participants' operational control experience. As part of their air traffic controller training, the participants controlled in the actual ATC operational environment under the supervision of fully certified controllers, for an average of 24 months (SD=0.899). Their experience was in Enroute

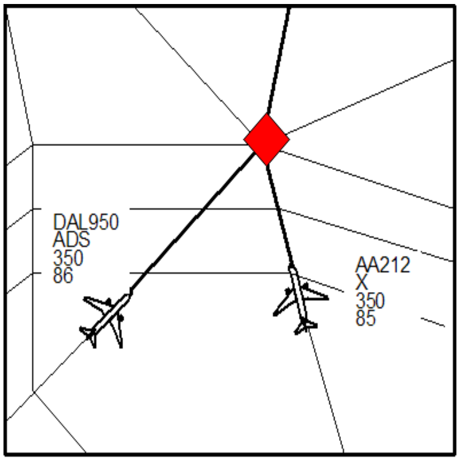


Figure 5-3: Example of the second merging conflict used in the three scenarios. The point of conflict is shown with a diamond.

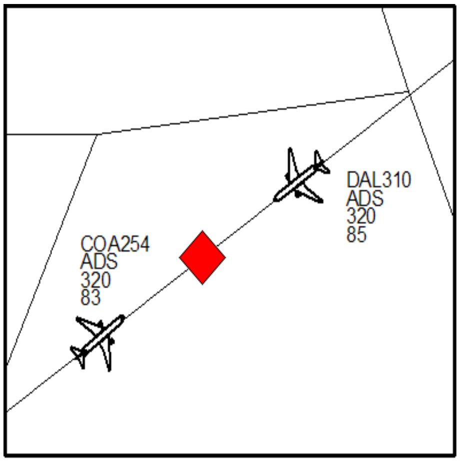


Figure 5-4: Example of the head on conflict used in the three scenarios. The point of conflict is shown with a diamond.

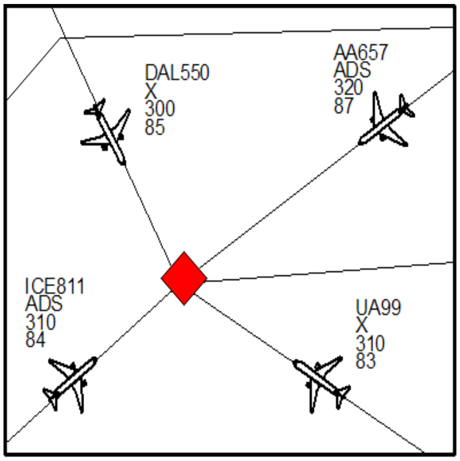


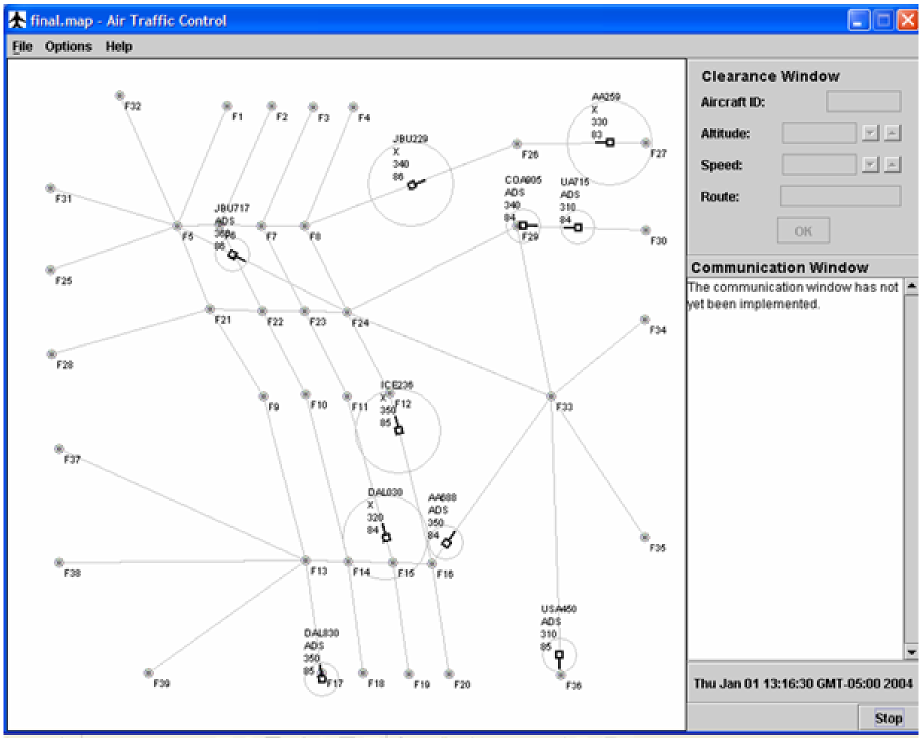
Figure 5-5: Example of the fourth conflict used in the three scenarios. The point of conflict is shown with a diamond.

Centers and Approach Centers (TRACON and Tower).

5.5 Air Traffic Control Simulator

A PC-based low fidelity ATC simulator was developed for this experiment. The display, shown in Figure 5-6, is a spatial representation of air traffic, which simulates generic oceanic airspace. The scale of the screen is 1 inch = 100 nm. The display consists of aircraft targets (a small box with a tail extended to represent the direction of flight), data blocks, jet routes, and fixes. A circle with a radius equal to the minimum separation surrounds each aircraft target. The circle can be removed during the simulation by right clicking the aircraft icon. The datablock includes the aircraft callsign, equipage information (ADS or non-ADS), altitude (flight level), and speed (Mach number). Each fix is labeled with a fix number to provide a means for the subjects to issue relative commands, such as "climb to FL330 after F5". The aircraft position on the spatial display is updated once per surveillance update. In the mixed equipage scenario, aircraft with different surveillance types update at different frequencies.

Aircraft information can be changed by left clicking on the aircraft icon. When this is done the route of the aircraft is highlighted and the information about the



The communication window has not yet been implemented.

Figure 5-6: Low fidelity ATC simulator designed at MIT and used for the experimental analysis.

aircraft appears in the “Clearance Window”. Here, subjects can make changes to the current flight plan of an aircraft. Changes appear with the next refresh, except for flight level changes, which update at a rate of 950 feet per second. This is modeled after the average climb rate of oceanic aircraft.

A trial run with five air traffic controller trainees was conducted prior to the experimental runs to verify the simulator and collect comments on both the simulator and the mixed equipage environment. Some of the functions of the simulator described above were added based on the feedback from this trial run.

5.6 Procedures

Participants were individually brought into a conference room to run the experiment. First, they received written instructions, included in Appendix B, explaining the procedures, the simulator, high frequency and low frequency surveillance capabilities, and separation standards. They then performed a training scenario that consisted of mixed equipage, three to four conflicts, and two pilot requests. The participants were instructed to maintain specified separation standards and reply to pilot requests. The three scenarios were administered in random order. During each of the scenarios there were three pilot requests and four scripted conflicts. The participants completed a difficulty rating following each of the scenarios and a post-experiment questionnaire after completion of the three scenarios.

Following the experiment the controllers were given a presentation on the research activities surrounding this experiment, including results from the field studies and modeling analysis. They were also given a handout with a description of the objectives of the experiment. The handout is included in Appendix C.

5.7 Metrics and Data Analysis

Performance metrics included notes taken during the observations and a log of the actions the subjects took. Subjective data was collected after each scenario and following the completion of the experiment. A log records the change, aircraft ID, and time of change. After each scenario, the subjects rated the difficulty of that scenario. The post-experiment survey was used to gather further data. The survey can be found in Appendix D. The post-experiment survey consisted of ratings, rankings, and free response questions. Participants' answers to the free response questions are included in Appendix E.

Since there was a limited amount of time with each group of controllers and the number of subjects needed to be maximized, the options for workload metrics were limited. NASA-TLX, performance on a secondary task, and subjective assessment of difficulty rating were all considered. The first two options required a significant increase in the total experiment time, therefore the difficulty rating was chosen. The subjects completed a post-scenario rating of the difficulty of each scenario. They also completed a post-experiment survey ranking of the scenarios. Participants were also given a free response space to justify the most and least difficult scenarios. In order to learn more about controller workload the subjects were asked to state how many aircraft they felt they could safely handle in each scenario after the completion of the experiment.

Situation awareness is challenging to measure. Several methods were explored and the performance-based testable response method was chosen because of its non-intrusive nature. Subject performance and the time required for the subjects to recognize and resolve the four planned conflicts was measured and compared across the scenarios to gain insight on their situation awareness. The time a conflict was recognized was an observable measure, defined as the time at which the controller first looked at the pair in conflict or began to click on them. The simulator automatically recorded all actions by the subject, therefore the time to resolve a conflict was extracted from the participant action data. During data analysis some of the subjects reported different strategies than others, which affected their situation awareness. This was analyzed further and will be discussed in the section 5.8.

Trust was measured through a confidence rating. During the post-experiment survey the subjects were asked to rate their confidence in the position of aircraft with high frequency surveillance and those with low frequency surveillance on an anchored scale of 1 to 5. This data was used to gain a better understanding of how controller trust is affected by varying surveillance frequency.

In order to determine whether the aircraft equipped with high frequency surveillance were receiving the full benefits of equipping in the mixed scenario, the subjects were asked which aircraft they were more likely to maneuver, aircraft with high or low frequency surveillance, when resolving a conflict between the two. The subject responses were compared to their performance during mixed conflicts.

Each of the dependent variables were analyzed using a one way ANOVA. The ANOVA analysis was used to test the difference in the means of the three scenarios for each of the dependent variables for statistical significance, within an acceptable amount of error. The α-value represents the acceptable amount of error. Typically 5% (0.05) or less is considered acceptable for significance, this is the critical value that was used for the analysis in this thesis. To further determine if there was a significant difference in the means of the high frequency surveillance and mixed scenario pair and the low frequency and mixed scenario pair analysis using the related-pairs *t*-test was used. This *t*-test is commonly used to determine if the difference in the means of two factors is truly different or if the observed difference is coincidental. To do this the amount of error in the data is estimated by computing the *t*-value, which is then compared with the acceptable amount of error. Significance is determined by comparing the *t*-value to the table containing the critical points of the one-sided *t*-distribution, which can be found in Appendix F. This table gives *t*-values for different degrees of freedom (df) and α-values. The df is equal to the number of participants minus one, therefore the df used for the analysis is eight, unless otherwise stated. Based on the Bonferroni correction, the critical α value used in the related-pairs *t*-tests was .025 ($.05/n$, where n=2 for the two additional tests required). Therefore *t*-values less than or equal to 2.306 are statistically significant in this study, unless otherwise stated.

5.8 Results

The analysis was organized into four parts. The first part examined the subjective assessment of the difficulty of each scenario by the participants. The second part of the analysis examined participant situation awareness, based on the performance-based testable response method. The third part of the analysis evaluated participant confidence in the position information. Finally, the fourth part of the analysis examined participant bias towards equipped aircraft in the mixed scenario.

5.8.1 Scenario Difficulty

After each scenario, the subjects were asked to rate the difficulty of the scenario on an anchored scale of 1 to 5, with 5 being the most difficult. The results from the rating showed a significant positive effect of surveillance frequency, F(2, 8)=4.795, p<.018. Using the related-pairs *t*-test, a significant difference was identified between the high frequency and mixed scenario pair, p<.003. The results can be seen in

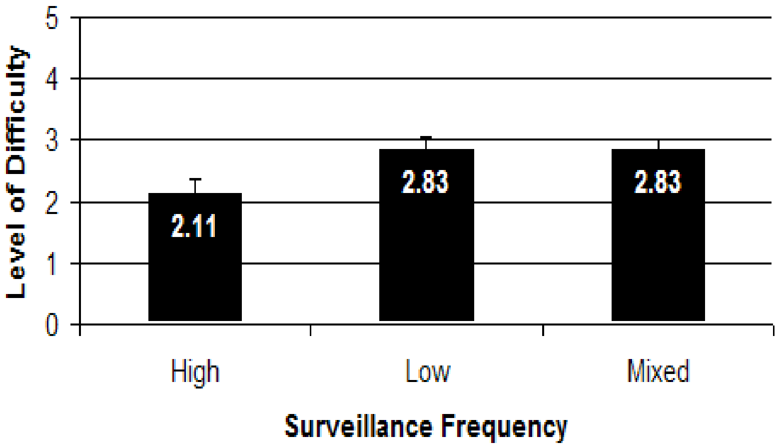


Figure 5-7: Results from the subjective assessment of difficulty for each of the three scenarios. The mixed scenario and the scenario with low frequency surveillance were both rated the most difficult.

Figure 5-7. The mixed and non-ADS scenarios received the highest, or most difficult rating. There was not a significant difference between the rating given to these two scenarios. This implies that the addition of a partially equipped fleet will not result in a reduction in controller workload, compared with the current environment.

The post-experiment ranking of the difficulty of the three scenarios also revealed a significant effect consistent with the post-scenario ranking, F(2, 8)=7.44, p<.004. Six out of the nine subjects reported that the mixed scenario was the most difficult. The remaining three subjects found the scenario with low frequency surveillance to be the most difficult, as is shown in Figure 5-8. The "Easiest Scenario" chart shows that six out of the nine subjects found the scenario with high frequency surveillance to be the easiest. Two of them found the scenario with low frequency surveillance to be the easiest and only one found the mixed scenario to be the easiest. The subject that found the mixed scenario to be the easiest reported that he/she thought there were less conflicts.

The final test for workload was attained through asking the subjects how many aircraft they felt they could safely handle in each scenario. An understanding of how many aircraft can be safely handled is common in ATC since controllers, with the

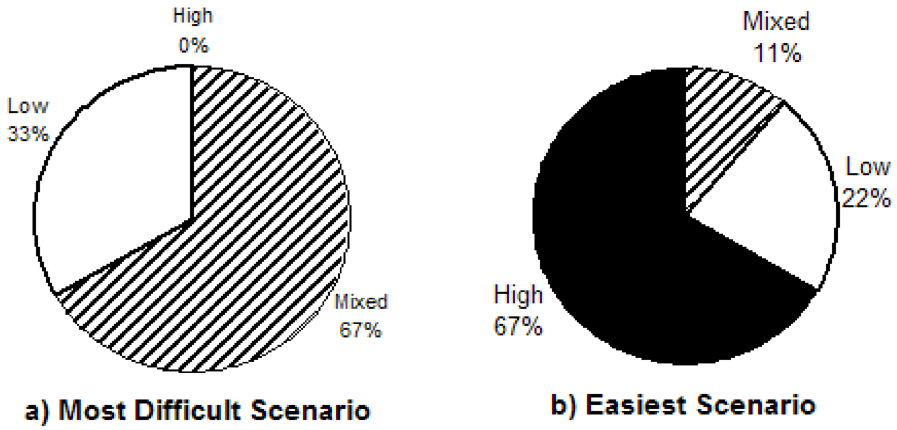


Figure 5-8: Results from the subjective ranking of the three scenarios.

	High Frequency	**Low Frequency**	**Mixed**
High Frequency	X	1.91	3.55
Low Frequency	X	X	2.03
Mixed	X	X	X

Table 5.2: Results of the related-pairs *t*-test reveals a significant difference between each of the three scenarios.

help of their supervisor, continually monitor their workload and ask for help when they become overloaded. The participants were assumed to be comfortable handling more aircraft when the scenario was less difficult. A non-significant trend was found in the subject responses across the three scenarios, $F(2, 8) = 3.207$, $p=.061$, with the mixed scenario having the least throughput. Figure 5-9 shows the results. The results from the related-pairs *t*-test, shown in Table 5.2 revealed a significant difference in the high frequency ($M=11$) and mixed cases ($M=7.125$), $p<.005$.

Overall, the three measures point to the same result, workload increases in an environment with mixed equipage. At the very least workload will not improve from an environment with low surveillance update rate to one with a fleet partially equipped with high frequency surveillance. This will have an impact on controller acceptance of the incorporation of this new surveillance information and also airline motivation to equip, since increased workload results in lower throughput. Increased workload

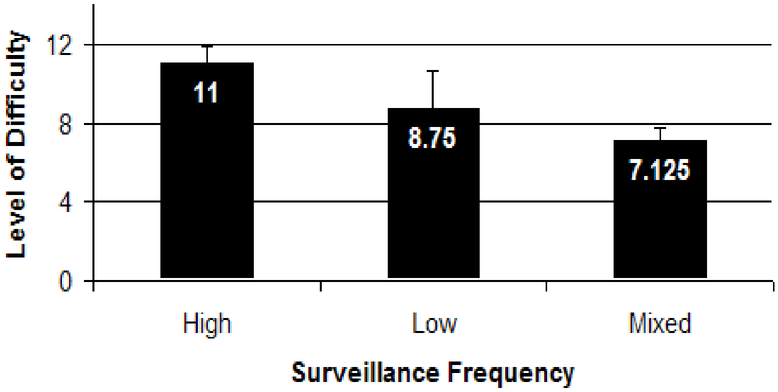


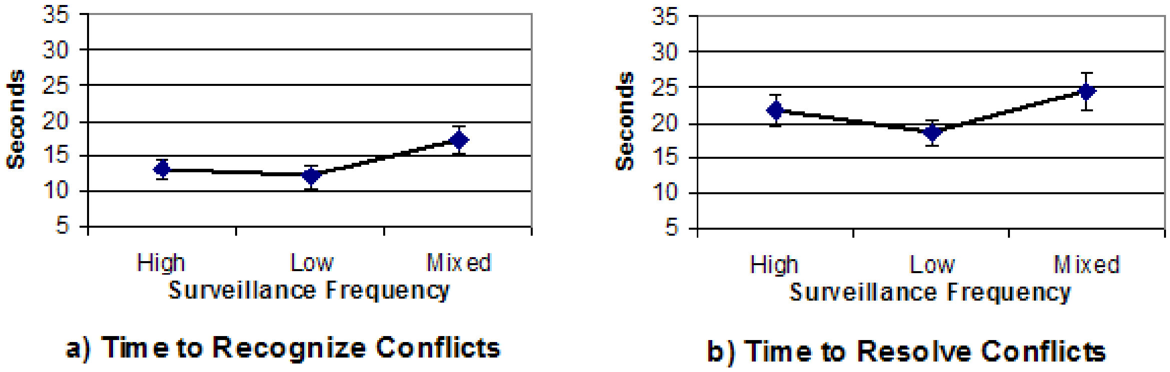
Figure 5-9: The number of aircraft the subjects felt they could safely handle in each scenario was used to gain additional insight on workload for the three scenarios. According to the results, the mixed scenario yields the lowest efficiency.

can also lead to a decrease in safety.

5.8.2 Situation Awareness

Four scripted conflicts were included in each scenario. Participant response to these situations was used to monitor situation awareness. There was a non-significant trend in the time to recognize the conflicts in the three scenarios, F(2, 8)=2.400, p=.115. The pattern of increasing situation awareness was most clear between the low frequency and mixed scenario pair, t=2.07, p=.039. The difference in the high frequency and mixed scenarios was not as apparent, t=1.395, p=.102. There was not a significant trend evident in the time required to resolve the conflicts. Both of these results can be seen in Figure 5-10. The subjects were asked to describe the strategies they used in the mixed scenario. When their responses were examined there was an anomaly. Two of the subjects (Subject 6 and 4b) reported that they applied strategies that allowed them to project the aircraft route earlier to anticipate conflicts well in advance. In other words, they increased their situation awareness. As expected, their performance data reveals that they reduced the amount of time required to recognize and resolve conflicts in the mixed scenario, as shown in Figure 5-11.

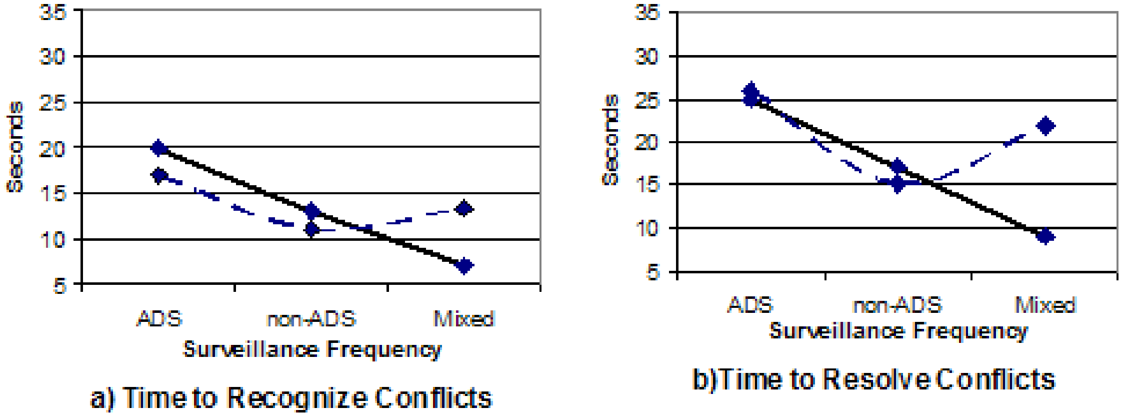
When Subject 6 and 4b are removed from the data the trend in the time to



a) Time to Recognize Conflicts

b) Time to Resolve Conflicts

Figure 5-10: Results from the average time required for the subjects to recognize (left) and resolve (right) the four conflicts.



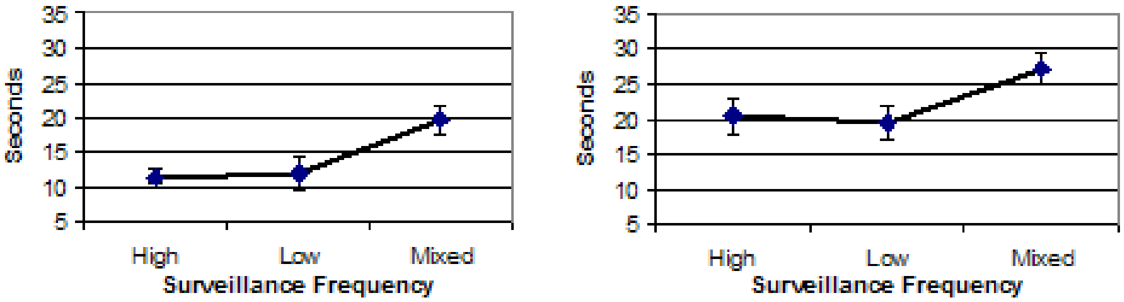
a) Time to Recognize Conflicts

b)Time to Resolve Conflicts

Figure 5-11: The time required by Subject 6 and 4b to recognize and resolve the conflicts increased in the mixed scenario because they applied a strategy to purposely increase their situation awareness.

recognize and resolve conflicts becomes much more distinguishable, as can be seen in Figure 5-12. There is a significant effect in the time required by the participants to recognize conflicts, F(2, 6)=5.827, p<.015. This measure significantly increased in the mixed scenario, compared to both the scenarios with high frequency, p<.002, and low frequency surveillance, p<.015. There is a non-significant trend in the time required to resolve conflicts, F(2,6)=2.398, p=.119. Both measures show that participant situation awareness degraded in the mixed equipage scenario.

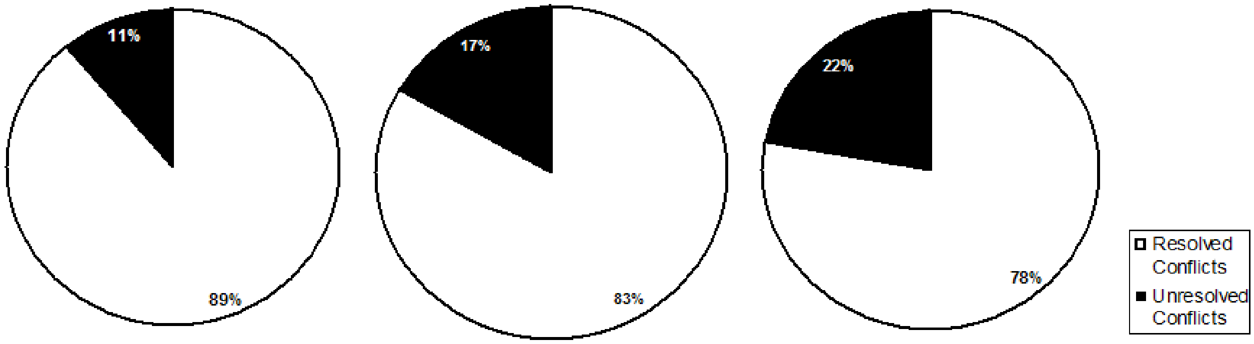
The final measure of situation awareness was in the number of conflicts detected and resolved. Figure 5-13 shows that there was an non-significant increasing trend



a) Time to Recognize Conflicts

b) Time to Resolve Conflicts

Figure 5-12: Results from the average time required by the subjects to recognize (left) and resolve (right) the four conflicts, without Subject 6 and 4a. The trend becomes more clear with these subjects removed from the sample.



a) High Frequency Surveillance

b) Low Frequency Surveillance

c) Mixed Surveillance

Figure 5-13: Proportion of resolved and unresolved conflicts in each of the scenarios.

in the number of unresolved conflicts in the mixed scenario. The pattern was most clear in unresolved conflicts between the mixed and high frequency scenario, p=.136. Participants were expected to miss very few conflicts overall because safety is the main focus of ATC and missed conflicts are in direct opposition to this goal. Therefore any differences in the scenarios were expected to be small. The difference is predicted to grow with more subjects, although a great number of subjects would be needed for statistical significance.

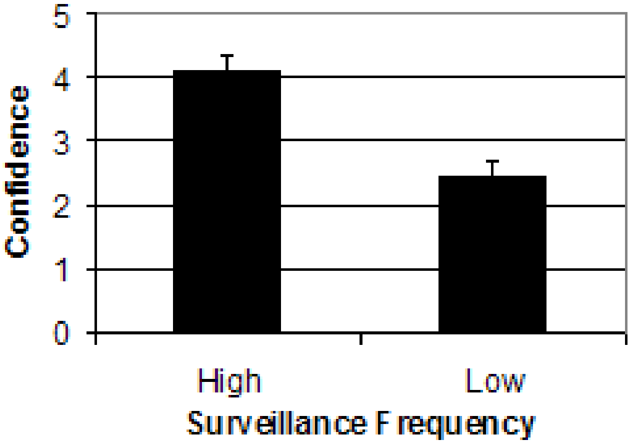


Figure 5-14: Subject confidence in aircraft position information rating for aircraft equipped with high and low frequency surveillance.

5.8.3 Subject Confidence

Subjective confidence rating by the participants on an anchored scaler of 1 to 5 yielded the expected results. There was a significant effect of surveillance frequency on confidence, F(2,8)=21.951, p=.002. As shown in Figure 5-14, the subjects rated their confidence in the position of aircraft with high frequency surveillance much higher than their confidence in that of aircraft with low frequency surveillance. Controller confidence effects the way controllers handle traffic. Since the participants had more confidence in the position of aircraft with high frequency surveillance, they were hypothesized to be more likely to maneuver these aircraft when there was a conflict with an aircraft with low frequency surveillance. This in turn reduces the efficiency of the flight for the aircraft equipped with high frequency surveillance. This was tested further with the next part of the analysis.

5.8.4 Aircraft Maneuvered

During the post-experiment survey the participants were asked which aircraft they were more likely to maneuver to resolve a mixed equipage conflict, aircraft equipped with high frequency surveillance or aircraft equipped with low frequency surveillance.

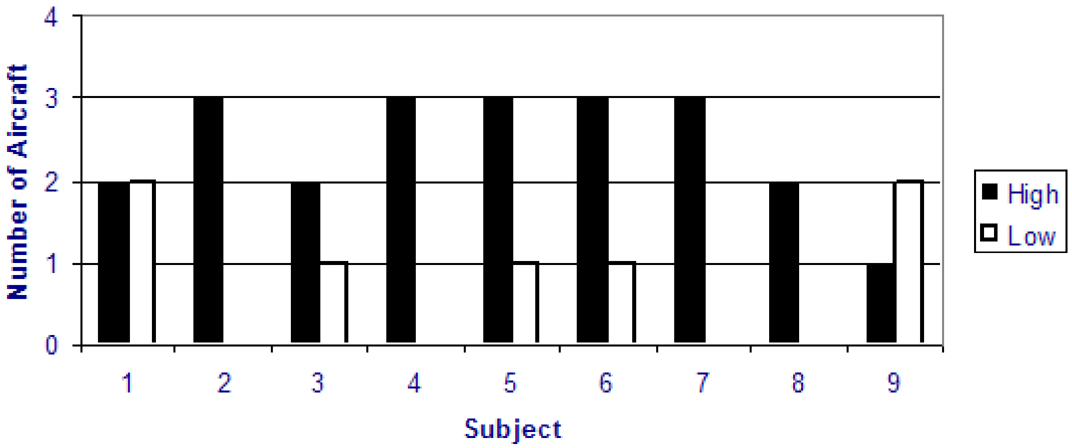


Figure 5-15: Performance results of the number of aircraft with high and low frequency surveillance that were maneuvered to resolve the four mixed conflicts.

All nine of the participants reported that they were more likely to maneuver aircraft with high frequency surveillance. This result matches their performance. A significant difference was found between the number of high frequency and low frequency aircraft chosen to maneuver by they participants, F(1,8)=20.455, p<.0003. The number of high frequency and low frequency aircraft that each participant chose to maneuver to resolve the four conflicts in the mixed scenario is shown in Figure 5-15. Some participants did not resolve all four conflicts because some of the conflicts were missed or averted with a previous maneuver.

5.8.5 Strategy for Determining which Procedures to Apply

The issues of applying varying procedures was discussed in the previous chapter. During this experiment this issue was examined further. The participants were found to deal with the mixed procedures by eliminating the variations as much as possible. One way they accomplished this was by maneuvering equipped aircraft when possible, as described above. This method was effective because the same procedures applied to all equipped aircraft. Secondly, most subjects used vertical separation to resolve conflicts. Vertical separation minima remained constant across all levels of equipage. This was discovered through the subject response to Question 8: “How did you determine which procedures to apply when you were shown aircraft with high and low frequency surveillance?" Seven out of nine of the subjects mentioned the use of vertical separation in resolving mixed conflicts. The full responses can be seen in Appendix E.

5.9 Conclusions

The data from this experiment proved the hypotheses to be true. The subjects found the mixed scenario to be the most difficult, their situation awareness decreased in the mixed scenario, they had less confidence in the position of the aircraft without ADS and therefore chose to maneuver aircraft equipped with ADS when in conflict with an unequipped aircraft. The following chapter discusses the implications of these experimental results on oceanic ATC.

Chapter 6

Implications for ATC Environment

Mixed equipage currently exists on a limited basis. CNS improvements planned for the near future are going to exacerbate current problems experienced. Cognitive issues were identified during the field studies and further determined through the experimental analysis. The experimental results show that cognitive limitations, such as increased workload and decreased situation awareness, will compromise safety and increase the potential for errors. Therefore serious consideration must be given to the integration of CNS capabilities and reduced separation standards. If methods for supporting the controller are not developed then the controller will continue using the current control tasks, since they guarantee safety for the lowest equipage capabilities. This will limit the evolution of oceanic ATC.

6.1 Phases of Implementation

The homogeneity of the oceanic fleet can be used to guide the development of methods for supporting the controller in the mixed equipage environment. The appropriate approach will be dependent on the current transition phase. Three phases were identified in this study. The first is titled “early adopters”. This is when a small portion of the fleet is equipped. The second phase is titled “partially equipped”. During this phase there is a split in equipage of the fleet, with approximately 30% - 70% equipped. The final mixed equipage phase is titled the “exception” phase. This is when most aircraft are equipped and only a few unequipped aircraft need to be dealt with. These three phases are not independent. The oceanic environment can be in different phases for each of the three CNS components. An understanding of the three phases can help in identifying solutions for the future.

6.2 Airspace Segregation Strategies

The experimental results presented reveals that controller workload increases, situation awareness degrades, and equipped aircraft do not receive the full benefits when varying surveillance update rates are combined in the same airspace. However, airspace segregation can be used to divide the airspace between varying levels of equipage. The grouping of aircraft with similar CNS performance will provide a structure-based abstraction for the controller. This cognitive mechanism will reduce the complexity of the control task in the mixed equipage environment.

Airspace segregation is currently used to dedicate flight levels for RVSM certified aircraft and tracks for aircraft with an RNP-10 rating. The type of segregation used should be based on the phase of implementation. Currently 98% of aircraft are certified for RVSM and RNP-10, therefore we are in an "exception" phase. During this phase the most desired airspace should be dedicated to highly equipped aircraft. The airspace dedicated to unequipped aircraft can be minimized and pushed far from the optimal airspace.

During an "early adopters" phase, difficulty will be experienced in providing full benefits to the equipped aircraft because the large portion of unequipped aircraft must be serviced. Once a critical mass is reached and the air traffic situation reaches the "partially equipped" phase a desired portion of the airspace can be carved out and dedicated to the equipped aircraft. As more aircraft become equipped, the airspace dedicated to equipped aircraft can grow and the unequipped aircraft can be pushed further from the desired airspace. Once the "exception" phase is reached unequipped aircraft can be pushed far enough away from the desired airspace that they are almost excluded, as is done for non-RVSM aircraft.

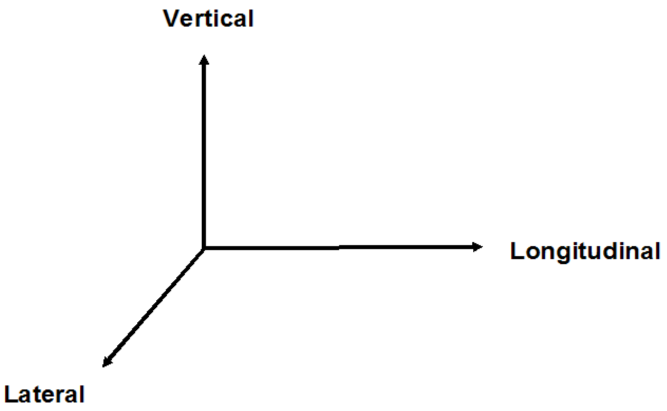


Figure 6-1: The three degrees of freedom for static segregation of airspace.

Strategies for segregation have been identified. There are four degrees of freedom about which airspace can be segregated. They are the vertical, lateral, longitudinal, and time axes. Vertical, lateral, and longitudinal separation can be used for static segregation, which is most appropriate for the "partially equipped" and "exception" phases. Time introduces a dynamic aspect of segregation. Therefore smaller areas of airspace can be carved out for equipped aircraft. This is most appropriate during the "early adopters" phase. The model for the three degrees of freedom for static segregation is given in Figure 6-1.

6.2.1 Vertical Segregation

Segregation along the vertical axis is currently used for RVSM aircraft, allowing only equipped aircraft between flight levels 290 and 410, as illustrated in Figure 6-2. Vertical segregation is used in other ATC domains for designating the direction of flight (e.g., odd flight levels are dedicated to one direction and even the other). Vertical segregation is limited though because it inhibits vertical flexibility. Changes in vertical position are currently used for resolving most oceanic conflicts, with other aircraft, turbulent conditions, etc. This may change in the future environment when separation standards are reduced, although training would be required to transition out of this model of conflict resolution. Therefore vertical segregation needs careful consideration before implementation.

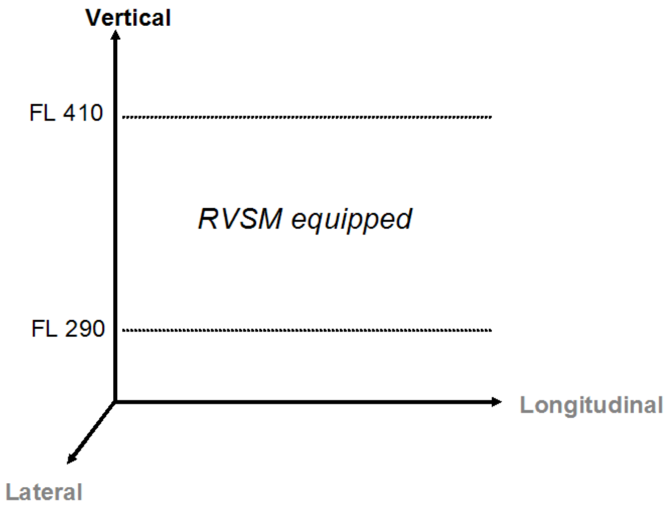


Figure 6-2: Static segregation of airspace along the vertical axis is currently used for segregation of RVSM airspace.

6.2.2 Lateral Segregation

Lateral segregation is also currently used in the Pacific. The most desired tracks are dedicated to aircraft certified for RNP-10, as illustrated in Figure 6-3. The current track structure in the oceanic environment is conducive to lateral segregation by track.

Ruigrok *et al.* proposed segregation of airways in the mixed ADS-B and non-ADS-B environment [24]. The airways were proposed to be used for unequipped aircraft only, allowing the equipped aircraft to fly anywhere outside of this airway. Through experimentation it was found that this approach is sensitive to the proportion of equipped aircraft. Pilot workload increased as the proportion of equipped aircraft increased. The effects on the controller were not reported.

6.2.3 Segregated Maneuvering Zones

Airspace can also be segregated by designating lateral and longitudinal maneuvering zones, as shown in Figure 6-4. In the maneuvering zone a higher level of performance would be required and separation would be reduced. Areas of increased crossings and mergings would benefit from a reduction in separation minima. An analogy to this type of segregation was observed at Reykjavik Center in the sectors with both traffic

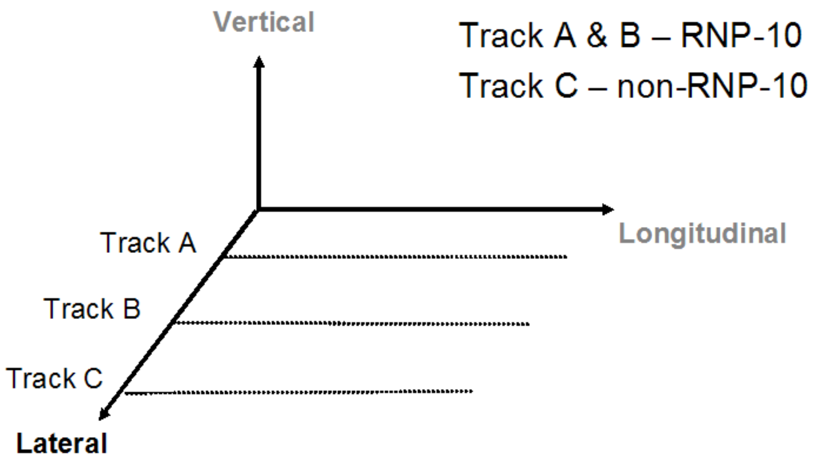


Figure 6-3: Static segregation of airspace along the lateral axis.

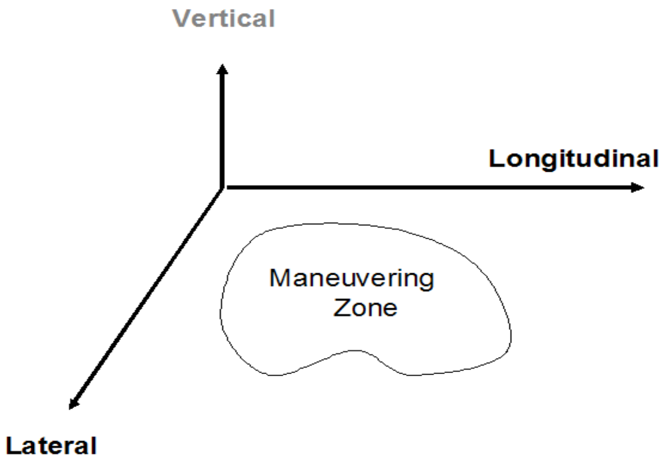


Figure 6-4: Airspace segregation by lateral and longitudinal maneuvering zones.

covered and not covered by radar. The longitudinal separation minima within the radar coverage is reduced from 10 minutes to 3 minutes. It was observed that the controllers manage most of the crossing and climbing traffic during the radar coverage because of the increased flexibility.

6.2.4 Dynamic Segregation

Dynamic segregation allows several highly equipped aircraft to be grouped together and traverse the ocean with a bubble of protected airspace around the group. The separation minima can be reduced within the group and the group should be given

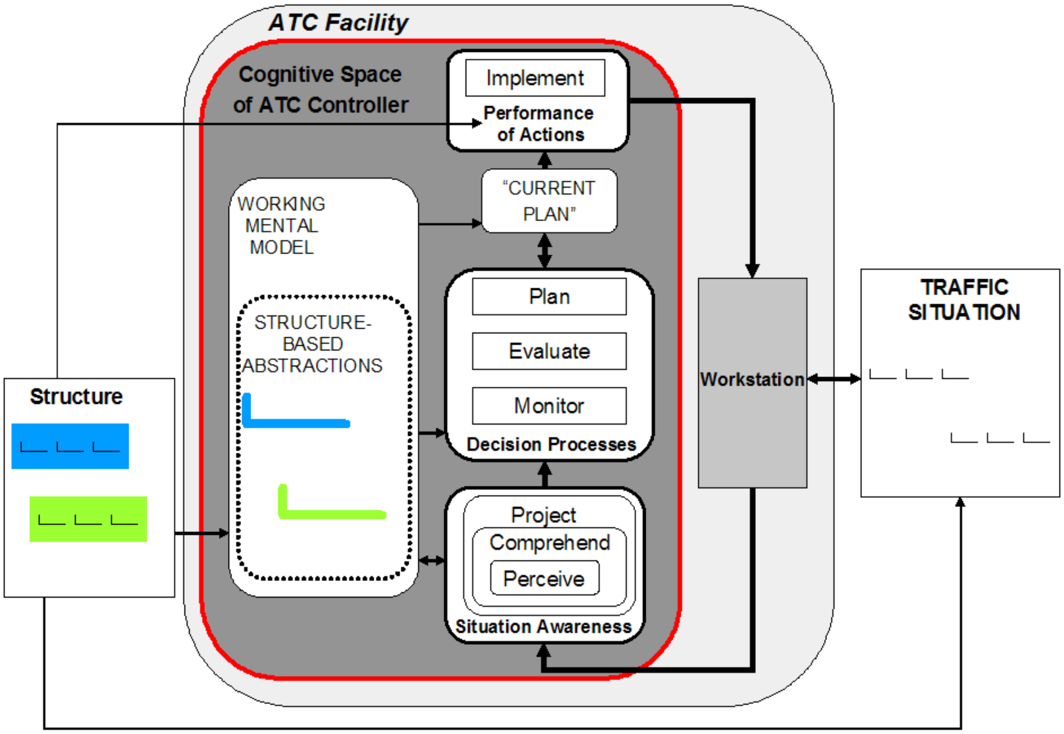


Figure 6-5: Dynamic segregation can allow for ADS-B equipped aircraft to be cognitively grouped together and treated as a single aircraft.

the highest priority. During the "exception" phase dynamic segregation supplies the opportunity to provide immediate benefits to equipped aircraft without disrupting the operations of the majority of the oceanic fleet.

If the aircraft in the group are equipped with ADS-B, within group separation responsibility can be transferred to the flight deck. The controller can then maneuver the group as if they are one aircraft. Figure 6-5 illustrates this concept within the framework of the cognitive model introduced in chapter 4. In this example, the grouping abstraction allows the six aircraft to be controlled as if there were two aircraft. This segregation strategy is only feasible during the "early adopters" phase.

6.2.5 Incentivization

Providing incentives for equipping with the technologies discussed in this thesis is critical to the evolution of the oceanic air transportation system. If the full advantages are not attained, then aircraft will choose to not equip, which will produce a stalemate in the transition. Therefore, future procedures should benefit equipped aircraft, while considering the phase of implementation so that all aircraft can be serviced. Airspace segregation offers an opportunity to accomplish this objective. In order to do so, airspace segregation must dedicate the most desired airspace to fully equipped aircraft and consider how the segregation will effect the flight of equipped aircraft. As shown in the results from the experimental analysis, cognitive issues can limit the controllers ability to grant the equipped aircraft full benefits. Thus, human-centered systems issues need to be taken into consideration when designing future procedures.

6.3 Display of Equipage Information

Since an increase in equipage variations can be expected in oceanic ATC, the controller needs a clear way of distinguishing between the different types of equipage. The current letter indicator for displaying equipage information is limited. There is a need to be flexible to accommodate the new wave of technologies that are coming. The current methods are not easily adaptable to these future technology changes or equipment failures.

There are two approaches for displaying equipage information in the future: centralized and decentralized. The centralized approach groups the three CNS components together on the display. The decentralized approach is to decouple the CNS components and display each component near similar information. The decentralized approach is planned for future U.S. and Iceland ground stations. For ATOP, the surveillance information will be indicated by aircraft target symbology, Datalink equipage will be indicated on the datablock, and navigation equipage will be indicated by color-coding the altitude information on the datablock for anomalies (e.g., non-RVSM aircraft) [25].

A possible centralized approach had been developed based on the work presented in this thesis. The proposed approach is a three character alpha-numeric-alpha code, with each of the characters representing one of the CNS components, as shown in Figure 6-6. The primary benefits of the three character code is that it is adaptable

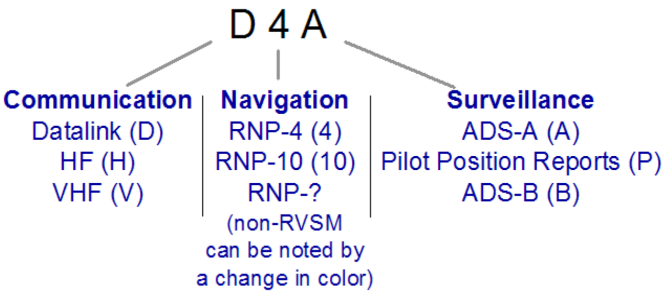


Figure 6-6: A possible method for displaying equipage information in the future environment.

to equipage changes because each of the CNS components can be independently updated as the technologies evolve. The near-term expected equipage changes alone motivate the need for flexibility. The near-term possibilities for each of the three values are shown in Figure 6-6. Another benefit of the three character code is the capability of dynamic adaptation during an equipment failure. An equipment failure can be easily communicated to the controller by changing the CNS code appropriately, and providing an alert such as changing the color of the code or flashing the code, depending on the severity of the failure.

The three character code can be placed either on the flight strip or on the datablock, depending on the primary display in the oceanic environment. For the current workstation equipage information should be displayed on the flight strip since the spatial display is rarely used. The precedent for the location of equipage information on the flight strip has been established in the United States. Currently, equipage information is displayed next to the aircraft type. Coupling the aircraft type and equipage follows ecological design principles, which calls for the environmental factors that influence human decision making and actions be the driving force in design [26]. In the future environment, if the spatial display becomes a primary tool for oceanic controllers, the CNS code can be included as a third line on the datablock.

Consideration of the phase of implementation should be given when deciding between the distributed and centralized approaches. For example, during the "partially equipped" phase the controller will need to monitor the equipage closely to determine separation minima and ATC procedures. This may be easier to do using the centralized three character CNS code. However, when most of the aircraft are equipped with a certain level of equipage, in either an “early adopters” or “exception” phase, the CNS components can be distributed and highlighted when there is an anomaly. This can be done through changing the color of the information or some other alerting scheme.

Chapter 7

Conclusions

Mixed equipage is rapidly emerging in oceanic ATC. Datalink is used by approximately 30% of the oceanic fleet and ADS-A surveillance reports will soon be accepted by the United States oceanic facilities. These improvements have a considerable impact on the control task. However, there have not previously been human-centered systems studies on the effects of combining aircraft with significant variations in control inertia. This forces the responsibility of maintaining an acceptable level of safety despite variations in control inertia and separation standards on the controller.

The findings presented in this thesis show that there are limitations to maintaining an acceptable level of safety in mixed equipage environment. The experimental analysis reveals that there is the risk of an increase in controller workload and a degradation in situation awareness in the mixed equipage environment. Also, control inertia was shown to effect the controllers' decision processes. During the planning process, the controller attempts to minimize control inertia, which reduces the uncertainty in modifications to their plan. In the mixed equipage environment this may translate into maneuvering the aircraft equipped with the highest capabilities, which will limit the increased flexibility and efficiency that is expected with improved equipage. The reduction in benefits attained by equipped aircraft was also demonstrated during the experimental study.

Issues of trust and controller acceptance will also limit the full integration of the expected CNS improvements. Several examples of controller rejection of improved tools was given during the discussion of the field studies. If enhanced CNS is not utilized by the controllers, then aircraft operators will not receive a return on their investment in the equipage and the evolution of oceanic ATC will be restrained.

In order to achieve the benefits of improved CNS, careful consideration needs to be given to the mixed equipage problem. Segregated operations are suggested as a means of providing procedural support to the controller. The structure-based abstraction of grouping aircraft with similar CNS capabilities and dedicating airspace to the groups will reduce the complexity of the mixed equipage problem. The strategies used for segregation should be dependent on the phase of implementation, so that the majority of the aircraft can be serviced and immediate benefits can be granted to highly equipped aircraft. Improvements in automation tools will also better support the controller. As reductions in separation minima are introduced, the constraints in the automation tools must be immediately updated to reflect the changes. If the separation standards are dynamically updated then the controllers will have more trust in the conflict alerts and they will no longer need to manually monitor for conflicts, which will reduce their workload. The methods for displaying equipage information needs to be carefully considered so that the controllers have the information they need at all times.

Appendix A

Human Factors Studies on ADS-B

There have been various human factors studies on self separation using ADS-B, sometimes referred to as “Free Flight”. The role of the controller drastically changes in such an environment. Rather than actively controlling the aircraft, the controller passively monitors aircraft for separation conflicts [27].

Studies have shown that there are serious controller-centered concerns with unmanaged (self separating) traffic, especially during times of dense traffic. Corker, Fleming, and Lane found that once 80% of the traffic are unmanaged workload significantly increased compared to 20% and 0% unmanaged scenario [28]. Metzger *et al.* found that performance degrades when passively monitoring, as opposed to actively controlling [27]. Endsley also found that there was a decrement in controller performance when pilots were allowed to deviate from their filed flight plan compared to fully managed traffic. Ensldey’s studies also revealed an increase in workload and a decrease in situation awareness for the controllers when pilots assumed some level of separation responsibility [23].

The overwhelming theme in the literature is that the controller is not capable of performing at the current level when passively monitoring. Most studies show that there is an increase in controller workload and missed detections, and the time to detection increases in a self separating environment. The primary source of cognitive degradation when monitoring unmanaged traffic is the possible loss of Situation Awareness. If Situation Awareness is not adequately developed then the controller will not be equipped to make decisions when necessary. When the controller is pulled out-of-the-loop, he/she is no longer capable of detecting conflicts and instantly responding to critical situations. One of the limiting factors is the lack of pilot intent information. In order to determine the reason for a pilot action the controller must communicate to gather information about their intent. Endsley identified the need for increased communications as a possible source of increased controller workload in unmanaged situations [23]. Also structure inherent in ATC is removed in “Free Flight” conditions, which increases the complexity of the traffic scenarios [18]. Deviation from structure, such as a standard routing, is much easier to detect than random deviations.

There is hope for the integration of ADS-B operations though. In an experiment performed by the National Aerospace Laboratory (NLR) in Amsterdam pilots gave the “Free Flight” scenario, in which all aircraft were equipped for self separation, a high acceptability and safety rating [24]. This shows that self separation is feasible from the pilots’ perspective. Further research needs to be done into the type of automation and the information requirements for the automation in order for acceptable controller performance and workload.

Appendix B

Preliminary Briefing

Instructions:

You will view 3 traffic situations, which involve multiple aircraft. All aircraft are Boeing 747-400s. The average climb rate is 950 feet/minute. The simulator time scale is faster than real time, 1 observed second equals 30 actual seconds. This is done so that a longer situation can be reduced to a reasonable amount of time. The spatial scale of the screen is 1 inch = 100 nm. All traffic will follow standard routings, designated by the lines that connect the fixes. The actual route of the aircraft can be viewed by making a left click of the mouse on top of the aircraft icon.

The surveillance update rate will vary between the scenarios and in one case between the aircraft in a scenario. This is similar to the difference between the surveillance update rate for radar and for pilot position reports. The surveillance update rate will depend on whether the aircraft is equipped with Automatic Dependent Surveillance (ADS). ADS is a form of satellite surveillance that is being incorporated into oceanic ATC to provide higher frequency surveillance. For this experiment, aircraft equipped with ADS will have an update rate of 1 update every 1 real second (or 30 simulation seconds) and aircraft not equipped with ADS will have an update rate of 1 update every 30 real seconds (or 900 simulation seconds - 15 minutes).

During the scenario aircraft will make requests and you need to decide what response you will give and make this command verbally and digitally (you will be shown how to do this). You can: grant the request, refuse the request, or give

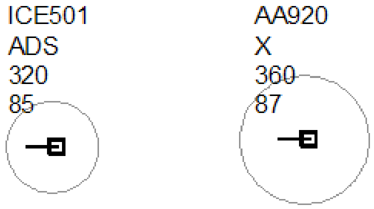
Equipage	**Surveillance Frequency**	**Minimum Lateral Separation**
non-ADS	30 observed s	50 nm
ADS	1 observed s	20 nm
Mixed	mixed	mixed

Table B.1: Three scenarios used in this experiment.

another command (the fixes are numbered so that you can refer to them for other commands if necessary). You must always ensure 1000 ft. vertical separation and minimum lateral separation. The minimum lateral separation will depend on the aircraft equipage:

You must also keep in mind that there are high costs for not granting requests in oceanic ATC because of the fuel efficiencies. All requests made are for the route with the lowest fuel burn.

There will be a circle around the aircraft with a radius equal to the minimum lateral separation. If you would like to remove this circle you can do so by making a right click of the mouse on top of the aircraft icon. There will be a datablock next to the aircraft icons. The datablock will contain the following: aircraft ID, an indicator of whether the aircraft is equipped with ADS ("ADS" if it is and "X" if it is not), altitude, and speed. Below is an example of an equipped and unequipped aircraft:



Each scenario will take approximately 5 minutes. At the end of each scenario you will be asked to rate the difficulty of the scenario. At the end of the 3 scenarios you will be given a post-experiment survey.

Summary of Key Information:

- 1 inch = 100 nm
- 1 observed second = 30 actual seconds
- Left click of the mouse on an aircraft icon shows the route

- Right click of the mouse on an aircraft icon removes the circle of minimum separation
- **ADS equipped aircraft:** Surveillance Frequency: 1 update every 1 observed second (or 30 actual seconds)& Minimum Separation: 20 nm
- **Non ADS equipped aircraft:** Surveillance Frequency: 1 update every 30 observed seconds (or 15 actual minutes)& Minimum Separation: 50 nm

Appendix C

Debriefing

This experiment was designed to understand how the frequency of aircraft surveillance affects controller decisions and whether it is more difficult to control aircraft with different surveillance update rates. The post-experiment questions were designed to probe the decisions further by understanding why the decision was made, what strategies were used, and whether trust in the information about the aircraft was affected by the update rate.

There are plans to integrate Automatic Dependent Surveillance (ADS), which receives aircraft position directly using satellites, into the future oceanic environment. This will increase the surveillance update rate from one hour (pilot position reports) in the current environment to as low as 5 seconds (ADS) in the future environment. However, not all aircraft will be equipped for ADS, therefore a mixed equipage environment will exist. The current plans are for the controller to cognitively integrate aircraft information with different frequencies. But, there have not been any studies to determine how the mixed equipage environment will affect controller workload, situation awareness, trust, and performance. Based on these and future experiments, procedures and workstation displays can be designed to better support controllers in the future oceanic environment.

If you wish for a copy of future publications resulting from your participation in this research, please provide the information below:

Name:

Email address:

If no email, provide postal mailing address:

Appendix D

Post-Experiment Survey

1. Which scenario was the most difficult?

2. Why was this scenario the most difficult?

3. Which scenario was the easiest?

4. Why was this scenario the easiest?

5. Rate your confidence in the position of the aircraft with high frequency surveillance:

No confidence at all	Some significant concerns	Generally confident with some smaller concerns	Confident	Very confident
1	2	3	4	5

6. Rate your confidence in the position of the aircraft with low frequency surveillance:

No confidence at all	Some significant concerns	Generally confident with some smaller concerns	Confident	Very confident
1	2	3	4	5

7. What was your strategy in the scenario in which you were shown aircraft with both high and low frequency surveillance?

8. How did you determine which procedures to apply when you were shown aircraft with high and low frequency surveillance?

9. When there was a conflict between an aircraft with high frequency and an aircraft with low frequency, which aircraft were you more likely to maneuver to resolve the conflict? Circle one.

Aircraft with high frequency

Aircraft with low frequency

10. Why do you prefer to maneuver aircraft with the type of frequency you chose above?

11. How many aircraft did you feel you could safely control at one time in each of the 3 scenarios of this experiment?

High Frequency aircraft	Low Frequency aircraft	Mixed aircraft equipage

Appendix E

Subject Answers to Free Response Survey Questions

Question 7: What was your strategy in the scenario in which you were shown aircraft with both high and low frequency surveillance?

Subject 2: I imagined the future position of the aircraft with low frequency surveillance while I was watching the other moving fast

Subject 4: Remembering the flight level and path so when a new aircraft appeared I could think: “he is at FL 310 and I know there is another one at FL 310”. So I’d look each one and I remembered the path to see if there was a conflict or not.

Subject 5: I tried to guess the current position of non-ADS planes to find conflict points.

Subject 6: To anticipate movements of low frequency aircraft by showing the route well in advance.

Subject 7: The strategy was to trust the position of high frequency aircraft and to solve the problems with them first, since we know immediately if they’re really climbing or not.

Subject 1b: I had to pay attention to the aircraft with low frequency suveillance because they were actually very fast whereas you don't think so at the first sight but the circle moves rapidly.

Subject 2b: Vertical separation.

Subject 3b: To give instructions to the ADS aircraft.

Subject 4b: To anticipate a lot, mostly with the aircraft with low frequency surveillance...to analyse their route first.

Question 8: How did you determine which procedures to apply when you were shown aircraft with high and low frequency surveillance?

Subject 2: It depends on their route and level. I watch the other planes and determine which one is easier to maneuver.

Subject 4: When I have a conflict I immediately move the one with ADS so like that I know nearly immediately that he has gone up so he is clear of the traffic. For example, if I had 2 aircraft at FL 330, I'd give 360 to the one with ADS, so I could see 360 nearly immediately so I knew he was 1000 feet above the non-ADS one.

Subject 5: I tried to get a different FL for every aircraft.

Subject 6: Anticipate the conflict fix, if there was one and act on the low frequency aircraft first.

Subject 7: I tried to apply vertical separation only and as early as possible.

Subject 1b: I think that in case of separation it's easier to change the level of an aircraft with high frequency surveillance because you are aware of its moving in real time.

Subject 2b: It's easier with vertical separation.

Subject 3b: I was looking for the nearest Flight Level which was available.

Subject 4b: I was descending or climbing the low frequency if he had just updated or the other one if not.

Question 10: Why do you prefer to manuever aircraft with the type of frequency you chose above? (all chose aircraft with high frequency surveillance)

Subject 2: Because I can see clearly on my screen that the aircraft with high frequency is at the assigned level to be sure that the separation is effective.

Subject 4: no answer

Subject 5: It was quicker and easier to check the effect of my clearance (more precise feedback).

Subject 6: You can notice almost immediately that the flight level changes, so you get more confident.

Subject 7: You know immediately if your order has been followed or not.

Subject 1b: same answer as Question 8

Subject 2b: You can feel the "movements" of the aircraft easier

Subject 3b: To be sure of the position of the aircraft.

Subject 4b: Because I can see how he is climbing or descending and if he respect my clearance or not.

Appendix F

Critical Values of the *t*-distribution

Significance for a one-tailed test

Degrees of freedom (df)	α .10	 .05	 .025
1	3.078	6.314	12.706
2	1.886	2.920	4.303
3	1.638	2.353	3.182
4	1.533	2.132	2.776
5	1.476	2.015	2.571
6	1.440	1.943	2.447
7	1.415	1.895	2.365
8	1.397	1.860	2.306
9	1.383	1.833	2.262

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