4D Trajectory Determination and Prediction for NextGen

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Abstract: The Next Generation Air Transportation System (NextGen) is the Federal Aviation Administration’s (FAA) plan to modernize the National Airspace System (NAS) through 2025. Four dimensional (4D) trajectory determination and prediction is the core component for NextGen. The interacting multiple model (IMM) tracker is a state-of-art technique for maneuvering target tracking. In the NextGen, there are many types of aircraft, including manned/unmanned and fixed-wing/rotary-wing, each of which could have different flight modes such as steady-state flight/general aviation-like maneuvering/high maneuvering. It is a big challenge for fixed-structure interacting multiple model (FSIMM) algorithms to consider so many possible flight modes. In this paper, we propose Cognitive Integrated Interval and Point-Variable Structure Interacting Multiple Model (CIIP-VSIMM) for real-time determination and prediction of 4D gate-to-gate aircraft trajectories using different sets of sensor data. Our algorithm can provide accurate 4D trajectory determination and gate-to-gate prediction of aircraft in the NAS with low computational load and high adaptability.

Key words: 4D trajectory, trajectory determination and prediction, NextGen, FSIMM, CVSIMM

I. Introduction

To meet the significant increase of air traffic demand in the NAS, NextGen is being developed. The present Air Traffic Control (ATC) adopts an airspace design process, which results in low predictability and a huge waste of the airspace resource. The concept of Trajectory Based Operations (TBO) has been introduced in NextGen in order to overcome the shortcomings of the present ATC.

TBO requires that the aircraft trajectories be expressed in four dimensions (3 space position and 1 time) with a very high precision, which is then carried over into actual execution of the trajectories. 4D trajectory determination and gate-to-gate prediction is one of the core components for TBO [1-4, 15-20]. Based on our extensive survey, we realize that only limited approaches are available, and a number of challenging problems remain for accurate 4D gate-to-gate trajectory determination and prediction. For example, the trajectory of civilian aircraft was predicted in [15] by using a fixed-structure hybrid estimation algorithm to estimate the aircraft’s state and flight mode and infer its intention from its flight plan and the environment. In [2], both point estimation and interval estimation were proposed for civilian aircraft, but they were again limited to a fixed structure and to the case of precise knowledge about the intention without any navigation error. In reality, there are various types of aircraft, including fixed-wing/rotary wing, and manned/unmanned. They each have different flight modes: takeoff/cruise/descending/ascending, steady-state flight/low maneuver/high maneuver, etc. As a result, the primary challenge is how to deal with so many possible flight modes which the trajectory depends critically on. A solution with a fixed structure cannot meet this challenge well in real applications. Another major challenge is that gate-to-gate trajectory determination and prediction must be done under different cases of sensor data, ranging from those with very limited information (such as search radar data) to those with a near-complete set of data (such as Automatic Dependent Surveillance – Broadcast (ADS-B)).
In this paper, we propose our solution based on a variable-structure IMM (VSIMM) approach, which uses a variable set of models that overcomes the above-mentioned fundamental limitations of FSMM [9, 10]. The key is adaptation of the model set (and models, if needed) to the changing/uncertain situation, guided by online data as well as prior knowledge, if available. Here we propose to combine cognitive techniques and VSIMM algorithms to adaptively select a relatively small model subset. A cognitive system is an intelligent system that is aware of its environment and uses the methodology of understanding-by-building to learn from the environment and adapt to statistical variation [11]. In the case of position-only data, a simpler aircraft kinematic model without aircraft mass and environmental parameters is selected. When given sufficient aircraft state data including aircraft type, mass, thrust, drag, and environmental parameters, a higher-order aircraft kinetic model will be determined accounting for the effect of aircraft and environmental parameters. Kinetic models can result in more accurate estimation at the cost of higher computational load.

Although one can obtain the “most probable trajectory” with some error probability distribution, this hinges critically on the validity of the underlying models. For instance, the results may suffer severely if the sensor noise model is not accurate. In this paper, we propose an interval estimation [2] to deal with the uncertainty of 4D trajectory. Instead of using the noise probability distribution as done by the conventional probabilistic target tracking and prediction, interval estimation defines upper and lower bounds of the sensor errors. It then determines and/or predicts the trajectory to be within a guaranteed interval, which represents bounded estimation errors. An interval 4D trajectory has been defined by NASA for high-capacity ATC [1]. However, all existing interval state estimation methods consider only a single model or a fixed structure [1-2, 5-7, 12-14]. We propose an interval VSIMM combined with the conventional point VSIMM for 4D trajectory determination and prediction in order to enhance error tolerance and uncertainty processing.

4D trajectory prediction can be categorized into: very short-term, short-term, medium-term, and long – term [15, 20]. For (very) short-term 4D trajectory prediction, usually only the aircraft present state and dynamic models are applied. For medium-term prediction, both aircraft present state and intention have to be considered. For long-term prediction, aircraft intention has more and more influence on the prediction accuracy [20]. One way to obtain the intention is from ADS-B sensors. A main challenge of trajectory determination and prediction is that the intent or flight plan of the aircraft is not necessarily known or easy to infer from sensor data. Without ADS-B data, we propose to infer the intention by high-level information fusion.

This paper is organized as follows. In Section II, we survey the 4D trajectory determination and prediction algorithm proposed in the literature. Section III discusses our proposed Cognitive VSIMM algorithms. Section IV presents performance metrics to evaluate various algorithms. Finally, Section V contains the conclusion.

II. Survey of 4D trajectory determination and Prediction

2.1 4D Trajectory Prediction Types

TBO needs 4D gate-to-gate trajectory determination and prediction [21]. We can categorize it based on prediction time as well as trajectory characteristics.
**Prediction time [20]**
According to prediction time, 4D trajectory prediction can be categorized into four classes:

(a) Very short time: < 1 minute  
(b) Short-term: between 1 and 10 minutes  
(c) Mid-term: between 10 and 30 minutes  
(d) Long-term: >30 minutes

**Trajectory characteristics [2]**
According to trajectory characteristics, 4D trajectory prediction can be categorized into four classes: nominal, probabilistic, worst case, and mixed:

(a) Nominal trajectory prediction projects the current state into the future along a single trajectory. The trajectory uncertainty is not considered.
(b) Probabilistic scheme describes the predicted trajectory with probability density functions.
(c) Worst case prediction considers the projection with high probability of hazardous trajectory.
(d) Mixed method such as combination of worst case and probability methods.

### 2.2 FSIMM/VSIMM Based of 4D Trajectory Determination and Prediction Algorithms
Most 4D trajectory determination and prediction algorithms proposed in the literature are based on FSIMM [2, 15]. Very few papers have proposed to apply VSIMM to track and predict special aircraft in limited airspace [18].

#### 2.2.1 FSIMM
The architecture of a FSIMM based 4D trajectory determination and prediction is shown in Fig. 1. There are mainly three modules: (1) FSIMM for state estimation. Popular aircraft kinematic models in FSIMM are constant velocity (CV), constant acceleration (CA), coordinated turn (CT), etc; (2) Intention inference. Aircraft Intent Description Language (AIDL) was developed by Boeing as a standard to describe and exchange predicted aircraft trajectories in TBO [18]. Aircraft intention can be derived based on aircraft state and other information such as weather, obstacles; (3) 4D trajectory prediction. (Very) short-term prediction is computed by using the aircraft state and fixed dynamic models. Medium-term prediction is computed based on both state and intention. Long-term prediction mainly utilizes aircraft intention.

#### 2.2.2 VSIMM for Target Tracking on Airport Surface [18]
Very few papers have initially applied the concept of VSIMM for target tracking on the airport surface. The basic idea is shown in Fig. 2. The multiple kinematic model set is tuned based on the airport map information. Then IMM is applied to estimate the target state.

III. Our Proposed CVSIMM Algorithm

Accurate 4D gate-to-gate trajectory determination and prediction of all types of aircraft in the NAS is needed in TBO. Because there are many different kinds of aircraft flying in different modes, FSIMM is not efficient enough to deal with this challenging problem. We propose - Cognitive VSIMM (CVSIMM) where multiple models are adaptively selected based on the aircraft type and flight mode through the cognitive technique. Three kinds of CVSIMM algorithms will be designed: point CVSIMM, interval CVSIMM, and mixed algorithm - Cognitive Integrated Interval and Point - Variable Structure Interacting Multiple Model (CIIP-VSIMM).

3.1 Aircraft Dynamic Model

There are two kinds of aircraft dynamic models: kinematic and kinetic. Kinematic models do not consider the influence of aircraft parameters such as mass, thrust, and environmental parameters such as wind and temperature. Kinetic models are more accurate with consideration of more aircraft and environmental information. Kinetic models can result in better tracking and prediction results at the cost of higher computational load. A few typical kinematic and kinetic models are given below.

**Discrete-time kinematic models [8, 9]:**

CV and CT are two popular discrete-time kinematic models. The CV model describes the uniform target motion. The CT model represents the kinematics of a turn, performing in the horizontal plane, with constant angular rate $\omega$. When only radar data is available, we have to select kinematic models such as CV and CT for aircraft tracking and trajectory prediction.

**Continuous-time kinetic model [3]:**

Given sufficient data (e.g., near-complete aircraft parameters and environmental parameters), kinetic models are a better choice. Some government organizations such as Global Aircraft Modeling Environment (GAME) and Base of Aircraft Data (BADA) are trying to define kinematic and kinetic aircraft models for each aircraft. GAME builds kinematic models without attempting to model the underlying physics. BADA utilizes the kinetic approach based on independent modeling of thrust and drag. A kinetic model for takeoff is given here as an example. The aircraft is modeled using a Point Mass Model (PMM). The major variables that describe the continuous state of the model are the horizontal position $(X, Y)$, aircraft’s altitude $H$, true airspeed $V$, heading $\psi$, and mass $m$. The three inputs of the model are thrust $T$, bank angle $\phi$, and flight angle $\gamma$. BADA contains kinetic models for many aircraft in different flight modes.

3.2 CVSIMM
To determine and predict the 4D trajectory of different aircraft in different flight modes, we have to adaptively select the aircraft dynamic models. The platform could be manned/unmanned, or fixed wing or rotary wing. Multi-mode sensors may consist of ground surveillance radar, Primary Surveillance Radar (PSR), Secondary Surveillance Radar (SSR), Multilateration, ADS-B, or onboard EO/IR sensors.

Cognitive technique means prior knowledge and online learning. The model subset is adaptively selected through cognition. After the aircraft model subset is determined, IMM is applied to 4D trajectory determination and prediction. The aircraft intention will be inferred through high-level information fusion techniques. For short-term 4D trajectory prediction, a state-only based CVSIMM algorithm is developed. For medium-term prediction, the 4D trajectory is predicted by using both aircraft state and inferred intention. Two kinds of CVSIMM algorithms are first developed: point based and interval based. Then Cognitive Integrated Interval and Point - VSIMM (CIIP-VSIMM) is designed for real-time determination and prediction of 4D aircraft trajectories. Point CVSIMM provides the probabilistic trajectory determination and prediction while interval CVSIMM provides 4D trajectory determination and prediction with error bound.

For long-term 4D trajectory prediction (especially larger than one hour), the accuracy depends more on flight intention [20]. As shown in Fig. 3, we first plan the initial 4D trajectory by some Air Traffic Management (ATM) tools. Then CVSIMM is applied to determine the aircraft present state. The Flight conformance monitoring module compares the present aircraft state from CVSIMM. If the present aircraft trajectory cannot meet the initially planned 4D waypoints, we need to modify the future trajectory as little as possible. Long-term 4D trajectory can also be considered as online re-planning of 4D trajectory with minor modification under various constraints.

![Initial 4D trajectory planning by ATM tool](image)

Online trajectory determination ➔ Flight conformance monitoring ➔ Minor modification to meet constraints if possible ➔ Modify the flight plan 4D waypoints

Fig. 3. Long-term 4D trajectory prediction.

IV. Performance Evaluation Metrics
How to evaluate and compare various 4D trajectory determination and prediction algorithms is an important topic. Typical performance metrics for 4D trajectory determination and prediction include [17]:

- **Accuracy**: Accuracy is measured in multiple dimensions including lateral, vertical, longitudinal, and time.
- **Confidence**: Having high confidence means that a specified accuracy is achieved with a high probability. Probability is often used to do confidence analysis.
- **Computational complexity**: It is important to achieve high accuracy with low computational complexity because of the limit of computational power of computers. The algorithms must be able to deal with a large number of aircraft in the NAS.
• Stability: Stability means that the current prediction will not undergo significant changes between predictions as a result of the prediction process.

V. Conclusion
In this paper, we first summarize trajectory determination and prediction algorithms for ATC in the literature. Then a cognitive VSIMM architecture has been developed to determine and predict 4D gate-to-gate trajectory in NextGen. Based on cognitive techniques, the dynamic model set is adaptively selected. For trajectory determination and short-term 4D trajectory prediction, the aircraft dynamic model is mainly applied. For medium-term 4D trajectory prediction, both aircraft dynamic models and intention are applied. For long-term 4D trajectory prediction, aircraft intention has more influence compared with short-term and medium-term prediction. Our algorithm can determine and predict the 4D gate-to-gate trajectory of various aircraft with low computational complexity, high accuracy, and high environmental adaptability.

References

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ACHIEVING NEXTGEN AND AUTOMATION CONVERGENCE

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ABSTRACT
The 2010 NextGen growth projections suggest annual growth rates that will double domestic air traffic as early as 2030. However, the workload and congestion in the system is not uniformly distributed. Inefficiencies and delays are most prevalent and acute around major metropolitan areas. The delays and inefficiencies ripple through the National Airspace System (NAS), magnifying their scope, impact, and their cost.

The FAA relies on a variety of automation systems that focus on safe and expeditious movement of aircraft, people, and goods through the NAS. There is increased focus on converging multiple automation systems to reduce cost of ownership while continuing to enhance safety, capacity, and efficiency. Convergence leverages the tools already in the FAA’s inventory to address both the current automation needs as well as to meet emerging future challenges. By promoting an enterprise wide perspective on key data and function for stakeholders throughout the NAS, convergence ensures that all decision makers have identical and up to date data - thereby promoting timely and accurate decision making.

In 2009, Lockheed Martin’s NextGen Automation Platform (NGAP) Independent Research & Development (IRAD) effort focused on convergence across en route and terminal domains. Using the FAA’s Enterprise Architecture (EA) as guidance, we conducted a detailed engineering analysis of en route and terminal automation requirements and current automation systems to develop a convergence strategy. As part of this effort, we investigated implementation alternatives specifically for addressing the Big Airspace requirement. In 2010, Lockheed Martin continued this work by developing two “proof of concept” prototypes that converge the Common Automated Radar Terminal System (CARTS) automation currently certified for 3 nm separation and in operational service across the US with En Route Automation Modernization (ERAM), the FAA’s most advanced en route automation platform.

KEY WORDS
NextGen, Convergence, Big Airspace, Terminal Automation, En Route Automation

1. NextGen and Convergence
The FAA deploys and manages an array of automation systems that ensure safe and expeditious movement of aircraft, people, and goods through the NAS. The FAA’s NextGen Initiative is increasing focus on converging these automation systems to reduce the cost of ownership while continuing to enhance safety, capacity, and efficiency.

Reflecting this, the concept of convergence across en route, terminal, and oceanic domains features prominently in the FAA’s NAS EA Roadmap and in the various lower level work package descriptions. The strategic view laid out in the FAA’s EA is that these domains should use “common automation platforms” where possible. A number of the supporting work packages anticipate identifying domain specific requirements that are derived...
largely from existing automation baselines. The strategic objective is for the common automation platform to incorporate requirements from all three domains into a single integration automation baseline. This work is targeted at both the NextGen Midterm and Far Term milestones.

**Big Airspace is an Early Opportunity**
The 2010 NextGen growth projections suggest annual growth on the order of 3.0-3.5%, promising to double domestic air traffic as early as 2030. This increasing demand has severely strained the efficiency of the NAS. However, the workload and congestion in the system is not uniformly distributed. Not surprisingly, inefficiencies and delays are most acute around major metropolitan areas. As many major metropolitan areas serve as air carrier hubs, these delays and inefficiencies tend to ripple through the NAS, magnifying their scope, impact, and their cost. There is intense pressure on the FAA and on the NAS to manage traffic differently and it is almost certain to intensify.

A number of factors combine to complicate the provision of efficient and optimized service across the range of operational and environmental conditions that are typically encountered in the NAS. Arrival and departure airspace surrounding major metropolitan often contains multiple major and satellite airports, each with their own interacting and competing traffic flows. In some cases the configuration of adjacent en route airspace includes boundaries with multiple Air Route Traffic Control Centers (ARTCCs). The complexity of the airspace and the amount of coordination required with adjacent facilities increase controller workload. Adverse weather can have a substantial impact on aircraft movement within the close quarters of today's terminal airspace. Often this leads to "no warning holding" in adjacent en route airspace. The overall impact is loss of predictability, operational inefficiency, increased airline and passenger costs, and high FAA costs to provide air traffic control.

The key challenge is converging the automation systems in such a way as to support effectively the integration of staff and services into a single facility. Convergence to a set of common data and common functions further facilitates the collaborative interworking and decision making among the operational team. All of these factors argue in favor of a solution that is based on converging today's independent automation solutions.

**2. Big Airspace Prototypes**

In 2010, Lockheed Martin continued work previously accomplished under our 2009 NGAP IRAD by developing several "proof of concept" prototypes that converge the CARTS automation currently certified for 3 nm separation and in operational service across the US with ERAM, the FAA's most advanced en route automation platform.

**Pre-Cursor Efforts**

In 2009, Lockheed Martin's NGAP IRAD effort focused on convergence across en route and terminal domains. Using the FAA's EA as guidance, we conducted a detailed engineering analysis of en route and terminal automation requirements and automation to develop a convergence strategy and several implementation alternatives for specifically addressing the Big Airspace requirement.

Two strong alternative implementations emerged from the engineering analysis. Both alternatives make use of existing automation baselines currently in the FAA's inventory – ERAM from the en route domain and CARTS from the terminal domain. Both alternatives make use of System Wide Information Management (SWIM) services as the means for accessing key data on an enterprise wide basis in concert with the FAA's concept of SWIM being an enabling component of the NextGen architecture.

Implementation alternative 1 is based on integrating CARTS terminal automation capable of supporting 3 nm separation and the associated terminal procedures into the ARTCC. This solution uses ERAM as the strategic platform with which CARTS is integrated and assumes that the ARTCC is the strategic facility that hosts the collaborating operational team using CARTS terminal services.

Implementation alternative 2 is based on integrating additional flight data related functionality into the CARTS baseline to enhance its ability to support the transition airspace requirement. This alternative relies on CARTS as the strategic platform for the Big Airspace application and envisions the Terminal Radar Approach Control (TRACON) as the hosting facility for the integrated operational team. In this case the Big Airspace is supported by remote, SWIM-enabled ERAM Flight Information Services.

The engineering analysis from the 2009 effort provided a jumping off point for the 2010 NGAP work actually to develop initial prototypes for both identified implementation alternatives. Early in the prototype development activity we chose to focus on
a small set of user requirements for transition and terminal airspace including the following core user capabilities:

- A Radar Picture suitable for 3 nm separation – this is derived from the existing CARTS tracking functions that produce fused mode system track outputs. In addition, special track symbology that indicates those tracks that are eligible for 3 nm separation.
- Safety Alert functions – these make direct use of existing CARTS functionality and include Conflict Alert for 3 nm separation and Minimum Safe Altitude Warning (MSAW).
- Maps Suitable for transition airspace – we implemented some simple maps that show the Standard Terminal Arrival Routes (STARs) and Standard Instrument Departures (SIDs) appropriate for the target transition airspace.
- Ability to Select 5 nm or 3 nm radar pictures – we incorporated a user control for selecting either 5 nm (ERAM) or 3 nm (CARTS) radar picture.

**Alternative 1 Prototype**

Figure 1 below depicts the initial Alternative 1 prototype converged automation solution for Big Airspace. The prototype integrates CARTS automation into an ERAM based framework that includes both application and infrastructure functions. The main elements of the ERAM baseline that are relevant for Big Airspace are depicted in green and include Surveillance (SURV), Flight Data Processing (FLTS), Safety (SAFE), and En Route Display Manager (EDSM) applications functions. For purposes of development and demonstration, the configuration is driven by Simulation Engine (SIME) which uses a scenario with surveillance and flight data inputs derived from real operational traffic in the Washington, DC area.

The CARTS application is integrated with Flight Deck, the ERAM middleware, and executes on an ERAM hardware platform. CARTS has access to surveillance inputs sourced by SIME and can interact with ERAM flight data by means of a prototype version of the SWIM Flight Information Service (FIS).

FAA certified and currently operational in the NAS, CARTS tracking functions employ the Fused Mode tracking shown in Figure 2 to meet stringent performance and accuracy required for 3 nm separation in transition and terminal airspace. This approach makes use of all sources of tracking data available to CARTS and thus provides a more accurate presentation of aircraft locations to controllers. The Fused Mode design decouples sensor updates from the display update in order to ensure that display updates occur at a known and predictable frequency. At the time of each display update, each track is drawn at its calculated position using position, time and velocity from the Tracker. In addition, CARTS uses special track symbology to denote those aircraft that are eligible for 3 nm versus 5 nm separation. Eligibility for 3 nm separation is determined by comparing the track position’s uncertainty estimate with a set of adapted parameters. When the uncertainty estimate is sufficiently small, the track is eligible for 3 nm separation and highlighted with the corresponding symbology.

The CARTS track updates and safety alert outputs are delivered to EDSM by means of the same server/mirror mechanism that is utilized internal to the ERAM architecture. While CARTS itself is extended to publish its Fused Mode track updates and safety alerts via newly added server functions, EDSM is augmented with new CARTS track and safety alert mirrors. By means of a simple control on the ERAM EDSM CHI, the workstation can select either the ERAM radar picture suitable for 5 nm en route separation as sourced by the ERAM SURV and SAFE CSCIs or the CARTS radar picture suitable for 3 nm terminal separation as sourced by CARTS. Since EDSM has access to both sets of mirrors, it will simply display the data in the ERAM mirrors or alternatively, display the data in the CARTS mirrors in response to the user selection at the CHI.

The initial prototype does not attempt to define Computer Human Interface (CHI) specifically tailored for transition airspace. Rather, it takes a simple approach and integrates ERAM CHI with CARTS Fused Mode track updates and safety alerts. While there may well be unique CHI requirements associated with the Big Airspace application, no special CHI features were highlighted in the FAA’s Integrated Arrival/Departure Control Service (Big Airspace) Concept Validation [1]. For the “proof of concept” prototype, this effectively defers the CHI development task until such time as proper controller participation can be arranged.

**Alternative 2 Prototype**

Following on from the implementation of the initial prototype described above a second set of incremental functions were developed and integrated to enhance the prototype. This second phase of development adds a new set of flight data
functions that permit entry, display, and amendment of flight plans consistent with Implementation alternative 2. This Flight Data Display (FDD) capability was added to form the initial Alternative 2 prototype depicted in Figure 3.
The FDD displays data on a dedicated display that is separate from the CARTS ACD. This implementation was used for concept development purposes and could readily be integrated with the main ACD. Flight data sourced via the SWIM FIS is visually presented as a series of electronic strips or flight data entries and those in turn are organized into strip bays. The FDD displays strips bays for both Arrivals (Future, Controlled, and Landed) as well as for Departures (Pending and Controlled). Each Bay permits the individual strips to be sorted by various user selectable sort criteria. The FDD also provides flight data entry and amendment panels that offer the user structured entry or update of the various data fields.

In addition, the ACD and FDD are integrated such that dwelling on a particular datablock on the ACD causes the corresponding electronic strip to be highlighted. Dwelling on a particular electronic strip also causes the corresponding datablock to be highlighted on the ACD.

3. Conclusion

The Big Airspace “proof of concept” prototypes effectively demonstrate the power of convergence as a strategy for leveraging today’s automation solutions - addressing emerging requirements and delivering controller function where it is needed. They also highlight the flexibility and extensibility built into some of the automation that is currently in the FAA’s inventory. The prototypes employ a modular architecture and design that permit function to be readily moved between ARTCC and TRACON facilities as needed.

Downstream, Tech Refresh activities will provide numerous and timely “best” opportunities for implementing convergence in an incremental fashion. This is well aligned with the strategy outlined in the NAS EA that today’s automation solutions will provide the basis for implementing the NextGen Midterm and Far Term capabilities.

References


Figure 3 Alternative 2 - Flight Data Display (FDD)
Airport Data as the Centerpiece of Traffic Flow Management

An Opportunity for Constructive Change

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Introduction

The emerging availability of airport operations information as a timely input to the management of the National Airspace System (NAS) presents a unique opportunity for the transformation of traffic flow management philosophies and methodologies. Focusing on the airport as the limiting factor in the efficient use of the available airspace resources will require a break from the legacy approach of using aircraft schedule performance as the decision making pivot point. However, greater focus on the airport connected to the en-route constraints, will allow a better balance of total airspace utilization.

Because the primary limiting resource in the NAS is, and will continue to be, runway availability followed closely by gate availability, airport efficiency is the most important factor in improving overall NAS efficiency. The fundamental airline operations strategy of hub-and-spoke routes only amplifies the importance of the hub airport performance and a need for reliable predictions of aircraft turn times.

At the core of the required airport operations information is high confidence gate release predictions founded on the collection of real-time status reports and well-founded business rules for the airport ramp operations. It is not enough to simply know where the assets are and that they are ready for transfer of control from gate to surface to air traffic control.

The alternative is to tighten up on the adherence to published schedules, but the loss of adaptability to changing conditions has a direct and undesirable impact on the ultimate airspace users, the passengers and shippers.
The Need

Predictability: The key to stability, congruency, and efficiency in NAS resource allocations

The National Airspace System is a complex array of systems and subsystems which strive to efficiently and sequentially allocate NAS resources to individual flights to maintain separation assurance and safe flight to destination. The capacity and associated resources of this system-of-systems are finite. Further they are widely subject to variability with weather, safety limitations, staffing, component failure impacts, and airport configurations. Today’s unpredictable flow of traffic out of the ramps to the runways leads to delays and lost throughput opportunities at the threshold of the runway.

Each flight departing each airport gateway represents a demand for NAS air navigation service provider (ANSP) resources which must be assembled sequentially and bundled for each flight at the points of entry into the system, specifically the runways. In practice, the assembly process during peak demand and disruptions can be expected to take longer than the nominal or expected taxi time once the seminal event of the aircraft requesting service makes formal contact with controllers and air traffic managers. Traffic managers can often see the opportunities within the confines of the restrictions they face, but they may not be able to sort through the chaotic variability in the sequence of departures in time to clear each flight for takeoff without delay or lost throughput.

The current environment forces the traffic managers to address the chaotic flow prior to flight, but after pushback or after the call for service at the transition spot. Controllers and traffic managers are challenged to match the supply of NAS resources opportunities afforded them to a predictable, and to the extent possible, prescribed sequence of departing traffic.

The Problem

Airport Ramp Operations: A major source of NAS uncertainty

Airports ramp operations, as the largest source of NAS demand, are also a major source of NAS demand uncertainty. Even scheduled operators with published departure times do not operate with the levels of schedule precision required to properly prepare and allocate the limited NAS resources necessary to provide efficient and effective air traffic services under all conditions.

Hub airports in particular with their high levels of compacted schedule demand make successful and seamless allocation of NAS resources challenging. This peak demand for service associated with network carrier hub operations is the direct result and reflection of the market meeting the mobility demands of the traveling public. The highly variable demand may indeed be a
poor business plan for NAS operations, however, it remains a well established and firm practice of providing airline service.

The “Hub and Spoke” systems, although their numbers are decreasing somewhat, are unlikely to go away because they provide a network of effective services across multiple markets more effectively than any other transportation concept yet conceived. Unfortunately, hub airports exaggerate an asymmetric demand and the poor ramp operations schedule predictability creates uncertainty that propagates through the terminal airspace and into the en-route NAS.

Ultimately the human decision maker response to NAS uncertainty employs the broad use of delay tactics as a control method to bring the demand in line with capacity, essentially an artificial demand limiting environment. This results in significant losses of NAS throughput. As delays and congestion manifest themselves at an airport, second order effects impact the NAS. As a result, congestion on the airport surface and in terminal areas creates obstructions between flights and the NAS resources being managed resulting in even more delays. Assembling the proper mix of NAS resources required for a given flight becomes more difficult to allocate smoothly and seamlessly in point of time.

These local compounded delays in conjunction with the scheduled congestion produce compacted demand, but, more importantly, off-time irregularities that degrade the future traffic management system (FTMS) predictions for traffic demand in the en-route NAS decision support systems. Uncertainty and delays propagate deeper and demand becomes a choppy mix of spikes and valleys. NAS resource utilization drops off and short demand overages produce more reactive responses from controllers and traffic managers, delays from Miles in Trail (MITs) and other Traffic Management Initiatives (TMIs) until the NAS resources assembly process is once again smoothed. Often this is only fully accomplished when the demand drops off at the end of the day.

“It is usually thought that errors in the prediction of OFF times are the largest source of error in the future traffic management system (FTMS) predictions”

Rick Oiesen
John A. Volpe National Transportation System Center

The poor reliability of these off-time predictions in FTMS results in a systemic loss of confidence in the demand predictions across most traffic management decision support tools. Traffic managers, when faced with high uncertainty and poor predictability, are relegated to simplistic rules of thumb, overly tactical procedures, and assignment of delays to remediate the situation. Unfortunately these options result in remediation that overcorrects and further impacts the capacity of the NAS, jeopardizing the integrity of the system. The problem propagates
nationally all the way to the System Operations level at the ATC System Command Center (DCC) where traffic managers often have to choose between two undesirable courses of action:

- a Wait-and-See approach, almost entirely tactical and subject to wholesale shut downs of NAS resources should demand exceed the capacity or,
- a broad and strategic approach such as an airspace flow program (AFP) based on high levels of weather impact uncertainty which often over-restricts the system.

The Legacy Solutions

Airport Surface Surveillance: Why it is not enough

The past decade has seen limited, but significant deployment of surface surveillance tools. These systems have improved situational awareness and helped remove some of the uncertainty created by airport surface movement and terminal congestion. These systems support the management of surface traffic congestion, including both arriving and departing aircraft moving under their own power or pushed back from a gate. But how good are these systems in making demand predictions into future?

Surface surveillance, while helpful, only provides situational awareness of events as they happen and not before they happen. Thus, day-after-day, bank-after-bank, the NAS service assembly problem changes and the controllers and traffic managers attempt to maintain a first-come, first-served (FCFS) approach, as a polite and orderly allocation of NAS resources. However, during the complexities and overwhelming uncertainties of congestion, even FCFS is lost as the basis for resource allocation in the face of surface chaos where controllers fall back to individual survival techniques. This chaotic parsing of who goes first and who goes next includes a reactive assignment of delay that is in fact a diversion from the other duties that assure the safe and orderly flow of traffic from the ramps to the runway.

The current tool set does not address the fundamental source of the loss of ramp schedule integrity; the ability of the operator to comply with the filed gate push off time or make reliable adjustments based on actual progress. The out or push time translates directly into the critical departure or wheels-up event with the addition of nominal taxi times and thus it drives a large portion of the rest of NAS predictability. A reliable, advanced notice of true push back time is not currently part of the suite of available tools that are based on after-the-fact reporting.

Congestion initiatives affecting departures such as approval requests (APREQs), miles-in-trail (MIT) restrictions and formally issued expect departure clearance times (EDCTs) for TMLs, all require planning and special handling of departures by the traffic managers and controllers. This may further involve management and balancing of arrivals in relation to departures.
Traffic Managers indicate they would prescribe their desired sequence and queuing if they had confidence the airline could strive to deliver the aircraft accordingly. However, lacking such assurances and faced with overwhelming uncertainty, the controller and traffic manager currently can make only limited attempts to manage the queue toward an ideal sequence of departures. As the desired terminal area density increases and as the complexity of the arrival and departure procedures increases with the implementation of Required Navigation Performance (RNP), this condition is further compounded.

What is missing is predictability of incoming demand at the beginning of, and across the NAS resource chain. What is missing is the precursor to the queuing, the determinant of the order or sequence, and the control mechanisms to satisfy both the operator imperatives within the ramp and gates as well as the air traffic need to assemble effectively the bundle of services required for each flight trajectory at the point of entry. What is missing is predictability prior to surveillance.

This pre-surveillance predictability can be provided by a complete surface management system collaboratively transforming the chaotic logistics of the ramp into reliable gate release times and ultimately a fully managed sequence of departures.
A Different Direction

The traditional solution set for improving ramp and surface performance is limited to the improvement of each of the individual aspects of the problem. Built-in schedule slack to account for the apparently unavoidable events is a notable condition, but the optimization of each potential contribution to delay and inefficiency is not enough. It takes a more holistic approach, a thorough understanding of the operational and business processes of the ramp, and the logic behind all surface operations including the ramp. Once the interactions of operations are understood, modeling of the entire operation can be used to find opportunities amongst the seemingly random occurrences that ripple into unmanageable circumstances.

Most approaches to surface management have focused on a particular, often singular perspective attempting to address surveillance, clearance delivery, ground control, gate or ramp control logistics, and the customer service side of gate or ramp operations themselves. In each of the vertically structured “stove pipes” one finds a unique view of the surface problem, access to the directly associated data and information which, although narrow in focus, has the potential to improve the management process in a limited way. Examples include more accurate surveillance, improved calculation of taxi times, and greater attention to historical connection times.

The use of a modern, automated, cross-cutting approach with no regard for the existing operational stove pipes and apparent data access limitations has proven that the requisite critical mass of data already exists. Though embedded within these various stove pipes, a modern database approach allows data exchange and enrichment toward the creation of actionable information and holds promise for major improvements for decision-makers and all NAS stakeholders. This critical mass of collective information, when combined with modeling and predictive algorithms, can be leveraged to transform many of the ways operations are managed on the ramp and airport surface leading to positive affects beyond the terminal airspace.

Lockheed Martin, in conjunction with a major U.S. Airline and a large a regional hub-and-spoke airport on the East Coast, has produced a demonstration environment for the evaluation of a ramp logic modeling capability. The modeling considers historical performance and current conditions to assess likely outcomes and deliver appropriate information mixes of the previously stove piped data to operators and supervisors to support decision making. The decision support tools are customized to the airline operations at the airport, but the underlying modeling is common to all the outputs.

The capability, known as Ramp Logic, will soon include a surface movement component.
The Integrated Solution

Data Discovery

Much is known about the data available to better manage the airport ramp and terminal operations, but until recently the robust data required for better management has remained out of reach for a variety of reasons. In order to meet the challenge, a comprehensive survey of the available data sources to better manage the airport surface is required. FAA and related surveillance data are readily available, but insufficient to provide the critical mass of data for gate release predictability because much of the data resides deep within the operator business processes. A deep dive into the available data sources is required. Most of the requisite data exists, but the key is exchanging and integrating that data in a manner that brings it to the decision makers in a coherent, predictable, and actionable manner, thus providing a comprehensive solution to better manage airport congestion.

Data Feeds

Once the critical mass of data is identified, feeding it into the gateway may present several additional challenges. The unique data challenges of formats, transmission vehicles, refresh rates, latency, and efficacy all must be considered and solved with an eye on cost efficient exchange and processing downstream at the gateway and beyond.

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Data Gateway

The need to leverage the relevant data requires an addressing of the disparate data sources, formats, and refresh rates. One approach would be to standardize the data sources based on the intended data uses. However, the significant implications to the many legacy data source applications are daunting and a successful standard would potentially limit the breadth of possible uses. A more pragmatic approach is establishing a data gateway as a repository of the various sources of data and to ultimately feed enhanced decision support tools. Each data source must be wrapped into a service for efficient processing and ease of reuse, but the legacy applications do not require change and the reuse opportunities are unencumbered.

Data Enhancements and Process Changes

As the data elements are assembled and the exchange opportunities are identified there may be gaps between the requirements of the solutions and the critical mass of data discovered. Development of robust and effective solutions may require the data to be enhanced beyond the discovery process. It may also require the operator to assess its own internal processes, procedures, and requirements to provide adequate information for the desired solutions.

Data Fusion

Once the array of FAA and operator data is assembled at the gateway it can be analyzed, then weighted and modeled to provide improved predictions of the all too uncertain events in today’s NAS. These predictions include at what time, and with what level of confidence, individual flights will actually push the gate and call for service.

Operator Intent and Flight Status

The required outcome of the deep dive into the operator side of the data is better knowledge of the operator’s intent and status for each flight well before and during the utilization of the airport ramp and surface resources. This implies that uncertainty can be characterized and managed, if not fully eliminated.

Perfect ramp-side predictability is not attainable, nor is it required, but a performance-based, probabilistic approach can eliminate a significant amount of the uncertainty which today precludes taking effective actions. This implies the ability to discriminate between a flight free of the indicators and precursors of delay which is ready to request air traffic service and one that has clear historical and real–time indications that a delay is inevitable. The confidence in the predictions based on the reliability of the data source is an important aspect of integrating the predictions into the decision making process practical.
Actual Pre-departure Performance

The data fusion process should lead to and provide a window into the actual operator performance in critical pre-pushback and pre-flight event horizon. Not every flight critical event can be known or foreseen. For example, the failure of a required aircraft system after pushback can occur randomly. However, the pre-departure flight specific data once assembled, fused, and analyzed can allow the flight to be categorized as a flight exhibiting the pre-departure behavior of a nominal on-time flight versus the pre-departure behavior of an unreliable flight subject to internal delay.

This allows applications and decision support tools to inform decision makers pointing them toward differentiated actionable pre-departure flights from those of flights which will likely have to be reconsidered when delays manifest themselves. This keeps the human decision makers satisfied that they are not simply making more work for themselves by planning ahead and that the predictive information presented prior to pushback is good enough to formulate realistic plans and take effective control actions in the pre-departure event horizon.

Surface Trajectory Modeling and Surveillance

The ability to focus control actions on a subset of flights which are unlikely to manifest delays opens the door to the opportunities of improved overall surface management. Taking advantage of those opportunities requires the proper matching of airport and eventually NAS-wide resources required by each flight to fulfill its surface trajectory and well beyond.

Modeling the surface trajectory of each actionable flight into the flow of ramp and airport surface traffic assists in finding opportunities to match current resources. It requires the continued surveillance and conformance monitoring to both enable the ordering and sequencing of flights and allow for re-planning when unexpected events occur, such as a flight returning to the gate or a sudden loss of departure capacity due to an unexpected weather impact.

Ramp Logic leverages the extensive experience of Lockheed Martin and its partners in airport surface trajectory modeling and integration of airport surface surveillance in FAA and NASA research to facilitate accurate surface trajectories and capture opportunities for greater efficiency. Along with access to the airport data sets Ramp Logic models the entire airport operation and builds an assessment of gate release readiness with an assignment of confidence.
Sequencing and Queuing Algorithms

When congestion and air traffic restrictions impact local airport operations the Ramp Logic system creates the pre-departure predictability to order and sequence departures to best fit the available capacity limitations and opportunities discovered in the surface trajectory modeling. This opportunity to produce alignment of the departure sequence to best utilize limited NAS resources is a major source of local airport benefits. Today these include better meeting EDCTs and better compliance with MIT restrictions and approval requests for associated en route spacing in the overhead traffic stream through improved automation.

These benefits are currently beyond reach because of the data void, the subsequent uncertainty in the pre-departure event horizon, and the inability to accomplish reliable and actionable flight specific planning. These are, however, only present day benefits in legacy systems which can expand greatly as Ramp Logic enriches modernized, time-based approaches to flow management. Both the terminal and en-route domains will be more tightly connected to the actionable flights calling for service and the better defined targets of NAS opportunities can be captured as actual throughput.
The algorithms for sequencing and runway queuing can account for the highly complex and dynamic airport environment, including airport configuration, aircraft type specific spacing requirements, traffic density, noise restrictions, and special operator requests. Business rules of both the operator and the ATSP can be incorporated producing a desired baseline or prescribed sequence and runway queuing of known or prescribed duration. This implies efficient two-way data exchange and common situational awareness among ramp operations and air traffic operations to best accommodate the goals of both stakeholders sharing the common resources of the airport.

Ramp Logic further enables the operator to make precise internal trade-offs between short queuing delays and passenger and bag connectivity. Ultimately this allows the carrier to meet the individual needs of its customers within the constraints and flexibilities afforded by air traffic flow and control.

**Compatibility with FAA Surface Management Systems**

In development of an airline centric solution, it is critical that the data and its use be compatible with other independent systems employed on the surface. This extends to and includes the development of algorithms for ANSP surface management. Ramp Logic is designed with this compatibility in mind such that airline operations personnel and air traffic personnel maintain common situational awareness when working together in coordination or collaboration. This enables synchronous and asynchronous decisions and actions to be directed toward compatible solutions where common situational awareness is inherent.

The Ramp Logic effort includes a partner with an established leadership role in developing surface management systems for the FAA. They provide for commonality in the algorithms associated with FAA airport surface systems. This assures that any independent air traffic systems will display common data with Ramp Logic displays and vice versa.

**The Benefits**

*Ramp Logic: Comprehensive data exchange as the key to unlocking NAS-wide benefits as well as flight specific reductions in the cost of available seat miles (CASM).*

The benefits of improved surface management are promising on several levels, but any serious discussion of these benefits begins with the hard and fast benefits of reduced taxi-out times and should include fuel burn reductions and maintenance costs closely related with reduced taxi-out times. A more subtle argument can be made in support of taxi-in time reductions, but initial analysis is limited to the simplistic and believable benefit of taxi-out time reduction.
There are other CASM benefits which track with taxi time reduction such as crew costs, but these are more complicated to determine and not considered at this time.

The easily related costs can be calculated at the lowest possible unit value of savings per flight, specifically one, two, or three minutes of taxi-out reduction per flight. There are several organizations who claim savings of a minute or more with basic improvements in surface surveillance alone and operators deploying such systems report additional operational savings. Even comprehensive surface management with surveillance, but lacking the gate release predictability provided by Ramp Logic, can argue for significantly increased savings per flight over basic surveillance improvements.

Using fuel and maintenance alone to calculate saving of a generic major airline with three major hubs in the 35 OEP airports at 1-, 2- or 3-minute increments result in annual savings of $5 million, $10 million and $15 million per year respectively. The payback period is likely 4 to 12 months, but could be financially managed as an expense versus a capital investment.

So how much more could a comprehensive approach to surface management beginning with the ramp data of the operators really save?

The comprehensive approach to taxi time reduction could reduce each surface trajectory to a minimum taxi time with zero delay plus a small queuing buffer to maintain pressure on the runway resource under most all circumstances. The rest of the delays could be taken at the gate unless the gate resource was needed. In our analysis at a major airport, average taxi time was 20 minutes and zero delay taxi time was about 5 minutes. With a 3-minute demand buffer that could be an 8-minute average taxi with a 12-minute average reduction.

Optimistically, flight block time reductions may even be possible once sufficient confidence in the performance of the predictions and systemic value of the decision support tools is realized.

**Other Benefits**

**Network Carrier Connections at Hub Airports**

The network airline benefits extend well beyond direct reductions in CASM and impact the revenue side as well by preserving it. While those flights are at the gate awaiting their planned release time, they can continue to catch any late connecting passenger and bags which would otherwise have been lost at pushback only to stand in queue.

Passengers and their bags will also connect more effectively because, through improved data management and modeling, the airline can better predict the effectiveness of holding a flight to recapture passenger and bag connections on late flights.
Emissions

One of the more obvious gains of implementing Ramp Logic is a significant reduction in emissions driven by taxi time reductions. Government policy on emissions is evolving but likely to be far more significant in its future impact.

Surface Congestion and Occupancy

There are clear gains when surface congestion and taxiway occupancy is reduced although they may be difficult to quantify. Last-minute adjustments to sequencing departures can be easier when there are eight aircraft in queue rather than eighteen. A safety or risk gain could be claimed by simply reducing the physical presence of aircraft on the airport taxiways and movement areas. Ramp congestion and a resulting reduction in ramp damage to aircraft and equipment is difficult to project, but a likely outcome of the capability which deserves further consideration along with the overall safety improvement.

Workload and Exception Handling

Once the algorithms are developed and the Ramp Logic automation system implemented, the decision-makers’ workload during peak demand will likely be reduced significantly. A smoothing of workload is anticipated with more time and attention paid in planning prior to these peak demand periods. This creates the opportunity for greater focus by air traffic and operators alike in handling the more challenged flights and exceptions while the system handles the nominal cases.

Second Order Benefits and Opportunities

The Trade Space Opportunity

Ramp Logic: The ability to balance the future of dynamic and competing interests

Fuel prices continue to fluctuate greatly within short periods of time. Industry economics continue to undergo tumultuous change. Environmental concerns now include not only noise but emissions. Energy policy shifts are moving the nation toward greater emphasis on fuel conservation. It is highly likely that the mix of priorities for future operations within the NAS will undergo many changes and even multiple reversals.

One of the greatest opportunities of improved and more comprehensive surface management is the ability to balance the shifting priorities for future operations. Beyond the hard and simple CASM metrics of time, burn, and maintenance are more detailed priorities including core business performance metrics for the operators such as completion factor, passenger and bag
connectivity, on-time performance, and block time minimization. Balancing these alone can be challenging for the operator themselves, but add in the ATM and national priorities and you have a very rich space for trade-offs and optimization. The national and ATM priorities will include metrics of safety, maximizing throughput, minimizing congestion and occupancy, and lowering noise, emissions and energy use.

Operations Researchers have found collaborative ATM solutions to be most challenging. One subject matter expert\(^1\) often cited in CDM meetings, describes the problem and solution space as among the most difficult (paraphrasing):

\[
\text{It involves all of the following: stochastic elements, ever changing conditions, non-linear effects, interdependencies between elements, competing autonomous agents acting in own self-interest, public good criteria and potential conflicts between the pursuit of safety and efficiency}\,^1.
\]

It is not surprising that the fullest and richest solutions to the surface management challenge have yet to be implemented. The opportunity for a focused solution on a singular element of surface management is tempting but the greater benefit is likely found in the ability to be agile and to flex the mix of solutions in response to the changing desires and transitory requirements placed upon the aviation community.

**The Incremental Trajectory Planning Opportunity**

**Ramp Logic: Enabling dynamic trajectory management**

A more stable and predictable NAS offers a whole new set of solution paths not available in today’s comparatively volatile system. Today’s system generally does not allow Instrument Flight Rules (IFR) traffic to depart without a full flight plan to destination. In-flight re-planning is cumbersome and constrained by the lack of effective pilot-to-controller data link communications and other more agile communication, navigation and surveillance (CNS) capabilities. This required deterministic trajectory to destination is based on an assumption as flawed as the scheduled departure time assumption when departing into areas of uncertain weather impacts. In fact, for flights in the current NAS, transiting multiple areas where the combined weather uncertainty is too high to allow the flights to depart has become a common event. These weather impacted flights are often held on the ground indefinitely because the traffic manager concludes there are “no routes available”.

The future management of trajectories in a more stable and predictable NAS could employ an incremental assembly line where an end-to-end flight trajectory is only notionally assigned with identified decision points along the trajectory. The final assembly of the route would be
segmented, adjustable, and cleared by ATC prior to each decision point as the uncertainty of weather and other impacts are reduced and the best and final solutions for each subsequent segment clarify themselves in the more tactical event horizons.

**The Systemic Decision Support Opportunity**

**Ramp Logic: Extending the event horizon for actionable demand predictions, enabling effective strategic actions**

National Traffic Managers in the present NAS are continually limited by the efficacy of the data feeding the major decision support tools which they rely upon. This means that prudent TFM solutions often must be delayed until the data firms and the solution defined actually has a reasonable probability of being executed. As time passes, and predictions improve, two important aspects of traffic flow management decline:

1. The ability to affect and control flights.
2. The size of the strategic solution space.

**Predictability and Effective Control Curves**

Therefore, improving the data in the strategic event horizon unburdens the system tactically by expanding the ability of the traffic manager to formulate realistic plans earlier and implement more limited and effective strategic solutions. Traffic managers are no longer forced to “wait-and-see” only to find that the problem has grown in magnitude to the point that tactical solution space is exhausted and shutting off whole nodes of the NAS is the only remaining option.
Conclusion

Every airport, but certainly the major hub airports, needs to become an integral element of the NAS traffic flow management scheme. The information contributed by the airport needs to be a high confidence projection of the ability to accept aircraft and return aircraft to the skies.

When ramp operations are based on impacts to not just the gates, but to the entire NAS resource chain as well, the taxiways, runways and terminal airspace, then the airport surface management process is transformed. Synergistically, when the airspace operations are based on actual airport and airline capabilities, the management of the NAS becomes a truly collaborative environment with opportunities for previously unrecognizable efficiencies.
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Footnotes:

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Altitude Tracker in Co-Existence of Different Quantization Levels with a Pre-Filtering Approach

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Abstract
In current air traffic control systems, an IMM tracker is now the typical tracker for horizontal tracking. It has recently been adopted for altitude tracking as well. The IMM tracker is based on the assumption of Gaussian measurement noise. However, current ground tracking systems receive measurements of an aircraft’s altitude through two independent signals: ADS-B and mode C. Although the source of the information is the same, the ADS-B applies to it a quantization of 25 feet, while mode C applies a quantization of 100 feet. The mixed quantization of the reports poses a challenge for the estimation of an aircraft’s state, in particular its vertical velocity, by the standard filtering approaches, namely an IMM Kalman filter. Typically, this problem has been addressed with partial success by some form of toggle logic used to explicitly detect toggling events caused by the quantized measurements. The approach proposed here by ARCON focuses on pre-processing the altitude measurements before providing it to the estimator. This approach is based on a pre-filtering architecture developed to address most issues introduced by the mixed quantization of the reports, improving the smoothness and accuracy of the information. Comprehensive simulation results show the significant improvement brought by the pre-filtering method both during level flight and in altitude change maneuvers.

Introduction
In air traffic control it is important for navigation and safety purposes to obtain accurate estimations of both altitude (Z) and the vertical velocity (ZDOT) of all aircraft that share a common airspace. Traditionally, the estimation of both variables was performed by a ground tracker based only on reports received from each radar site that successfully scanned the aircraft. However, due to bandwidth limitations on the transponder signal used by the aircraft to broadcast its altitude to the radar sites through mode C messages, the altitude reported by radar sites to the tracker in this fashion is restricted to a 100 feet resolution. To account for the lower perceived precision of the altitude measurements, a Kalman filter with a proportionally larger measurement noise was used to combine the information in multiple radar altitude reports and generate Z and ZDOT estimates. The 100 feet quantization error of the altitude measurement posed some challenge to the Kalman filter, which theoretically assumes Gaussian noise over the measurement [1]. While in most level flight cases the reports would be fairly consistent, in particular scenarios in which the aircraft sustained an altitude at around XX50 feet (where the notation XX indicates any altitude whose last digits match those indicated), the reports would toggle between the two neighboring 100 feet quantization levels. Even so, because radar reports have a coarse temporal resolution in addition to the coarse quantization resolution, simple tuning of filter parameters was in most cases accepted to be sufficient to address this issue and reach estimation accuracy levels that could be expected from the coarseness of the radar reports.

Currently, the GPS/INS systems installed in the vast majority of the commercial aircraft in the United States provide an additional source of reports containing altitude information through Automatic Dependent Surveillance-Broadcast (ADS-B) messages. Although the altitude signal itself is originated in the same differential barometric pressure sensor from which mode C data is acquired, ADS-B signals are generated consistently at 1Hz, do not depend on the presence or efficacy of ground sensors, and provide to the ground tracker altitude measurements with the smaller quantization level of 25 feet [2]. While all these advantages indicate the capability
to obtain more accurate estimates of Z and ZDOT, aggravated toggling issues prevent the originally designed Kalman filter to reap these benefits and, in some cases, the presence of the ADS-B signals in addition to the radar reports can even deteriorate the overall estimation performance, leading to significant losses on the performance of conflict detection and resolution algorithms [3]. Specifically, the smaller quantization of ADS-B signals makes the altitude regions around XX12.5, XX37.5, XX62.5, and XX87.5 feet prone to toggling issues. Considering that the typical barometric sensor in usage today presents a Gaussian error with standard deviation ranging from 5 feet to 15 feet, the proximity between these toggling regions effectively makes the reported measurements prone to toggle at any altitude. Furthermore, when radar and ADS-B reports are both fed to the tracker, as exemplified in Figure 1, the mixed quantization of the signals combine to generate a discrete measurement profile that is further away from the zero mean Gaussian distribution assumed by the Kalman filter.

To address the issues related to the mixed quantization measurements, the most straightforward solution seems to use some form of logic to detect toggling events and limit their impact by modifying the states of the Kalman filter to prevent the incorrect estimations to be output or propagated. While some level of success can be achieved by this toggle logic approach, its dependence on explicit detection of toggling events limits their reaction time and prevents any corrective action to be taken when the detection algorithm fails. We propose a pre-filtering method to handle mixed quantization estimation scenarios which does not require explicit detection of each toggling event, instead minimizing the impact of potential toggling events by improving the smoothness and accuracy of all the measurements provided to the Kalman filter.

The Toggle Logic Approach
Challenges exist in the straightforward toggle logic approach shown in Figure 2, which includes a Kalman filter, the toggle logic itself, and a Level Flight Threshold (LFT) responsible for smoothing the ZDOT estimation during level flight by forcing it to zero when it falls below a given threshold. First, the detection of toggle events is not an easy task. Since the toggle logic at the tracker only has access to the quantized measurements, there are no means to differentiate between a true altitude change and an artifact of toggling until a following measurement “jumps” to another quantized value in the opposite direction. Furthermore, in such cases a toggling event is detected only if the three measurements in question occur in fast enough succession such that the change between quantization levels is not feasible within the dynamic constraints of an aircraft.

Next, limiting the impact of incorrect estimation is also a challenging task. After the toggle event is detected, the reaction step must, in addition to preventing further degradation of the position and velocity estimates being output by the filter, also recover the filter states from the update of the previous misleading measurement. Therefore direct alteration of the filter’s states is needed after the filter is updated using the new measurement. One state alteration option in such cases is to force the ZDOT state of the filter to zero, ensuring that the output of the filter from that update will indicate a zero estimated velocity, effectively erasing the memory of the filter related to the artificial high velocity it incorrectly estimated. It is trivial to see that this simple reaction approach will have significant detrimental effects on the estimation of ZDOT when the aircraft is performing true altitude
change maneuvers. Another option, to substitute erroneous ZDOT estimations with averages of past estimates, can also be implemented. Nevertheless, all these approaches for the reaction step not only are subject to the efficiency of their detection methods, but also tamper with the Kalman filter in a manner which can potentially significantly deteriorate its dynamic performance.

ARCON's Pre-Filtering Approach
The proposed pre-filtering approach is not reactive, and therefore operates without requiring a dedicated detection algorithm by constantly improving the smoothness and accuracy of the reported altitude measurements before they are provided to the tracker’s Kalman filter. As illustrated in Figure 3, the pre-filter is composed of three stages, each sequentially addressing a specific issue regarding the data that reaches the tracker. As in the toggle logic architecture, this approach also contains a Kalman filter and an LFT block.

The first stage of the pre-filter is the radar report correction stage. The purpose of this stage is to address the features introduced by the mixed quantization levels by improving the accuracy of radar reports using the measurements of recent ADS-B reports. The underlying assumption of this stage is that whatever filtering occurs to the original barometric altitude measurement within the GPS/INS unit in the aircraft, the prior to quantization measurements available to the ADS-B signal have greater or equal accuracy than those available to the radar mode C signal. Under this very realistic assumption, if a radar report is received by the tracker within a few seconds of an ADS-B signal (typically a fraction of a second if the ADS-B signal has no losses) it is possible to use it to recover some of the accuracy of the radar report lost in the larger quantization of 100 feet. In particular, if the difference between a radar report and the previous ADS-B report is less than 50 feet, the radar report value takes on the ADS-B report value. If the difference is greater, the accuracy of the radar report can also be improved by decreasing or increasing the reported value by half of its quantization (50 feet) in the direction of the previous ADS-B report.

The second stage of the pre-filter is the overlapping gates stage. The goal of this stage is to filter out the small oscillations around the 25 feet quantization level caused by toggling in such a manner that there is no impact on the response time to the larger measurement value changes caused by true aircraft maneuvers. To understand this stage one can visualize a series of brackets, or gates, positioned at each 25 feet quantization level; each gate with a length of 50 feet encompassing three consecutive quantization levels. The overlapped gates form hysteresis regions that are used to prevent variations within the 25 feet quantization level from reaching the Kalman filter.
without sacrificing the resolution precision of the altitude measurements. If, on the other hand, a measurement arrives from an ADS-B or mode C report with an altitude outside the range of the current gate, the active gate immediately shifts to the new measured altitude, ensuring that the response time to significant altitude changes is not negatively impacted.

Finally, the third stage of the pre-filter is the steady state correction stage. This stage’s purpose is to prevent the overlapping gates of the second stage from perpetuating a 25 feet steady state error in the measurements reported to the Kalman filter. Such steady state error can only occur under very specific scenarios to aircraft with very accurate ADS-B reports. Such scenarios are characterized by a level flight maneuver at the start of which the last gate selected by the second stage of the pre-filter was centered 25 feet away from the true aircraft’s altitude. Even in the rare occasions when such situations occur, its impact would be limited to a 25 feet error in the estimation of Z, with no impact on the accuracy of ZDOT. Nevertheless, the third stage addresses this issue by retaining a moving window of past received reports, which has all its elements set to match the altitude at the center of a gate every time a new gate is selected. If the average of such window falls within the upper or lower quarter of the current gate range, the new gate is selected immediately above or below the current one, respectively. In our study we have used a window of ten reports.

By applying the three stages sequentially and providing the center value of the selected gates to the Kalman filter as measurements, the pre-filter improves the efficiency of the Kalman filter. Since it does not require explicit detection of the toggling events, the pre-filtering approach provides superior performance than toggle logic approaches even in the cases with the most measurement error at the barometric sensor. Furthermore, since it does not interfere with the update process of the Kalman filter, pre-filtering is also a more stable and reliable solution. Due to the small hysteresis regions within each gate, the pre-filtering approach tends to provide a slower ZDOT estimation response for maneuvers that start with slow altitude changes. Nevertheless, this incurred delay lasts only 5 seconds on average, depending on the steepness of the maneuver, when compared to the response of the standard system. Overall, this increase in the response time of the filter still results in a system well within the acceptable time frame for aircraft tracking.

**Simulation Results**

Two sets of simulation scenarios were developed to evaluate the effectiveness of the proposed pre-filtering method in accurately estimating ZDOT, and to compare it against a toggle logic method and a standard ZDOT estimation algorithm (Kalman filter and LFT only). The two simulation sets were divided into level flight scenarios and altitude change scenarios. All simulations were conducted with ADS-B enabled aircraft flying within the coverage of two short range and two long range radars such that, on average, the tracker receives radar reports at a rate slightly higher than one for each two ADS-B reports. To verify the capability of each method to cope with different noise levels in the altitude sensor of the aircraft, independent simulations runs were conducted with sensors subject to representative zero mean Gaussian errors with standard deviation of 5, 7.5, 10, and 15 feet.

The level flight scenarios contain 20 aircraft flying at all combinations of the base altitudes of 4000, 6000, 10000, and 20000 feet, incremented by 0, 12.5, 25, 37.5, and 50 feet (i.e. 4000, 4012.5, 4025, etc.). Aircraft flying at the different small increments were necessary to evaluate the performance of the algorithms at the different mixed quantization circumstances illustrated in Figure 1. Indeed, as shown in the sample runs in Figure 4, the performances of the algorithms vary significantly depending on the specific altitude range (e.g. XX00, XX12.5, etc.). As summarized in Figure 5 (left), the toggle logic is significantly more efficient in reducing the number of occurrences of incorrect ZDOT estimations during level flight when the maneuver occurs in between the ADS-B quantization (i.e. at XX12.5 and XX37.5), when compared to all other altitude ranges. One the other hand, the same regions present the greatest challenge for the pre-filtering method. Nevertheless, when compared to one another, the pre-filtering method outperforms toggle logic in level flight in all evaluated scenarios. In particular, the pre-filtering method generated sporadic incorrect ZDOT estimates only at the maximum measurement noise level considered, as shown in Figure 5 (right).
The altitude change scenarios consist of 12 trajectories covering all combinations of maneuvers starting at level flight at 4000, 6000, 10000, and 20000 feet, followed by two minutes of a descent maneuver with a vertical speed of 600, 1000, and 2500 feet/minute. The left frame of Figure 6 illustrates the quantized altitude reports that arrive in the tracker and are provided directly to the Kalman filter in the standard and toggle logic methods. Note that toggling events cause spikes of varying magnitudes during the descent maneuvers as well, providing a clear challenge for the estimation of ZDOT by the filter. On the other hand, the right frame of Figure 6 shows the output of the pre-filter over the same data, corresponding to the data that in this case is provided to the Kalman filter. As shown in these examples, the altitude measurements available to the filter in the proposed method are smoother and with fewer spurious oscillations (both factors beneficial to ZDOT estimation), although there is a tendency of the measurements to lag a few seconds behind the maneuver.
Figure 5. Average number of incorrect ZDOT estimations (i.e. greater than the level flight threshold) per minute of level flight. The performances of the three estimation methods are compared grouped by the different altitude ranges (left) and measurement noise levels (right).

Figure 6. Altitude measurements provided to the Kalman filter in the toggle logic (left) and the pre-filtering (right) architectures. In the framed simulation period, the aircraft initiates a descent with a fixed -600 feet/minute speed after flying level at 10,000 feet.

Examples of the ability of each method to estimate the ZDOT of the targets during descent maneuvers can be seen in Figure 7. In the standard method, with only a Kalman filter and the LFT, several toggling events introduced by the mixed quantization result in a large variance in the ZDOT estimation error during descent. The introduction of the toggle logic is capable of successfully detecting some of the toggling events and in such cases mitigate their effects. However, both in the descent and level flight segments the efficacy of the method is limited, as exemplified by the instances indicated by the arrows in the top-right frame of Figure 7. In comparison, the proposed pre-filtering method produces a significantly greater accuracy even at the slowest descent rate.
Figure 7. Tracker’s ZDOT estimation by the Kalman filter and LFT alone (top-left), applying the toggle logic method (top-right), and the pre-filtering method (bottom). The arrows in the top-right output indicate instances of excessive ZDOT error that were mitigated by the toggle logic. Original measurement subject to a Gaussian error with 10 feet of standard deviation.

Since during a descent maneuver the LFT cannot provide the same acceptable noise level as available during level flights, the average absolute estimation error is used here as the comparison metric instead of simply the number of incorrect ZDOT estimations. As shown in Figure 8, during descent maneuvers the toggle logic fails to improve the performance of the estimation of ZDOT in a significant manner, at times managing to deteriorate it through its exogenous manipulations of the filter’s states. On the other hand, the pre-filtering method displays a significantly enhanced performance that shows a very slow degradation curve as the sensor noise is increased. As previously mentioned, a reduction in the response time of the estimator was an expected outcome of the application of the pre-filtering method. Yet, as shown in Figure 8 (right), based on a compilation of all considered scenarios, the additional response time (estimation lag) is on average less than five seconds, with the pre-filtering method outperforming the response of the standard and toggle logic methods at 12 seconds after the start of the maneuver, on average. It is also important to note that the simulation scenarios were constructed without any assumption of the dynamic limitations of typical aircraft that would normally prevent a steady rate descent maneuver to start instantaneously. In practice, the smoother behavior imposed by the physical limits of the aircraft further reduces the response time of all methods.
Figure 8. Absolute ZDOT estimation error for the standard, toggle logic, and pre-filtering methods during a descent maneuver at steady state (left) and during the first 25 seconds of the maneuver (right).

Conclusion
How to deal with reports with mixed quantization is a realistic and challenging problem in many real world estimation systems, including the real time estimation of the vertical speeds of aircraft by a ground tracker. In this paper we have discussed the benefits and shortcomings of the most obvious solution, in which a dedicated logic is used to detect toggling events so that mitigation measures can be taken in response. As a better solution, we have proposed a pre-filtering method that operates directly over the received reports in order to address several issues introduced by the quantization processes without the need to explicitly detect each toggle event. Extensive simulation analysis has demonstrated that the application of the pre-filtering method increases performance of the estimation of ZDOT both in level flight and in altitude change maneuvers, with only a few seconds of increase on the response time during transitions between maneuvers when compared to the standard method.

References


Automated Terminal Proximity Alert (ATPA):
Improving Situational Awareness on the Final Approach Course

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1.0 History
In 2007, FAA Managers from seven of the busiest terminal facilities in the United States requested a software tool to help air traffic controllers avoid compression errors on the final approach course. Due to the inherent complexities in FAA Terminal airspace and procedures, the FAA formulated a systematic approach to incrementally define and deliver new Terminal Proximity Alert (TPA) software to air traffic control (ATC) facilities across the nation in stages. The TPA Team, consisting of air traffic controllers, software and system engineers and human factors specialists, was formed to define the requirements and the Computer Human Interaction (CHI) for each stage of the TPA software.

The FAA deployed the first stage of the TPA software to the FAA terminal facilities in March 2008. The TPA software provides the controller the ability to monitor separation between aircraft by entering a keyboard command to display a cone-shaped graphic in front of an aircraft or a circular-shaped J-Ring graphic around an aircraft. The size of the TPA graphic depicts the controller-selected distance, in nautical miles, between the aircraft. Additionally, the TPA software implements keyboard commands to modify the size of an individual TPA graphic, delete an individual TPA graphic, or delete all TPA graphics.

Following the deployment of TPA, the TPA Team defined the requirements and CHI for the next stage of the TPA software, referred to as the Automated Terminal Proximity Alert (ATPA) Phase 1 software. The ATPA Phase 1 software monitors the in-trail separation between aircraft located on a final approach course and will (a) automatically display the in-trail distance in the full data block (FDB) of the trailing aircraft, and (b) automatically display a color-coded cone-shaped graphic, originating at the location of the trailing aircraft and sized at the separation minima, and (c) automatically display two different color-coded cone-shaped graphics when a loss of in-trail separation is predicted to occur within two different look-ahead times. Each color-coded graphic corresponds to a unique look-ahead time parameter. Each graphic conveys a different message and may require a different response from the controller.

A primary concern in the development of the ATPA Phase 1 requirements was validating that both look-ahead time parameters would provide the terminal controllers ample time to resolve situations that indicate potential compression.

In order to accurately identify the optimum look-ahead times, Terminal Field Operational Support (TFOS) conducted Human-in-the-Loop (HITL) simulations in September 2009 involving field air traffic controllers, human factors researchers and pseudo pilots in the laboratories at the William J. Hughes Technical Center (WJHTC). The HITL simulations were designed to validate each of the two look-ahead time parameters. For each look-ahead time parameter, numerous look-ahead times were tested to determine which one would display the corresponding ATPA graphic in a manner that would (a) provide enough time for the controller to notice the graphic, evaluate the situation, take corrective action (if needed), relay commands to the pilot, pilot action and finally, aircraft response, and (b) not display unnecessary clutter on the ATC scope.
This paper discusses the development of the ATPA Phase 1 requirements and briefly speaks to planned future phases. It describes the ATPA Phase 1 functionality including the associated display graphics and in-trail distance that help increase situational awareness of the terminal controller workforce and potentially increase airport arrival rates. This paper will also describe how ATPA can be used to reduce compression errors and allow for more efficient aircraft spacing along the Final Approach Course. In addition to the potential ATPA Phase 1 benefits, the paper also discusses activities surrounding the HITL simulations and the identification of the ATPA look-ahead time parameters.

2.0 What is Automated Terminal Proximity Alert

The Automated Terminal Proximity Alert (ATPA) function is an enhancement to the Common Automated Radar Terminal System (CARTS) and Standard Terminal Automation Replacement System (STARS) software that works in concert with the current Terminal Proximity Alert (TPA) tool. The ATPA function automatically displays a visual notification, similar to the TPA graphic, to terminal controllers, when separation between aircraft on final approach is projected to be less than the prescribed minimum.

The ATPA function provides visual notifications via three differently colored ATPA cones:

Monitor cone. This is an advisory cone, colored blue, that is displayed when enabled and only at the owner’s position

Warning cone. ATPA displays a warning cone, colored yellow, when the distance between the trailing track and the lead aircraft is predicted to be equal to or less than the separation minima within a minimum period of time, referred to as the warning cone look-ahead time. An ATPA warning cone indicates a situation that may require the controller’s attention to ensure separation is maintained.

Alert cone. ATPA displays an alert cone, colored orange, when the distance between the trailing track and the lead aircraft is predicted to be equal to or less than the separation minima within a minimum period of time, referred to as the alert cone look-ahead time. Additionally, an alert cone will be displayed when the current distance between the trailing track and the lead track is equal to or less than the separation minima. An ATPA alert cone indicates that a loss of separation is predicted or imminent and the controller’s immediate attention and/or action are required to ensure separation.

The ATPA function currently is designed to perform the following tasks for aircraft located within a site-adapted final approach course.

- Determine the separation minima between associated aircraft being provided instrument flight rule (IFR) separation located within an enabled ATPA final approach course
- Automatically display an ATPA monitor, warning or alert cone to monitor separation or when a loss of lateral separation is predicted to occur or has occurred
- Ensure the size of a TPA graphic, currently displayed for a track that has just qualified for an enabled ATPA final approach course region, is not less than the required separation minima
- Display, in line three of the full data block (FDB) the distance between associated aircraft being provided IFR separation and located within an enabled or disabled ATPA final approach course
Automatic Terminal Proximity Alert is the next step in automating TPA. As noted earlier, TPA requires the controllers to enter keyboard commands to activate TPA display options. ATPA, once initiated for the controller, does not require key strokes for the display to be initiated. Once aircraft enter a predetermined alert area, ATPA will automatically display information to the controller. The alert area is a rectangular ‘box’ defined by the ATPA software that overlays the runways final approach course areas and can be locally adapted to accommodate various airport configurations (from landing threshold out to 50NM).

3.0 Determining the Optimal Alert Notification Timing

One key element in developing ATPA was determining the timing of the ATPA alert graphics. In other words, what’s the best time to display information to a controller that two (or more) aircraft on the final approach course that the controller is responsible for are compressing, and that there is potential that separation could be lost before the aircraft cross the landing threshold. Sending an indication too early could result in nuisance alerts and would reduce the effectiveness of the alert meaning. Not displaying the alert with sufficient time for the controller to react and take corrective action would also prove ineffective. To best determine an optimal alert time, the ATPA Workgroup recommended conducting a study using field controllers to better understand the relationship between providing alert notifications too early and providing them too late, and to develop a useful look-ahead time for the ATPA alert graphics.

The subsequent test series of ATPA alert cone look-ahead times was based on two factors: (1) the look-ahead times preferred by SMEs during the ATPA trials (22 seconds for alert cone and 45 seconds for warning cone) and (2) the controller/pilot total response time mean resulting from studies of terminal (PRM) and en route operations and recommended by Terminal Services Human Factors (24 seconds). A test series of three sets of the look-ahead times was used to enable testing with a full range of seven scenarios (21 runs) during the simulations.

4.0 The Simulations

The ATPA study was designed as a real-time, HITL simulation in two phases. During the initial phase an eight-day dry run simulation was conducted to test scenarios and select two optimal sets of look-ahead times for use in a formal simulation of ATPA. A three-day formal simulation was then conducted to evaluate the two sets of look-ahead times to select the set of look-ahead times that will be used in the
national deployment and operational use of ATPA. Airspace modeled on Dallas Fort-Worth (DFW) Approach Control Airspace was used to evaluate proposed look-ahead times for the ATPA warning and alert cones during both the dry run and formal simulations. Certified Professional Controllers (CPC) operated standard ARTS Color Displays (ACD) at each of three parallel arrival runways (18R, 17C, 17L). A similar approach was used for the dry run simulation and for the formal simulation. During both the dry run and formal simulations, each pair of numbers was tested using the same seven scenarios in the same sequence.

For the formal simulation, the two sets of ATPA look-ahead times that were identified as a result of the dry run simulation were tested.

4.1 HITL Dry Run Simulations

HITL simulations were conducted to dry run test scenarios and to select two optimal sets of look-ahead times that were used in the subsequent formal simulation. A set of look-ahead times includes the timing for the display of the warning cone and for the alert cone. The dry run took place in the CARTS laboratory of the WJHTC in conjunction with the Target Generation Facility (TGF). Participants were CPCs (see 5.1 Dry Run Participants) and pseudo-pilots (4.3 TGF Simulation Pseudo-Pilots). Each of seven custom-developed scenarios (see 6.1 Airspace and Scenarios) ran simultaneously on three CARTS controller positions. Objective and subjective data was collected from 42 runs over an eight-day period.

4.2 Look-Ahead Time Testing

The first dry run test series focused on selection of the alert cone look-ahead time. A test series of three candidate alert cone look-ahead times (26, 24 and 22 seconds) was created and tested with seven custom-developed scenarios. Each alert cone look-ahead time tested was paired with a warning cone look-ahead time that resulted in an equivalent delta time (23 seconds) between the warning cone look-ahead time and an alert cone look-ahead time. The look-ahead time pairs tested in the first series were 49/26, 47/24, and 45/22 seconds (warning cone look-ahead time/alert cone look-ahead time, respectively). The FAA reviewed the results of the first test series and selected an optimum alert time of 24 seconds, which was used to create a second test series for the examination of selected warning cone look-ahead times.

The second test series focused on the warning look-ahead time. Three pairs of look-ahead times were formed by using the optimum alert cone look-ahead time of 24 seconds resulting from the first test series, coupled with warning cone look-ahead times (49, 45, and 43 seconds) that resulted in varied delta times between the warning cone look-ahead times and the alert cones look-ahead times. The look-ahead time pairs that were used in the second test series were 49/24 (delta 25), 45/24 (delta 21), and 43/24 (delta 19) seconds.

From the results of the second test series of the dry run simulation, the two most promising pairs of warning cone and alert cone look-ahead times were selected by the FAA for testing during the subsequent formal simulation.

The look-ahead times that were tested in the dry run and formal simulations are listed in Table 1.

The most promising look-ahead times selected from each test series of the dry run simulations are shown in bold font. The most promising two pairs of look-ahead times that were selected for testing in the formal simulation were: 43/24 (delta 19) and 45/24 (delta 21) seconds.

The simulation was conducted using CPC’s from facility complexity level-10 or above terminal radar facilities with recent experience controlling live aircraft. Three scenarios were developed to emulate air traffic flows at Dallas-Fort Worth based on moderate to busy traffic densities. The scenarios were varied in complexity and traffic density to keep the controllers becoming too used to the scenarios.

Table 1 describes the three types of traffic flows used in the simulation:
### Table 1 Scenario Description

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monitor Scenario</td>
<td>Straight-in approach. Monitor controller responds to compressions on final approach course</td>
</tr>
<tr>
<td>Vectors to Final</td>
<td>40 NM to Touchdown. Aircraft vectored from downwind, base-leg and straight-in to final. Same controller works the aircraft from hand-off to threshold and monitors the approach for compression errors.</td>
</tr>
<tr>
<td>Feeder/Final</td>
<td>40 NM to Touchdown. Aircraft vectored to the final. Monitors approach for compression errors.</td>
</tr>
</tbody>
</table>

Each scenario had different levels of complexity. There were three variations of the monitor scenario, two variations of vector to final scenarios, and two variations of the feeder/final scenarios for a total of seven scenarios. The scenarios were used in both the dry run and formal simulations. The dry run HITL simulation analysis resulted in validating 24 seconds as the alert cone look-ahead timing to be used in the formal HITL simulation and as the basis for creating a second test series to examine selected warning cone look-ahead times. The final paired look-ahead timing would be used for ATPA national deployment.

#### 4.3 Dry Run HITL Scenarios

A set of look-ahead times includes the timing for the display of the warning cone and for the alert cone. The dry run took place in the CARTS laboratory of the WJHTC in conjunction with the TGF. Participants were CPCs and pseudo-pilots. Each of seven custom-developed scenarios ran simultaneously on three CARTS controller positions. Objective and subjective data was collected from 42 runs over an eight-day period.

#### 4.4 Formal HILT Simulation

HITL formal simulations were conducted to test the timing of the warning (varied look-ahead) and the alert (24 seconds) look-ahead timing. The objective of the formal simulation was to evaluate two sets of look-ahead times that were determined during the dry runs. Each set of times contained an alert cone look-ahead time (seconds) and warning cone look-ahead time (24-seconds). The ATPA function predicts where the location of two tracks will be in the amount of seconds defined by the alert cone look-ahead time. If the distance between the predicted locations of the two tracks is less than the separation minima, an alert cone will be displayed. Similarly, the ATPA function predicts where the location of two tracks will be in the amount of seconds defined by the warning cone look-ahead time. If the distance between the predicted locations of those two tracks is less than the separation minima, the warning cone will be displayed. The simulation used three separate sets of look-ahead times and tested controller responses’ and perceptions to each set. The criteria used to best balance the look-ahead times was:

1. The smallest ATPA alert cone look-ahead time, in seconds, that consistently results in:
   a. No loss of separation
   b. The highest percentage of aircraft landings (without missed approach)
   c. Acceptable controller workload
2. The smallest ATPA warning cone look-ahead time, in seconds, that consistently provides enough time for controllers to:
   a. Assess the situation and determine if corrective action is needed
   b. Take corrective action if needed
   c. Prevent the occurrence of an ATPA alert cone or loss of separation

#### 5.0 Testing Environment

The simulations were conducted in two laboratories of the WJHTC, the TGF and the CARTS laboratory. WJHTC personnel operated the labs. The TGF controlled the air traffic scenarios, generating aircraft targets that were sent to the CARTS lab for display on ACDs. Pseudo-pilots in the TGF controlled aircraft movement and interacted with controller participants in the CARTS lab via a voice communications system. The Communications Laboratory Maintenance team recorded the timing of the physical actions by controllers in
keying the microphone to issue instructions to pilots.

The times of the display and removal of ATPA warning and alert cones were recorded by the CARTS Continuous Data Recording (CDR) auto-functions class system. Each ACD was equipped with a pilot-to-controller communications system. An additional ACD located directly across from the three ACDs operated by CPC participants was used to monitor the performance of the ATPA software and the simulation scenarios.

Table 2 Look-ahead Timing Decision Progression

<table>
<thead>
<tr>
<th>Dry Run Test Series 1</th>
<th>Dry Run Test Series 2</th>
<th>Formal Simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>49/26</td>
<td>49/24</td>
<td>45/24</td>
</tr>
<tr>
<td>47/24</td>
<td>45/24</td>
<td>43/24</td>
</tr>
</tbody>
</table>

The times used during the formal simulation were selected as a result of analyzing controller responses to working traffic using test series 1 look-ahead times and series 2 look-ahead times.

6.0 Current Deployment Plans for ATPA

The results of the simulation analysis produced the ATPA alert graphic look-ahead timing that will be used during the national deployment to terminal facilities. ATPA software will be deployed in future CARTS and STARS software installations at the more busy terminal facilities. Current deployment plans are tied to established CARTS and STARS software drops.

6.1 Future Deployment

Work is underway developing ATPA Phase 2 (ATPA 2). ATPA 2 will monitor the diagonal separation between aircraft that are located on parallel dependent finals in accordance with FAA JO 7110.65 Paragraph 5-9-6. The ATPA 1 and ATPA 2 functions can be used individually or simultaneously.

ATPA Phase 2 will provide visual notifications when a potential loss of separation (LOS) is projected to occur. The manner in which the visual notifications will appear is still under development. One possible design includes displaying colored line graphics that start at the trailing track and end at the lead aircraft. Another possible design displays the diagonal minimum separation and the diagonal distance mileage at 100% bright in lieu of the line graphics. All designs will have the option to display the required diagonal minimum separation and the actual diagonal distance between aircraft on parallel dependent runways.

Using ATPA 2 to mitigate the effects of wake turbulence on subsequent arrivals on parallel runways is also proposed. At the time of this writing, the ATPA Workgroup is working with the Wake Turbulence Mitigate Arrival (WTMA) program representatives to evaluate the proposed CHI.

Using the ATPA look-ahead graphics could be operationally suitable at airports that experience departure delays. The look-ahead times in ATPA times can be adapted to accommodate in-trail spacing providing added situational
awareness to terminal controllers responsible for maintain departure separation. ATPA 2 will also include evaluation of separation while considering the proposed future changes to individual weight categories.

7.0 Conclusion
Four CPC volunteers participated in the HITL dry run simulations. The group included two CPCs from Northern California TRACON (NCT), one Tower/TRACON Operations Manager from Cincinnati (CVG), and one Traffic Management Coordinator from Atlanta TRACON (A80). Three CPCs participated in the formal HITL simulation. None of the CPCs had previously participated in the dry run HITL simulation or other ATPA HITL activities. The participants represented three Level 10 ATC facilities: Chicago TRACON (C90), Charlotte Tower/TRACON (CLT), and Cincinnati Tower/TRACON (CVG), and the workforce (National Air Traffic Controllers Association). All of the participants were CPCs who actively control air traffic on a daily basis at their facilities.

The participants were surveyed as to their individual preferences for the timing of the ATPA look-ahead. The following table represents the results of the controller responses.

Table 3 CPC Responses on ATPA Look-Ahead

<table>
<thead>
<tr>
<th>Question</th>
<th>Look-Ahead Timing (45/24)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATPA cones brought my attention to a potential compression error</td>
<td>4.2</td>
</tr>
<tr>
<td>ATPA allowed me to better manage the arrival flow</td>
<td>3.9</td>
</tr>
<tr>
<td>Did you think you worked harder with ATPA on?</td>
<td>2.1</td>
</tr>
<tr>
<td>The timing of the ATPA Yellow cone provided adequate notification to respond to a potential compression error</td>
<td>3.1</td>
</tr>
<tr>
<td>The timing of the ATPA Orange cone provided me adequate notification to respond to a potential compression error</td>
<td>3.2</td>
</tr>
<tr>
<td>The display of the ATPA cone was distracting</td>
<td>1.7</td>
</tr>
</tbody>
</table>

I used the mileage indicator in the 3rd line of the FDB more than the ATPA cone

Key:
1 strongly disagree, 2 disagree, 3 neutral, 4 agree, 5 strongly agree

The overall response from the participants was favorable. The CPCs all agreed that the ATPA look-head timing (45/24) would provide adequate notification to potential compression on the final approach course without increasing workloads. The CPCs did not find the ATPA alert graphics distracting. They especially liked the mileage displayed in the 3rd line of the FDB and found this information very helpful by increasing their situational awareness.

Some of the CPC comments indicated that the workforce would be better able to manage arrival traffic and maintain separation without having large gaps between aircraft. There were also comments about using ATPA cones to manage departure flows. An overall positive response was related to the 3rd line mileage displayed in the FDB. Having this real-time mileage (updating every second) data on in-trail aircraft established on the FAC added to the situational awareness of the final controller.

8.0 Acknowledgements
The planning, development and conduct of the ATPA simulations were sponsored by the FAA ATPA Project Team and was a collaborative effort by the ATPA Work Group, the WJHTC TGF and CARTS lab personnel, the Communications Laboratory Maintenance Team, controller participants and SMEs, and human factors specialists from Human Solutions, Inc.
Aviation Security Issues in NextGen

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Abstract: The Joint Planning and Development Office (JPDO) has developed a concept of operations (ConOps) for the Next Generation Air Transportation System (NextGen). ConOps has defined Layered Adaptive Security Services in NextGen. It is a risk-informed security system that depends on multiple technologies, policies, or procedures adaptively scaled and arranged to defeat various threats such as cyber attack and Chemical, Biological, Radiological, Nuclear, and Explosive (CBRNE) threats. Layered Security Services is one of the core modules in NextGen. Without security protection, all NextGen functions such as navigation, surveillance, communication, air traffic management, automation, IT services, and others will be vulnerable to various attacks and cannot work robustly. In this paper, we first introduce Aviation Security Concepts for the NextGen including (1) Integrated Risk Management, (2) Secure People, (3) Secure Airports, (4) Secure Checked Baggage, (5) Secure Cargo/Mail, (6) Secure Airspace, and (7) Secure Aircraft. Then we will present results of research and development related to NextGen security. Because the complex risks and security challenges come from different sources, such as insider and outsider attacks, IT and non-IT threats, we propose an innovative integrated physical and logical security technique to combine IT security, physical security, access control and monitoring of automation systems. Threats identified for any one of these systems may appear innocent, but when correlated against each other present a more sinister result. Integrating risk management across these domains enables a world-class response to all threats against the NextGen.

Key words: NextGen, aviation security, NAS, ATM, layered adaptive security

I. Introduction

There will be a significant increase in civil air traffic demand in the National Airspace System (NAS), ranging from a factor of two to three by 2025. However, the present Air Traffic Control (ATC) system is already strained and cannot scale to meet this demand. The Federal Aviation Administration (FAA) is cooperating with Department of Defense (DOD), National Aeronautics and Space Administration (NASA), Departments of Transportation (DOT), Department of Commerce (DOC), and Homeland Security (DHS) to develop NextGen [1-2]. NextGen will greatly increase the NAS capacity, efficiency, safety, flexibility, and environmental protection.

Enabler function groups of NextGen include: Trajectory and Performance-Based Operations, Surveillance Services, Layered Adaptive Security, Positioning Navigation and Timing, Environmental Management, Weather Information Service, Safety Management, Net—Centric Infrastructure, and Airport Operations [3]. Aviation security is a fundamental module of NextGen, which is also a hot topic in the aviation research community [4-29]. NextGen Concept of Operations (ConOps) Security Annex [3] defines a 7-layer adaptive security framework. Risk assessment and management have been developed in the
literature to manage risk [4-9, 21-27]. NextGen network security was discussed in [10-15]. Navigation security was discussed in [17-20, 28]. Secure surveillance was discussed in [11, 12, 16, 29]. Because NextGen is a very complex system, meeting the security requirements is very challenging. Traditionally the security module of each subsystem is designed independently. There is a trend to embed security into the design of multiple subsystems. For example, AlertEnterprise integrates IT and physical security across diverse systems, applications, databases and geographically distributed assets [21]. Threats identified for any one of these systems may appear innocent, but when correlated against each other present a more sinister result. Integrating risk management across these domains enables a world-class response to all threats against the NextGen. We have developed a physical layer enhanced information fusion approach to detect ADS-B spoofing reports by integrating surveillance, navigation and communication components [29]. It is necessary to develop an integrated aviation security architecture to meet the security requirement of NextGen. A cross-layer, cross-component, multi-plane structure will be proposed in this paper, which integrates multiple protocol layer, multiple components (such as communication, navigation, surveillance, Air Traffic management (ATM)), and multiple planes (data plane and control plane). The advantages of this Integrated Aviation Security (IAS) are enhancement of security performance of each subsystems and excellent ability of detection, prevention, and response of insider attacks, which is a tough task for individual subsystem.

This paper is organized as follows. Section II summarizes net-centric enabled, layered, adaptive security services of NextGen. Section III presents our solution concept to NextGen aviation security. Finally, we give the conclusion of this paper.

II. Net-Centric Enabled, Layered, Adaptive Security Services of NextGen

NextGen ConOps Security Annex defines a net-centric risk-informed security system that applies multiple technologies, policies, and procedures adaptively scaled and arranged to defeat various threats against the air transportation system. We first summarize various threats, then introduce the NextGen 7-Layer Framework for Aviation Security Services. Finally, we present cyber security in the Net-Centric Infrastructure (NEI) Services and Shared Situational Awareness (SSA) Services.

2.1 Threats in the NAS

Threat originators such as terrorist groups, hostile nation-states, and criminals may generate various attacks against the NextGen system. Typical threats are: (1) Cyber attack; (2) CBRNE: chemical, biological, radiological, nuclear, explosive; (3) MANPADS: man portable air defense systems; (4) aircraft used as a weapon.

2.2 Net-Centric, Layered, Adaptive Security Services

The net-centric, layered, adaptive security framework of NextGen is shown in Fig. 1. The 7 layers are: (1) Secure Aircraft; (2) Secure Airspace; (3) Secure Cargo/Mail; (4) Secure Checked Baggage; (5) Secure People; (6) Secure Airport; and (7) Integrated Risk Management (IRM). Subsystems are connected by net-centric operations.

IRM:
The primary objectives of the risk management process are evaluating the effects of defined threats, assessing the vulnerability, and evaluating and prioritizing assets and functions for a civil aviation system. The IRM process divides risk management into 5 phases:
- Threat analysis
- Vulnerability analysis and consequences assessment
- Countermeasures definition
- Countermeasures prioritization and acquisition strategy analysis
- Procedural and technology insertion with subsequent evaluation

**Secure Airports**
ConOps includes technological and procedural measures to protect against the dynamically evolving threat to the airports. Secure Airports includes:
- IRM – Secure Airports
  - Airport facilities: commercial (passenger/cargo) airport, remote terminal security screening, general aviation airports, commercial spaceports
  - Airside: Security identification display area, terminal perimeter, terminal airspace security
  - Landside: airport public and commercial roadways and parking lots, terminal departure curb, terminal entry portal, airline ticketing kiosk/counter, security checkpoint, sterile concourse, international arrival/customs, airport concessions, food, and beverage security
- Airport security control center
- Emergency Response and Recovery

**Secure People:**
Aviation security risks are mitigated by identifying and preventing people who are a potential threat from gaining access to the air transport system through prescreening and credentialing, screening, and intervention. Secure People includes:
- IRM – Secure People
  - Authentication and Credentialing: credentialing, passenger authentication, aviation industry worker authentication
  - Checkpoint Person Screening
  - Checkpoint Baggage Screening
Secure Checked Baggage:
The objective of secure checked baggage is to prevent checked baggage from endangering aircraft, aviation facilities, or people and from being used as a threat vector for the transport of CBRNE. Secure Checked Baggage includes:
- IRM – Secure Checked Baggage
- Checked Baggage Screening
- Checked Baggage Screening Installation
- Nonintegrated and Standard Baggage Screening
- Deployable Baggage Screening Operations

Secure Cargo and Mail:
Its objective is to prevent cargo and mail from endangering aircraft, aviation facilities, or people and from being used as a threat vector. Secure Cargo/Mail includes:
- IRM – Secure Cargo/Mail
- Shipper Credentialing
- Screening and Inspection
- Alarm Resolution
- Surface Transportation Security of Screened Cargo
- Hardened Doors and Baggage on All Cargo Aircraft
- Security Training of All Cargo Flight Crew and Staff
- Storage Security
- Cargo Tracking and Integrity

Secure Airspace
Its main purpose is to prevent external attacks on aircraft and other airborne vehicles in the NAS or to use an aircraft as a weapon to attack assets and events on the ground. Secure Airspace includes:
- IRM - Secure Airspace
- Verified Airspace Access
- Security Restricted Airspaces
- Airspace Violation Detection, Alerting, and Monitoring
- Integrated Management of Airspace Security
- Counter projectiles

Secure Aircraft:
Its purpose is to increase the safety and security of the NextGen aircraft and prevent various attacks such as hijacking, explosive destruction, CBRN, etc. Secure Aircraft includes:
- IRM- Secure Aircraft
- Authorized Control of the Aircraft
- Aircraft Monitoring and Surveillance
- Aircraft Hardening and Defensive Systems
- Safety Integration
2.3 Cyber Security of NextGen

Cyber security is defined in Net-Centric Operations (NCO) and Shared Situational Awareness (SSA) Services of NextGen ConOps. NCO is the realization of a globally interconnected network environment, including infrastructure, systems, processes, and people that enables an enhanced information sharing approach to aviation transportation. The key to NCO is to establish interoperable enterprise networks which are a combination of physical infrastructure and Infrastructure Services. SSA tries to share NextGen Information, Air Domain Awareness, and NextGen Weather Information through SSA information services. Cyber security is the fundamental to the success of NCO and SSA.

III. Our Solutions to NextGen Aviation Security

NextGen is an extremely complex system. How to keep the security of such a complex system is very challenging. In this section, we will develop an integrated aviation security framework for NextGen.

Fig. 2. Integrated Aviation Security (IAS).

3.1 Integrated Aviation Security (IAS) for NextGen

There are many silos of information in NextGen. NextGen 7-layered framework specifies aviation security service information about IRM, people, airports, checked baggage, cargo/mail, airspace, and aircraft. Other typical components include communication, navigation, surveillance, ATM, identity management, physical security, internal control policy, non-cryptographic access control, certification, etc (Fig. 2). In this section we propose an Integrated Aviation Security (IAS) concept to bridge the gap across various subsystems. Unique capabilities:

- Bridge all domains: cross-layer, cross-component, multi-plane (data plane and control plane)
Enhance the security of one component by fusing information from other components in NextGen
Detect, identify and eliminate risks before they manifest
True prevention of threats from thefts, sabotage and terrorism
Take security and incident management to the next level with built-in programmed remediation

3.2 AlertEnterprise Architecture for NextGen IRM

IRM is one of the seven layers in the NextGen layered, adaptive, security framework. We propose to apply the AlertEnterprise architecture [21] to implement NextGen IRM. AlertEnterprise delivers a unifying business layer that leverages existing IT systems, physical access systems and applications allowing organizations to manage security, risk and compliance for business applications, eliminate insider threat, and protect critical infrastructure. Powerful visualization enhances security and reduces access risk from complex processes like onboarding and offboarding while ensuring continuous compliance. Additionally AlertEnterprise delivers an incident management capability that includes live surveillance video and geo-spatial mapping for complete situational awareness so that seemingly innocent events when correlated across IT, physical access control and industrial control systems can be uncovered and dealt with.

The initial AlertEnterprise architecture (Fig. 3) has three layers: (1) Layer-1: IT systems, Physical Control Systems, and Industrial Control Systems. For NextGen aviation security applications, the detailed subsystems in Layer-1 include communication, navigation, surveillance, ATM, identification, NextGen 7-layer framework, etc; (2) Layer-2: Risk Analysis and Correlation; (3) Layer-3: AlertEnterprise Applications. A few commercial products have been developed to implement the whole AlertEnterprise architecture. AlertAccess is an intelligent user access management and provisioning application. Unlike other access control applications that operate in silos, AlertAccess can analyze risk across multiple domains that include IT Systems, Physical Access Control Systems and Industrial Control Systems to detect and monitor risks prior to enabling user access. AlertAccess correlates information from Human Resources (HR) applications, Identity Databases (HSPD-12, TWIC data, e-Verify and even no-fly lists etc.) to detect terminated or flagged employees and to validate required certifications in real-time just prior to the provisioning process. AlertAccess delivers key capabilities to conduct risk analysis prior to provisioning for multiple systems to address theft, fraud, sabotage and insider threat. AlertInsight makes analyzing and remediating risks easy and understandable. Assets (both IT and non-IT) can be identified. Drilling down on assets to view risk items can show the details of processes, transactions, roles with permissions and the users all in one screen. AlertInsight delivers powerful actionable response to risks. AlertAction combines risk analysis, continuous monitoring, geo-spatial scene analysis, fraud detection and real-time remedial action scripts to deliver the perfect visual command and control application for real-time situational awareness and incident management. Programmed guidance can be delivered on-screen to incident responders, eliminating the need to consult three-ring binders while incidents are unfolding.
3.3. Integrated Communication, Navigation, and Surveillance Cyber Security (ICNSC)

As a concept design example of IAS, we propose Integrated Communication, Navigation, and Surveillance Cyber security (ICNSC) for NextGen to prevent cyber attacks. NextGen is based on a satellite navigation system – GPS. Net-Centric Operations (NCO) in NextGen utilizes heterogeneous wire/wireless networks to store, transport, and retrieve air transportation related information between providers and consumers on a reliable, scalable, flexible, and secure enterprise network. IEEE 802.16 (WiMAX) is selected for airport wireless communication. Aeronautical telecommunication network (ATN) is used for air-to-air and air-to-ground communication. Satellite communication is often used to cover ocean and mountain areas. Multi-sensor fusion (radar, multilateration, ADS-B, and other sensors such as onboard EO/IR) provides secure surveillance.

Traditionally the security modules of communication, navigation, and surveillance are independent. In recent years there has been a trend to integrate various security modules. Here we propose the ICNSC structure as shown in Fig. 4. It is cross-layered, cross-componented, and multi-planed. For the communication module, the network security is based on (1) cross-layer design: Layer-7 Application (Digital signature, certificate), Layer-4 Transportation Layer (TLS), Layer-3 Network (IPSec), Layer-2 Data Link (AES, X.509), Layer-1 Physical Layer (direct sequence spread spectrum, frequency hopping, time hopping, cognitive radio, PHY encryption, secure SDR), PHY based IP spoofing detection, PHY based MAC spoofing detection, etc; (2) cross-component design: information from other components such as surveillance, navigation is applied to enhance the security performance of communication security. For example, positioning and sensor of the RF environments has been applied successfully not
only to detect spoofing attacks against the wireless network, but also to cancel interference/jamming by beamforming; (3) multi-plane design: Data plane based security uses encryption and non-cryptographic techniques (firewall, intrusion detection). The control plane based security is based on AlertEnterprise Integrated IRM. AlertEnterprise IRM can detect insider attackers by analyzing integratedly diverse systems, applications, databases, and geographically distributed assets.

Although GPS is very important to NextGen, it is vulnerable to various attacks such as jamming and spoofing. Popular countermeasures against GPS spoofing include: (1) Monitor the absolute GPS signal strength; (2) Monitor the relative GPS signal strength; (3) Monitor the strength of each received satellite signal; (4) Monitor satellite identification codes and the number of satellite signals received; (5) Check the time interval; (6) Perform a check using the information from other modules such as inertial navigation, radar tracking; (7) Apply communication security techniques such as public key infrastructure to meet the security requirement of WAAS/LAAS GPS. AlertEnterprise IRM –Navigation detects, prevents, and responds to various threats in the control plane. We have developed spatial-temporal adaptive processing and multi-sensor fusion techniques to cancel jamming against GPS receivers.

As for secure surveillance, multilateration is a new surveillance sensor based on measuring the arrival time of transmitted ADS-B RF signals on the ground. We have developed a physical layer enhanced information fusion technique to detect ADS-B spoofing reports (sponsored by US Air Force SBIR project) [29]. The ADS-B spoofing detector relies on communication signals and target tracking estimations. AlertEnterprise IRM-Surveillance is applied to detect, prevent, and respond to various attacks on the surveillance subsystem on the control plane.

![Diagram of Integrated Communication, Navigation, and Surveillance Security (ICNSS)](image)

**Fig. 4.** Integrated Communication, Navigation, and Surveillance Security (ICNSS).

**IV. Conclusion**

In this paper, we first introduce the Layered Adaptive Security Services in NextGen. Then an initial IAS architecture has been developed. IAS uses a multi-layered, cross-component, multi-planed (data plane and control plane) structure. NextGen 7 layered framework includes Secure Aircraft, Secure Airspace, Secure
Cargo, Secure Checked Baggage, Secure People, Secure Airport, and Integrated Risk Management. Multiple components in NextGen such as communication, navigation, surveillance, and Air Traffic Management, etc. are processed integratively through information fusion to enhance the security performance of each module. For example, the security of the Communication Components is aided by information from the GPS receiver and surveillance. Communication spoofing detection can be easily implemented by the navigation and tracking information. IAS also has a multi-plane structure including data plane encryption/firewall and control plane security (AlertEnterprise IRM). Our IAS has much higher security performance than solo systems, and in particular insider threats identified for any one of these systems may appear innocent, but when correlated against each other present a more sinister result. Our IAS can detect both external and insider attacks effectively.

References

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FAA TELECOMMUNICATIONS INFRASTRUCTURE (FTI) ARCHITECTURE  
PROVISIONING PROCESSES DESIGNED FOR NEXTGEN SUPPORT  

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ABSTRACT  
The FAA’s NextGen initiatives rely heavily on an underlying Telecommunications Infrastructure that provides assured, reliable service delivery. The existing NAS paradigm of diversity and availability become increasingly important as the NextGen Implementation Plan becomes reality. The FTI network architecture and deployment /maintenance /operations processes are optimized to not only meet current High Availability Service delivery needs, but to also fully support the FAA’s NextGen roadmap. This paper reviews the current FTI Service delivery architecture for legacy Carrier and dedicated Optical Network Backbone elements, illustrating its robustness and ability to provide diverse service routing. Optical Network Backbone availability models are reviewed and strategies for route provisioning are provided for DTS and IP traffic. An overview of the FTI Service design, and operations and maintenance processes is provided, highlighting those elements dedicated to ensuring NAS service delivery. Finally, a discussion is provided on how the existing FTI architectural framework, along with several key architectural enhancements currently underway, will fully support NextGen initiatives.  

KEY WORDS  
NextGen, FTI, High Availability, Diversity.  

1. INTRODUCTION  
This paper reviews the current FTI architecture including the recently incorporated private Optical Network Backbone, showing its inherent robustness and ability to meet the availability and diversity needs of the ongoing and planned NextGen initiatives.  

2. FTI SERVICE DELIVERY ARCHITECTURE  

The FAA’s Federal Telecommunications Infrastructure (FTI) is the primary means for telecommunications services and it forms the basic infrastructure for the Next Generation Air Transportation System, or NextGen. It replaces FAA’s legacy networks to provide consolidated telecom services for the 5,000 facilities and 30,000 circuits in the National Airspace System with reduced costs and improved bandwidth and security. The FTI network supports National Airspace System (NAS) operations by providing the connectivity required by systems such as Traffic Flow Management System (TFMS), En Route Automation Modernization (ERAM), and Integrated Terminal Weather System (ITWS). In addition, applications like e-mail, Internet, payroll, and other administrative services are on the FTI Mission Support Network.  

FTI service delivery is established through a combination of traditional Carrier-provided terrestrial segments, private Metropolitan area SONET rings, and private Dense Wavelength Division Multiplexed (DWDM) optical fiber for long-haul transport. FAA facilities in remote and geographically challenging locations utilize Satellite and Microwave links.  

Services and facilities within the NAS comprise varying levels of priority with respect to Air Traffic Control. The highest priority facilities are implemented with last mile access to diverse Serving Wire Center (SWC) Central Offices (COs); in some instances the alternate SWC CO is implemented as a Satellite or Microwave connection. The highest value FAA service assets within these dual entrance facilities are specified as either “High Availability” (HA) or “Avoided” and make full use of the facility’s physical access diversity. High Availability services are presented to the FAA as a single Service Delivery Point (SDP) handoff and FTI performs the Automatic Protection Switching (APS), while Avoided services are presented to the SDP as two separate services.  

NON-Export Control Information
and the FAA equipment performs the APS function. Figure 1 illustrates the underlying concept of diverse service delivery at a dual entrance facility, namely the absence of any single-point failure.

**Figure 1. Diverse Service Delivery for Terrestrial Carrier-Provided Access and Transport**

All Carrier orders into dual entrance facilities are placed specifying the required circuit diversity, and once delivered, the Carrier’s Design Layout Records (DLRs) are reviewed to ensure access was provided consistent with the order requirements. The diverse access into each dual entrance facility is mapped and archived for Operations and Maintenance (O&M) purposes (Figure 2).

**Figure 2. Sample Diverse Facility Access Map**

Arrangements have been made with all FTI-utilized Carriers to flag services ordered with diversity in their provisioning systems to ensure Carrier-initiated re-grooms do not compromise the required diversity. To further ensure this diversity is maintained, updated DLRs are provided by the Carriers every quarter and they are reviewed by an independent team of Harris Network Engineers. Results of these ongoing audits are provided to the FAA and FTI O&M organization to ensure accurate situational awareness. All identified diversity compromises are corrected and validated.

For FAA facilities not requiring diverse access delivery through dual entrance facilities, High Availability and Avoided services are implemented as “electrically avoided”. Electrical avoidance recognizes the lack of an alternate SWC by providing separate access circuits for segregation of High Availability and Avoided services within the shared facility conduit and default SWC. These electrically avoided access circuits are routed to diverse Interexchange Carrier (IXC) Points of Presence (PoPs) at the first possible location in the Carrier’s network.

In the summer of 2009, the FTI program completed the installation of its Optical Network Backbone (ONB) and associated Metropolitan SONET Rings (Metro-rings). With this infrastructure in place, the FTI program not only achieved the advantage of significantly increased bandwidth, but for the first time added private access and transport elements to its inventory of telecommunications options. Figure 3 illustrates the extent of the FTI ONB.

**Figure 3. FTI ONB**

The FTI ONB is made up of 42 independent Nodes and 58 interconnecting DWDM optical waves. Each of the nodes is paired, corresponding to locations geographically located near the FAA Air Route Traffic
Control Centers (ARTCCs) and other FAA specialty sites (e.g., the Mike Monroney Aeronautical Center in Oklahoma City), providing diverse access points. This Nodal pair-to-facility access is implemented either as a diverse pair of private Metro-rings (Figure 4) or a diverse set of OC3 connections. The Metro-rings in Figure 4 show one Primary and one Alternate, each connected to their respective FAA facility access point and to their respective connection to the FTI ONB through the appropriate Node, located in a contracted Carrier Collocation Facility.

**Figure 4. Dual Private Metro Ring Access to the FTI ONB**

These Metro-rings are implemented as Unidirectional Path Switched Ring (UPSR) SONET rings, offering working and protect paths on each. As private Metro-rings, they exclusively carry NAS traffic, eliminating any potential Carrier re-groom event that could potentially compromise the established diversity.

### 3. FTI ONB AVAILABILITY MODEL

The availability of the FTI ONB was analyzed, independently reviewed and has now been monitored for over 1 year with a demonstrated availability greater than 0.999999. Availability is modeled by combining the predicted failure rate of the long-haul fiber due to cuts, fires or other impacts with the predicted failure rate of the amplifier and repeater equipment along the expanse of the long-haul runs.

As shown in Figure 3, all NAS airspaces have a minimum of 3 physically diverse optical waves originating from the Nodal pairs, connected to adjacent FTI ONB Nodes. Figure 5 provides a simplified representation of the Nodal-to-Wave association. Availability for any given fiber span is represented as,

$$ A_F = \frac{\text{Hours per Year} \times (1 - \text{MTTR})}{\text{Hours per Year}} $$

[eq 1]

Where $A_F$ = Availability of any given Fiber Span. Failure rates for FTI long-haul Fiber Optic spans have demonstrated fewer failure events than Telcordia expectations for the number of failures per mile and Mean Time to Repair (MTTR). The availability for three parallel fiber spans is represented as,

$$ A_{FP} = 1 - [(1 - A_{FP}) \times (1 - A_{FP}) \times (1 - A_{FP})] $$

[eq 2]

Where

- $A_{FP} = \text{Availability of 3 parallel Fiber Spans}$
- $A_{FP} = \text{Availability of any given Fiber Span}$

Failure rates of optical equipment and active Line Repeater electronics are predicted using typical availability analysis. Each long haul fiber optic span utilizes long-haul line amplifiers at an average separation of 100 kilometres (Figure 6). Availability of any given optical equipment and/or line amplifier is expressed as,

$$ A_{Ai} = \left(1 - \frac{\text{MTTR}}{\text{MTBF}}\right) \times 100 $$

[eq 3]

Where

- $A_{Ai} = \text{Availability of any given Line Amp}$
- $\text{MTTR} = \text{Mean Time to Repair for any given Line Amp}$
- $\text{MTBF} = \text{Mean Time Between Failures pr Line Amp}$

Availability for $n$ concatenated line amplifiers is expressed as,

$$ A_{AT} = (A_{Ai})^n $$

[eq 4]

Where

- $A_{Ai}$ is as defined in [eq 3]
- $n = \text{number of serial Line Amps}$
Table 1 summarizes the worst case Nodal availabilities within the FTI ONB, and multiplying these values provides a worst case network availability of 0.99999916.

<table>
<thead>
<tr>
<th>Node</th>
<th>Connections</th>
<th>Distance (Miles)</th>
<th>Predicted Nodal Availability</th>
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</thead>
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<td>0.9999994166</td>
</tr>
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<td></td>
<td>699</td>
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<tr>
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<td></td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>ZME</td>
<td></td>
<td>643</td>
<td></td>
</tr>
</tbody>
</table>

Figure 5. Every Airspace has a Minimum of Three Optical Wave Connections to the ONB

Figure 6. Each Wave Connection is supported by Line Amplifiers Installed at 100 kilometre Increments

4. ROUTE PROVISIONING STRATEGIES

Once access is established using the FTI ONB Nodes, transport assignments are made across the backbone waves. In the legacy Carrier network, a High Availability service was transported using two separate and independent Carriers (reference Figure 1), each offering the equivalent of a Working and Protect path. When making assignments across the FTI ONB, this Transport model is replicated by assigning four paths between the two connecting nodal pairs. Figure 7 illustrated a TDM routing example for High Availability services between the Chicago and Minneapolis FAA Facilities. Note the indicated Primary working/protect and Alternate working/protect paths offering 3 physically diverse routes. This transport routing has been established for every combination of FAA facilities connected to the FTI ONB, establishing a priority diversity to all ONB routing, and just like the private Metro-rings, there is no possibility of Carrier-initiated re-grooming that could potentially compromise this diversity.

For Internet Protocol (IP) traffic on the FTI ONB, transport between Nodes utilizes Border Gateway Protocol (BGP) routing to implement the most efficient path selections. There are literally thousands of potential route paths for the transport of IP data, and analysis of these paths show dozens of valid routes meeting the NAS performance requirements.
NextGen objectives such as dynamic resectorization and facility consolidation will require a modern transport technology based on Internet Protocol (IP) where a flexible routing architecture can be used to provide the needed capabilities. The FTI optical backbone has implemented and cutover the NAS operational IP services to a private Multi-Protocol Label Switched (MPLS) architecture capable meeting these objectives. Only authorized NAS users and systems are allowed access to the FTI MPLS network.

The operational IP network is logically designed over the same physically diverse architecture described above and fully capable of providing high availability performance. Dijkstra’s algorithm for modern dynamic routing protocols provides thousands of alternate routes over the FTI physically diverse infrastructure and improves the overall survivability of the network. This flexibility is the essence of network-centric operations required and planned for NextGen.

The FTI private MPLS architecture partitions the network into logical routing domains where each airspace uses its own routing domain. Each one of the 21 airspaces is connected to the MPLS backbone through a pair of gateways for improved survivability. The airspace routing domains take care of routing within the airspace and pass off data destined for other airspaces through the dual gateway connections to the MPLS backbone. The backbone uses different protocols optimized for Wide Area Networks (WAN) and route the data to the destination airspace through its redundant gateways where the destination airspace routing domain takes over. Figure 8 depicts the FTI Operational IP routing architecture.

The partitioned routing architecture provides optimized routing with sub-second convergence in the MPLS core network. Operations and maintenance is simplified and improved as routing issues are contained within their respective domains minimizing impact to other NAS airspaces. Troubleshooting requires less time as the logical partitioning enables network operators to quickly isolate and resolve issues within the proper routing domain.

Because FTI is a performance based service contract, the FTI program office is able to continuously improve the network with enhancements. Improvements may come in the form of technology and process innovation or optimized performance. The FAA is ensured that FTI is providing the best possible service and technology for the NAS today and in the future for NextGen through its performance based incentives.

6. CONCLUSION

The FTI network architecture and operations processes have been optimized to meet the FAA’s current High Availability service delivery needs, and as shown in this paper, are fully ready to support the FAA’s NextGen roadmap. Diversity is a key element in all FTI service delivery, and with the
introduction of the FTI ONB, an architecture has been established that meets the diversity and routing flexibility demands of NextGen.
Integrating the Tower for NextGen

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ABSTRACT

Today’s tower air traffic control (ATC) automation adequately supports the existing services provided by ATC controllers with a series of separate, standalone systems that provide specific functions. Each system includes its own processing, displays and data entry devices, requiring controllers to move from display to display in order to make observations and data entries when providing ATC tower services. To support NextGen, this existing automation environment needs to be replaced with an integrated tower processing and display platform that provides the required ATC functionality and that is part of a common baseline, supported across all FAA towers. Also, as the airport environment evolves, the FAA needs a modern, integrated system in its towers to support the capacity, efficiency and environmental improvements envisioned in the NextGen timeframe. Other NextGen systems, such as En Route Automation Modernization (ERAM) and System Wide Information Management (SWIM), are being deployed, with which the new tower system must interface in order to support the tower’s evolution towards NextGen capabilities (e.g., replacement of paper flight strips with electronic flight data).

KEY WORDS

NextGen, TFDM, DST, Automation Processor, CDM, STBO

Introduction

The FAA has defined the need, in their National Airspace System (NAS) Enterprise Architecture [1], for a Tower Flight Data Manager (TFDM) that supports operational improvements related to several NextGen solution sets, such as High Density Airports, Trajectory Based Operations, Flexible Terminals and Airports, and Collaborative Air Traffic Management. TFDM will be the implementing platform for many surface-related improvements; it will converge capabilities from multiple, existing tower systems and provide a suite of Decision Support Tools (DSTs) to improve tower operations.

Today’s Tower Environment

The tower environment today consists of multiple separate systems and many of the towers are space constrained, making it difficult to add equipment to provide new capabilities. The inefficiencies resulting from so many different older systems can be remedied with the use of modern technologies to replace legacy systems as well as provide a platform capable of hosting NextGen capabilities.

As an example, today’s tower controllers still use flight data in the form of paper flight strips which contain a limited amount of information. The controllers manually annotate the strips and physically pass them from one tower position to another. Modern flight data communication and display capabilities will improve the flow and quality of shared flight information.

Also, today’s tower lacks integrated DSTs, meaning controllers do not have access to automated tools to assist in surface flow optimization. At many sites, current pre-departure coordination operations require controllers to manually issue complex clearance information via time-consuming and inefficient voice communications, increasing error rates and limiting throughput. Larger sites use a
limited, existing data link. NextGen Data Comm will significantly improve these tower operations.

Today’s tower environment lacks real-time information sharing between the airport stakeholders. The tower is not provided information from the flight operators, such as predicted pushback times, which would allow for more efficient departure scheduling. The flight operators are not aware of current traffic management initiatives in effect and therefore are unable to optimally adjust their flight plans. The existing tower systems do not use modern interfaces to exchange information, such as the SWIM infrastructure. Using modern interfaces would promote a collaborative decision making environment and enhance surface situational awareness to the benefit of all users.

Surface surveillance, while helpful, only provides situational awareness of events as they happen. What is missing is the predictability of events prior to surveillance; the precursor to the queuing, the determinant of the order or sequence, and the control mechanisms to satisfy both the operator imperatives within the ramp and gates as well as the air traffic need to assemble effectively the bundle of services required for each flight trajectory at the point of entry. Collaborative NextGen FAA/Operator DSTs will provide this predictability. [2]

NextGen’s Airport Operation Benefits

TFDM will integrate capabilities from existing tower systems and provide a suite of DSTs to improve airport operations in sync with RTCA NextGen Task Force 5 recommendations for the surface. From the FAA FY11 budget [3], the benefits realized are aligned with NextGen goals. These benefits include:

- Increased airport capacity. Controller decision support and monitoring aids will lead to more optimized runway assignments, departure sequencing, departure routing, and runway configuration selection for given arrival demand and weather constraints in an effort to reduce delays.

- Reduced environmental impacts. More efficient arrival and departure profiles, reduced departure runway queues and reduced engine-on time during taxi-in, taxi-out operations will reduce airport emissions and customer fuel burn.

- Reduced weather impacts. Airport capacity and efficiency will be maintained during a wider range of weather conditions (convection, snow, reduced visibility) with fewer unexpected drops in capacity.

- More accurate take-off time predictions. Improved NAS demand predictions and the appropriate implementation of necessary traffic management initiatives.

- Improved airport configuration planning. Better informed and more timely decisions on runway configuration changes considering weather constraints and predicted arrival and departure demand.

- Taxi conformance safety monitoring. Avoid blunders resulting in runway incursions during taxi and alert ATC and pilot to developing unsafe conditions.

Tower of the (Near) Future

The NextGen solution sets contain operational improvements which are aimed at meeting the overall NextGen goals of increased safety, increased operations and efficiency, and reduced environmental impact. The future TFDM system is a key ingredient to satisfying many of those operational improvements.

TFDM will make the airport surface safer. By using ADS-B and surface surveillance information, controllers and pilots will have better situational awareness in all types of weather conditions. TFDM will manage the movement of aircraft on the surface and perform taxi conformance monitoring which reduces the risk of runway incursions.

Airport operations and efficiency will be improved by providing controller decision support tools and monitoring aids that will lead to more optimized runway assignments, departure sequencing, departure routing, and runway configuration selection.

Environmental impact will be reduced by better scheduling of departures so that delays are absorbed at the gate and taxi times are reduced. Aircraft will burn less fuel resulting in less engine emissions and less operating cost for the airlines.

Real time information sharing will promote an environment of collaborative decision making. TFDM will provide flight specific traffic management
initiatives to flight operators and ramp towers enabling them to better plan their operations. The flight operators will provide TFDM with updated flight information such as predicted pushback times and gate assignments, making it possible to plan departure sequences and to modify those departure sequences, if needed. Interfaces with local airport authorities will provide coordinated runway configuration changes and airport maintenance activities. TFDM will provide surface information to other NAS systems enabling common surface situational awareness.

The legacy Tower Data Link System (TDLS) that currently provides the Pre-Departure clearance, Digital-Automatic Terminal Information System, and emulated Flight Data Input/Output (FDIO) services will be replaced. TFDM will be able to automatically send clearances, taxi instructions, weather information, and non-conformance alerts directly to the cockpit. Tower controllers will communicate instructions and clearances to pilots via Data Comm, eliminating errors and misunderstandings.

TFDM will make use of SWIM services to exchange information with airport stakeholders and other NAS systems. For example, the ERAM Flight Information Service will be used by TFDM to access flight data elements not currently available through the FDIO interface and to update surface elements in the flight data.

These TFDM SWIM services will provide surface information to other NAS systems. For example, TFDM will absorb the three services currently defined by the Terminal Data Distribution System (TDDS). These services are 1) the Tower Departure Event Service, which publishes departure events (clearance, start taxi, takeoff) for all flights from an airport; 2) the Surface Movement Event Service, which publishes surface movement events (spot out, spot in, off, on) and the position of all aircraft and vehicles for an airport; and 3) the Airport Data Service, which publishes runway visual range data for an airport.

TFDM serves as the basis for a Staffed NextGen Tower (SNT) solution, which provides full ATM services to flights in and out of one or more airports from a ground level facility. The SNT would need to provide service in all weather and reduced visibility conditions.

Multiple legacy system displays will be converged into a set of integrated displays, reducing the number of overall displays in the tower. TFDM’s display suite will consist of a set of configurable displays that provide surveillance data, flight data, weather information, airport status data, and DST information. Controllers will be able to access information on a single display with a consistent Human Machine Interface (HMI) rather than needing access to several displays, each with their own HMI. This makes controllers more efficient and reduces the number of displays required in some of the space constrained towers.

The TFDM architecture must be open and extensible so that new DSTs and functions can be easily integrated into the system. TFDM should provide a standard data access mechanism so the tools and functions reference the data in a consistent manner no matter where the data originates. The architecture must be scalable from a single local tower to multiple local and remote towers. The number of processors and displays must be adaptable to meet the requirements of the different tower environments.

In order to realize the NextGen operational improvements, TFDM will include a set of integrated DSTs that provide the surface tactical flow capabilities [3]:

Airport Configuration Management – provides automation assistance for setting up, assessing and changing the airport configuration.

Runway Assignment – automation tool assists controllers in planning runway assignments based on a variety of operational factors.

Departure Routing – tool provides assessments of departure routes particularly relative to weather and traffic flow constraints.

Taxi Routing – tool considers many factors such as aircraft current position and user preferences, to enable pre-planned and coordinated airport surface trajectories and controller monitoring of taxi conformance.

Scheduling and Sequencing – concept considers all resource constraints and optimizes the use of surface resources to meet demand, in collaboration with NAS stakeholders.

Prototyping
Since 2006, Lockheed Martin has taken a leadership role in the Integrated Airport NextGen Test Bed at the Daytona Beach International Airport. Working with several industry partners including Embry-Riddle Aeronautical University, ENSCO, Mosaic ATM, and Frequentis, Lockheed Martin has led integration of the Surface Decision Support System (SDSS), Common Automated Radar Terminal System (CARTS), ERAM, Electronic Flight Strips (EFS), Traffic Management Advisor (TMA), and other systems using a prototype SWIM Service Oriented Architecture. This project has successfully demonstrated a number of advanced capabilities in improving airport surface capacity and efficiency, trajectory based operations, arrival and departure management, and predictive weather capabilities. This work has made use of a prototype NextGen Flight Data Object (FDO) to improve situational awareness for all users, providing data such as the 4D surface trajectory that is not available in the tower today.

In 2009, Lockheed Martin partnered with Frequentis to install an EFS system at Vance Air Force Base. The solution automates production, distribution, and administrative management of flight plan information and other ATC/flight data for inter- and intra-facility coordination within and between the various airfield operations facilities (Radar Approach Control, Control Tower and Base Operations) and other command and control/emergency response nodes like the hospital and fire/crash/rescue dispatch. The system went live after passing a Site Acceptance Test and obtaining the required FAA certifications for use in the NAS, and is now being used by military air traffic controllers at Vance AFB in a one-year operational evaluation.

Today, in support of the FAA’s vision of an evolved tower environment, Lockheed Martin is developing a prototype Integrated Tower System (ITS) for NextGen.

ITS provides an integrated display of air and surface surveillance data, electronic flight data, safety data, weather data, airport status data, and Decision Support Tool (DST) information. The ITS open system architecture is scalable and extensible, allowing for the addition of new NextGen capabilities through new DSTs. ITS includes interfaces for legacy systems as well as new modern SWIM interfaces, such as the ERAM Flight Information Service. ITS is highly configurable, allowing it to be tailored to meet the needs of the various tower environments. The ITS software is portable, making it possible to run on a variety of platforms including the existing Common ARTS Automation Processor.

Information sharing among the airport stakeholders is one of the key concepts of Surface Trajectory-Based Operations (STBO), and the ITS prototype is providing a vehicle for the development of new CDM capabilities with the airlines, ramp towers, and airport authority. New collaborative departure scheduling and sequencing capabilities are being developed in conjunction with the Lockheed Martin Ramp Logic system. The Ramp Logic system [2] provides airlines with ramp management tools to optimize the turnaround for a flight and is undergoing operational trials by US Airways at the Charlotte airport.

Lockheed Martin was recently awarded the Time-Based Flow Management (TBFM) contract. The ITS prototype will enable future concept development as to how TFDM and TBFM will collaborate to help support the NextGen initiatives and to provide operational improvements such as Integrated Arrival/Departure Airspace Management.

MIT Lincoln Laboratory is currently overseeing the development of the FAA’s TFDM prototype [4]. The ITS prototype concepts and development are in sync with the FAA’s efforts. Both prototypes contain a set of adaptable and customized displays which can be consolidated among several tower user positions and both prototypes are developing an Arrival/Departure Management Tool (A/DMT) to meet the objectives of the surface tactical flow capabilities.

Conclusion

Today’s tower environment is workload inefficient and expensive to maintain. While there has been progress in recent years, it has been in bits and pieces with no integrated NAS-wide strategy. Proven technology exists today to address these shortcomings. The FAA’s NextGen Enterprise Architecture Roadmap identifies an evolution to integrate and modernize the tower with their Tower Flight Data Manager program. Lockheed Martin is leveraging its proven success in the terminal, en route, and oceanic domains to prototype an Integrated Tower System that will be open, efficient, affordable, scalable, and most importantly capable of providing the operational improvements required to achieve NextGen capacity goals.


**References**


OCAT – The Oceanic Conflict Advisory Trial

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ABSTRACT

The Oceanic Conflict Advisory Trial (OCAT) is a year-long FAA operational trial designed to help airlines to fly more of their preferred oceanic routings while additionally reducing air traffic controller and pilot workloads. By using a standalone service that allows dispatchers to “pre-probe” potential routing changes against the current oceanic environment, OCAT partner airlines will have the ability to determine if their desired changes would be potentially acceptable to Air Traffic Control (ATC) without requiring either controller or pilot involvement. In the future, the OCAT oceanic pre-probing service could be extended to Air Navigation Service Providers (ANSPs) and other authorized users.

This paper describes the operational concepts and technology behind the OCAT system and its planned operational trial.

KEY WORDS
OCAT, ATOP, Ocean21, conflict, probe, trial, ocean, web service, AIRE, ASPIRE

Introduction

"As aviation services continue to grow, we can anticipate an increase in the industry’s carbon emissions. This is happening against a background of (1) emission reductions from some sources other than aviation, and (2) the rising values we place on environmental quality. If not successfully addressed, environmental issues may significantly constrain air transportation growth in the 21st century.¹

The Asia and Pacific Initiative to Reduce Emissions (ASPIRE) and Atlantic Interoperability Initiative to Reduce Emissions (AIRE) were instituted to help address the aviation community’s concern over the expected increase in carbon emissions. Procedures such as the Dynamic Airborne Reroute Procedure (DARP) have also be introduced to allow airborne flights to modify their routings to achieve fuel savings by taking advantage of favorable winds and avoiding adverse weather. The on-going ASPIRE and AIRE trials have demonstrated that allowing airspace users to fly their optimal preferred oceanic routes does result in fuel savings as well as reduced engine emissions⁴,⁵.

¹ Asia and South Pacific Initiative to Reduce Emissions (ASPIRE)

⁴ E. Kelly, “Aspire makes progress on improving air traffic management efficiency”

⁵ J. McDaniel, "Atlantic Interoperability Initiative to Reduce Emissions (AIRE) Briefing to the ICNS”
http://i-cns.org/media/2009/05/presentations/Session_L1_FAA_Incentives_or_Mandates-Military/01-McDaniel.pdf
However, since airlines typically only have insight into their own operations and not into the complete current oceanic situation, requests to alter a flight’s current route can frequently result in oceanic conflicts being predicted by the FAA’s Ocean21 automation system. Such requests are subsequently denied by Air Traffic Control. While these denials serve to safely keep the required separation, they reduce potential flight efficiencies. Additionally, the need to constantly repeat such requests leads to increased frustration for both controllers and pilots alike. Once a request is denied due to a conflict, the airspace users frequently do not request alternatives due to workload and time constraints, so the potential reduction in fuel and emissions are not realized.

The Oceanic Conflict Advisory Trial (OCAT) is a year-long operational trial designed to address this problem while additionally reducing the controller and pilot workload associated with such requests. Using operational data and algorithms from the FAA’s current Ocean21 automation system, the OCAT system allows partner airlines and other authorized users to pre-probe potential routing changes.

OCAT makes the Ocean21 conflict probe capabilities available via a standard web service. During the operational trial, the OCAT system will assist users in determining which of their potential routing options are currently conflict-free and therefore more likely to be acceptable to oceanic air traffic control. Using the automated OCAT web service allows users to attempt various routing options to determine the candidate that best meets their business priorities without affecting either the pilot or air traffic control. Once determined, the pre-probed, conflict-free OCAT requests may then be submitted through the normal communication paths to the oceanic controller. Since the request had been pre-probed in OCAT, it should now have a much higher probability of being conflict-free in Ocean21 thus allowing the requesting aircraft to fly its preferred route without further modification or controller interaction.

### Oceanic Environment

By their very nature, oceanic flights are long-duration flights crossing vast airspaces with minimal surveillance monitoring. To ensure the safe separation of oceanic traffic, the FAA’s Advanced Technologies and Oceanic Procedures (ATOP) program positioned Lockheed Martin’s Ocean21 systems in New York, Oakland, and Anchorage. The Ocean21 systems use Adacel’s Aurora software to model the cleared and proposed trajectories of all known oceanic aircraft using the most up-to-date weather information. Whenever a change to an aircraft’s current routing is proposed, its proposed trajectory is modeled and “probed” against the other aircraft and oceanic airspace reservations to determine whether the change would result in any predicted violations of separation. This capability is referred to as the ATOP conflict probe. Complex probing algorithms are utilized to enforce the dozens of site-specific and equipment-specific oceanic separation rules.

Because oceanic flights are typically planned many hours in advance, the weather currently affecting a flight could drastically differ from that originally forecasted. Due to the long durations of these flights, airlines have found that making even minor modifications to an aircraft’s route to take advantage of the current weather conditions or to avoid blocking traffic can result in significant fuel and time savings thereby reducing emissions and operating costs.

However, Airline Operations Centers (AOCs) typically only have insight into their own flights and not into the other flights sharing the airspace, the separation standards applicable to those flights, the current airspace reservations, and the latest Ocean21 weather. Therefore, while AOCs may know the routes they would prefer to fly, they have no way of knowing if those new routings will be acceptable to oceanic Air Traffic Control (ATC).

In the current environment, when an AOC or aircraft would like to fly a more advantageous route, the pilot requests the new clearance from the oceanic controller using either Controller-Pilot Data Link Communications (CPDLC) or a high-frequency (HF) radio request. The controller uses the Ocean21 system to probe the proposed request against the current oceanic traffic and if conflict-free, clears the aircraft on the requested route. However, if the request results in a predicted conflict with other aircraft or airspace reservations, the controller would then need to either take additional actions to determine a different, conflict free alternative (resulting in additional controller workload and a potentially undesirable route from the airline’s point-of-view) or the controller simply denies the request. A denial would result in the flight remaining on the current, undesired routing or force the entire request process to start again. Multiple request
cycles result in additional ATC, pilot, and AOC workload and lead to frustration and increased delays and communication costs.

**Overview of OCAT**

OCAT allows airlines to pre-probe their proposed changes against the current oceanic situation using a "shadow system" utilizing the latest Ocean21 conflict probe algorithms. OCAT is planned as a year-long trial scheduled to start in the third-quarter of 2011 in which partner airlines are provided with a secure connection to the OCAT web service. Airline dispatchers can use the OCAT web service to pre-probe any number of proposed flight alternatives. Dispatchers can determine those routings that will be the most beneficial from the airline's point-of-view while also being likely to be conflict-free when probed by the oceanic controller. Since all OCAT probe requests are performed against an automated web service, this “pre-probing” process requires no controller or pilot involvement. The automated responses from the OCAT system are nearly instantaneous and delivered over the internet so no unnecessary delays or satellite or HF radio operator communication charges are incurred. Once an acceptable routing has been determined, the AOC can then relay the pre-probed request to the pilot who simply follows the normal oceanic procedure to make the request of ATC. However, since this request had been pre-probed in OCAT, the chances of it now being denied by ATC have been greatly reduced. While a change in the oceanic environment could cause the OCAT and ATOP probe results to differ, these differences should be minimal due to the relatively infrequent nature of oceanic changes. The aircraft will then be permitted to fly on its requested conflict-free route. In addition, controller and pilot workload is reduced since the repeated request-denial-request cycles are no longer necessary.

Figure 1 illustrates the differences between the current re-route procedure and the proposed OCAT procedure.
Today versus OCAT

Background – ATOP and Ocean21

One of the key elements in the OCAT concept is consistency. If the OCAT system was not capable of producing the same probe results as the ATOP Ocean21 system, its usefulness would be diminished. Additionally, it was crucial that the OCAT system not impact the operational ATOP ATC systems. Therefore, some background on the ATOP Ocean21 system design is necessary to explain how the OCAT system will meet the overall goals of being consistent with ATOP without adversely affecting it.

The ATOP Ocean21 system is designed as a dual-channel system. Each channel is fully-redundant and independent. Only one channel is ever active at a given time. The second channel may be isolated from the active channel for maintenance purposes or it may be linked using a redundant set of processors referred to as Synchronization (SYNC) servers. The active channel continuously streams updated information to the SYNCs. When the second, isolated channel is brought to backup mode, the SYNC transfers the data from the active channel to the backup channel using a process referred to as “reconstitution”. Once the reconstitution of the backup channel has completed, the SYNCs simply forward all active channel updates to the backup channel as they occur in real-time. This process ensures that the active and backup channels of each operational ATOP system process the exact same information. The data transfer is always unidirectional — from the active channel to the backup channel. No data is ever sent from the backup channel to the active channel.

Each channel performs its processing of the ATOP data independently. This means that the backup
channel is fully capable of performing trajectory modeling, conflict probing, and all other ATOP-related processing.

**OCAT to ATOP Interface**

As depicted in Figure 2, the OCAT concept takes advantage of the dual-channel nature of the ATOP system by essentially converting it into a three-channel system. With only minor modifications to the operational SYNC servers, a second instance of the synchronization database and processing has been added to support a third channel. This third channel behaves identically to the backup channel – it can be brought up independently of either of the other channels; it reconstitutes from the SYNC server; and subsequently receive all active channel updates from the SYNC just like a second back up channel. This “third-channel” does not affect the operation of either the active or backup channels on the operational ATOP system and the additional processing load on the SYNC servers is negligible. Once this “third-channel” synchronization capability is in place, we now have the ability to “shadow” the operational ATOP data in a fully independent system without affecting the operational system.

By instantiating the current ATOP processing in a single processor, a simple “third-channel” can be replicated. This processor, referred to as the OCAT Flight Data Server (OFDS), is essentially an “ATOP-in-a-box” running the ATOP processes and current adaptation required to ensure consistent processing results with the operational ATOP system. It is important to note that the OFDS processes include the same executables and adaptation files used by the operational ATOP system.
It is envisioned that each operational ATOP site participating in the trial will have an OFDS temporarily installed to support the operational trial. This means that new ATOP software/adaptation releases will simply be deployed to the OFDS just like any other ATOP processor thereby ensuring consistency of OCAT results.

By combining the identical flight data/conflict processing and adaptation with the active channel synchronization of all current flight plan, airspace, and weather data, we have the ability to create an independent OCAT system. OCAT is fully capable of producing ATOP probe results with minimal software development and most importantly, without impacting the operational ATOP systems.

**OCAT to AOC Interface**

Since OCAT is intended to be a year-long operational trial with multiple airline partners, the security and access concerns associated with connecting to an operational FAA site prevent the users from making direct connections with the OFDS. To allow multiple partners to easily access and freely use the OCAT system during the operational trial period, a secure, common web service is provided for all potential users. The OCAT web service not only provides a common interface for all users, but also acts as a single interface to each of the OFDS processors at the operational sites further isolating them from the external users. This provides the ability to have greater control over individual users’ capabilities and the ability to govern the overall usage of the OCAT system.

Since airlines capabilities vary greatly, an early decision was made to keep the OCAT-to-user interface at a web service Application Programming Interface (API) level and not include an actual User Interface (UI) as part of the OCAT system. This allows each participating airline to decide how much, or how little, they would like to invest in modifying their systems to interface with OCAT. Some airlines could choose to fully integrate the OCAT web service API into their existing flight planning systems while other airlines could choose to simply implement standalone, text-based UIs.

The web service will be housed in a single OCAT Message Processing Server (OMPS) processor at the Florida NextGen Test Bed (FNTB) in Daytona Beach and is designed using industry standard WSDL and SOAP protocols. In the future, the OCAT web service’s XML-based messaging can be easily converted to be compatible with the FAA’s System Wide Information Management (SWIM) infrastructure.

**OCAT User Capabilities**

The OCAT web service is designed to ensure that users only have access to the data for which they have been authorized. For example, Airline X can probe their own flights in OCAT against all oceanic traffic; however, requests to probe Airline Y’s flights will be rejected as “unauthorized”. This access is controlled through the use of a configured “ACID mask” for each participating airline. ACID masks are specified by the airlines, but configured by the FAA. An example of the ACID mask for Airline X could be: XAL*; QXY*; DEF*. Only probe requests for flights with call signs matching the one of the requestor’s configured ACID masks will be accepted. Similarly, the web service uses the ACID masks to filter the probe results. All conflict results are still provided back to the user; however, the call signs for the conflicting aircraft are only provided to the API if they too match the requestor’s ACID mask. Non-matching call signs will be replaced with generic names (e.g., AIRCRAFT-1).

Providing airlines with call sign information concerning conflicts with their other owned flights allows the airlines to make more educated conflict resolution decisions. The AOC may determine that it could be more beneficial to change the conflicting flight than the one originally probed.

OCAT users are not necessarily limited to airlines. The OCAT web service can be made available to all authorized users including the FAA en route facilities and international Air Navigation Service Providers (ANSPs). The FAA is the controlling entity for the authorized list of all OCAT users and their permissions.

To prevent potential misuse of the OCAT system during the operational trial, the web service also has the ability to limit on a per-user basis, the number of requests that a particular user group can make in a 24-hour period. The amount of time the airspace associated with a given request is reserved within the OCAT system is also configurable on a per user group basis. Additionally, each OMPS and OFDS request and response will be recorded for monitoring and accountability.

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It is currently envisioned that one or more ATOP sites will participate in the OCAT trial.
**ATOP and OCAT Probing**

In ATOP, all probing of potential routing changes are performed by the responsible controller using the Ocean21 user interface capabilities. When a downlink request is received from a pilot, the controller is presented with an associated set of potential uplink clearance options. The controller selects one option and probes the uplink. The ATOP system creates a proposed trajectory (referred to a 2nd profile) associated with the probed uplink (or set of uplinks). To ensure separation is maintained, the flight’s cleared trajectory (its 1st profile) is not affected by this request; however the airspace associated with the flight’s 2nd profile is additionally reserved in the ATOP system. The 2nd profile airspace is reserved until the probed clearance is either sent to and accepted by the pilot or cancelled. If the clearance is accepted, the 2nd profile becomes the new cleared profile and the airspace associated with the original 1st profile is released. If the probe is cancelled or rejected by the pilot, the 2nd profile is simply deleted and its associated airspace released.

Since the OCAT system uses ATOP processing for profile management and conflict probing, the OCAT probe processing is nearly identical to ATOP. The difference being that the OCAT system does not involve either the pilot or the controller. For OCAT, the OCAT Message Processing (OMP) software acts as both the pilot and the controller. Since the OCAT web service is envisioned to be used by various personnel most of which are unfamiliar with air traffic clearances, the OCAT system is designed to provide a simple, clearance-independent interface to its conflict probe capability. For example: If a user wanted to probe a requested climb to flight level 350 beginning at the point named “FIXA” with the climb completing by 1230Z, the user need simply send the OCAT web service a probe request containing the following information:

```xml
<Type> Climb
<AltI> 350
<AtTimePos> FIXA
<ByTimePos> 1230
```

When OMP receives the airline probe request from the web service, it is validated and a configuration-driven table is used to determine and automatically initiate the OCAT probing of the request’s associated uplink(s). For the above example, OMP would automatically convert the received web service request into the following uplink clearance elements for probing by the OFDS:

```
2252-AT FIXA CLIMB TO AND MAINTAIN F350
UM26-CLIMB TO REACH F350 BY 1230
```

In addition, since OCAT is a standalone service with no controller or pilot to release its probed airspace, OMP starts a timer to automatically cancel the probe at a configured time. Maintaining the probed airspace in OCAT for a set amount of time allows airlines to receive accurate results when probing the changes for multiple flights against each other and against those proposed by other OCAT users.

OCAT probes the request using the synchronized ATOP data, the current adaptation, and the Ocean21 conflict algorithms, and provides the result back to the requestor via the web service API. The web service probe results contain a formatted version of the same conflict information normally provided to a controller in the ATOP system.

To help ensure that airline’s requests to the air traffic controllers are equivalent to the pre-probed conflict-free OCAT requests, OMP additionally provides the corresponding recommended downlink requests. These recommended downlinks are provided in both a textual form for dispatchers to verbally relay to their pilots and a parsed form that could potentially be automatically uplinked to the aircraft by the AOC. Since the OCAT system acts as both the pilot and the controller, OCAT additionally includes a controller capability to probe restricted requests to help resolve conflicts. The ability to request a restricted clearance is not normally available to pilots.

For example, a normal pilot request of "Request Climb to 350" could result in a conflict, while a controller-entered restriction of "Climb to reach 350 by 2252" for the same flight would not. Since the intent is use OCAT to avoid potential conflicts, OCAT supports the probing and requesting of restricted clearances; however, CPDLC messaging does not support restriction requests in the defined aircraft downlink messages. To address this shortfall, OMP includes free text "restrictions" as part of the recommended downlinks returned to OCAT web service. For the above example, the OMP recommended downlinks provided to web service user would be:

```
DM9-REQUEST CLIMB TO F350
DM67-RESTRICTION – F350 BY 2252
```

If the aircraft includes the OCAT-recommended free text restriction in their ATC downlink request, the restriction will be displayed to the ATOP controller through the normal Ocean21 User Interface. This
will assist the controller in determining the best uplink option to probe. By observing this OCAT free text as part of the normal downlink procedure, the controller will know that the restricted request was pre-probed and conflict-free in OCAT, and therefore probing the same restricted clearance in ATOP will most likely result in the request being conflict free in Ocean21 as well.

**OCAT Profile Requests**

In addition to the probing of potential routing changes, the OCAT system can also be used to provide current ATOP profile information to authorized users. Since the OCAT system profiles are built from the synchronized ATOP data, the profiles in the OCAT system reflect the latest ATOP flight profile information as updated by controller clearances and weather updates. Authorized users may use the OCAT web service to request the current profiles for flights matching their ACID mask to see the latest cleared oceanic route including the estimated times at each point. The updated 2nd profile information associated with a request is also included as part of the probe response, so airlines can compare various profile requests against a flight’s current profile and against each other to determine the most beneficial routing based on the current conditions.

**OCAT User Interface**

Although as described above, no “official” user interface is being provided as part of the OCAT system, to help better the envision OCAT capabilities, an example of a potential representative OCAT user interface is provided in Figure 3.

This representative UI includes potential displays for both the unrestricted conflict response (left side) and the restricted conflict-free response (right side) cases. It also illustrates all the capabilities provided by the OCAT Web Service API.

**OCAT Operational Trial**

The OCAT system is designed to support a limited number of potential airline partners for a year-long trial planned in both the Atlantic and Pacific oceans beginning in the third quarter of 2011. During this trial, airline partners will use a secure VPN internet connection to the OCAT web service in the FNTB. The web service will use the FAA Telecommunications Infrastructure (FTI) to securely connect to the OFDS processors located at the operational ATOP site(s) participating in the OCAT trial.

OCAT partner airlines will make use of the OCAT web service to request flight profiles and pre-probe desired routing changes during the trial period. Specific metrics such as the number of OCAT requests, the number of OCAT-supported ATC requests, and the overall success rate will be tracked to determine the usage, accuracy, and benefits of the OCAT system during this trial period and to identify any desired changes in the OCAT capability. Interim and final benefits analyses will be performed to assess the usefulness and savings associated with the trial. The recommendation for implementation of the OCAT system into permanent operations is expected to follow shortly after the successful completion of the trial.
Future OCAT capabilities

Although the OCAT system is being put into place to support a specific operational trial associated with the probing of routing changes, the concepts introduced by OCAT offers numerous future possibilities. With the OCAT system in place, authorized users will have the ability to access live ATOP data without affecting the operational ATOP system.

For the purposes of the OCAT trial, the OFDS will run the same software release as the operational system; however in the future, the OFDS could be used to unobtrusively test new ATOP capabilities using synchronized live data. New oceanic concepts such as SWIM, flight data objects, and 4D trajectories, and new capabilities such as pre-flight planning and pre-defined conflict resolution strategies could all be validated using live oceanic data without ever affecting ATOP operations. In addition, new decision support tools such as the Collaborative Flight Planning and Monitoring (CFPM) tool could be integrated with OCAT to provide gate-to-gate services. By providing a secure, externally accessible, independent system that is capable of running operational ATOP software and synchronizing with live oceanic data, the OCAT system provides unlimited investigative possibilities for potential future concepts and capabilities.

Conclusion

In the oceanic environment, making even the slightest changes in aircraft’s route of flight to take advantage of the current conditions can result in significant savings in fuel consumption while bettering the environment by way of reduced emissions. However, since airline requests are typically made from only the requesting airline’s perspective with no insight to the other competing traffic in the ocean, it is frequently difficult for air traffic controllers to grant the airline requests for such routings.
In today's economic and environmental climate, airlines are looking for every advantage, so providing an efficient means of making such routing changes is becoming more and more critical. As the number of these requests grows in the future, the number of associated potential conflicts will also increase. This means that the controller and pilot workload involved in resolving those conflicts will likewise increase.

The goal of the Oceanic Conflict Advisory Trial is to address the above issues by providing authorized users with a web-accessible capability to pre-probe potential oceanic routings to see if they will be acceptable to air traffic control beginning in late 2011. The secure OCAT service will allow airline personnel to probe any number of route variations to determine the ATC-acceptable route that best meets their business and/or environmental needs without impacting either their pilots or the oceanic controllers. In addition, the OCAT capability opens vast opportunities to investigate new oceanic ATC concepts and capabilities using live data without impacting oceanic operations.
NextGen Trajectory-Based Integration of Grid-Based Weather Avoidance Fields

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ABSTRACT
In anticipation of NextGen requirements for probing of aircraft to weather conflicts within automation systems such as En Route Automation (ERAM), Time-Based Flow Management (TBFM), Common Automated Radar Terminal System (CARTS), and Advanced Technologies & Oceanic Procedures (ATOP), we have been investigating trajectory based methods to integrate gridded weather avoidance fields such as may be available from the 4-dimensional (4-D) weather data cube/Single Authoritative Source (SAS) across multiple ATC domains. The components of our work include 1) Generation of 4-D prototype weather avoidance fields, 2) Retrieval of net-enabled weather data based on Corridor Integrated Weather System (CIWS) derived products using a System Wide Information Management (SWIM) service, 3) Development of a conflict detection service between a hazardous weather data grid and aircraft trajectories, and 4) Visualization of the interaction of weather products, the resulting weather avoidance field and aircraft trajectories. This paper describes the results of the generation, integration and visualization of 4-D trajectories with grid-based hazardous weather avoidance fields.

KEY WORDS
NextGen, weather avoidance, integration, trajectory based

1. Introduction
In 2007, the REsearch and Development Advisory Committee (REDAC), Report of the Weather-Air Traffic Management (ATM) Integration Working Group [1] provided research recommendations to the FAA for the integration of air traffic management and weather. Among the several recommendations ranging from Near-Term to Far-Term, we took note of three particular recommendations:

- Develop adaptive integrated ATM procedures for tactical trajectories (Mid Term – 2015)
- Replace surrogate weather indicators with true measures of flight hazards Far Term (2015+), and
- Conduct research on gridded and scenario based probabilistic weather data for ATM decision tools (Far Term – 2015+)

According to the REDAC report, “integration is defined as translating traditional weather information into impact measures, such as capacity or flow rates and automatically or semi-automatically incorporating that data into traffic flow advisory information to improve the system capacity and safety in the face of weather hazards.” However, we believe additional work is needed in representing hazardous weather within automation systems and having a common understanding among controllers, traffic managers, pilots, dispatchers, etc. on just what hazardous weather
means before translating it to operational impacts. Thus, our definition of integration for the purposes of our research includes part of the REDAC definition. Before hazardous weather can be translated to ATM system capacity impacts for traffic flow management (TFM) collaborative decision making, it must first be ingested and represented within the automation system. This requires that there eventually be an agreed four dimensional (4-D) representation of various types of hazardous weather that could impact the ATC system. This weather data should be represented in a form consistent with the intended purpose of its use within the automation system. For example, since trajectory-based operations is a cornerstone of collaborative air traffic management (CATM), integrating weather information that can be evaluated collaboratively using trajectory tools allows for improved usability of the weather information for traffic flow decision making.

The work described in this paper documents the results of the generation, integration and visualization of 4-D trajectories with grid-based hazardous weather avoidance fields.

1.1 Previous Work

There are four areas of previous work that are key predecessors that have contributed to our research:

1) The 2005 NASA research on grid-based air traffic control strategic conflict detection [2]
2) The 2008 Convective Weather integration Demonstration at Daytona Beach Nextgen Test Bed (DNTB) [3],
3) The 2009 MIT Lincoln Laboratory and Jack May work on convective weather avoidance fields [4] [5] [6], and
4) The 2008/2009 Lockheed Martin/ENSCO research on integrating weather into ATM [7] [8]

In 2005, Matt Jardin of NASA Ames Research Center published reference [2] on Grid-Based Strategic conflict detection. While the primary objective of the technique described in the paper was improved computational efficiency of pair-wise aircraft conflict evaluation, the technique was adaptable to weather application by using a stochastic model to represent weather and its movement uncertainty in the conflict grid.

In November 2008, a demonstration was held at the NextGen test bed facility located at Daytona Beach International Airport by the Integrated Airport Initiative (IAI). The IAI is a consortium formed by Lockheed Martin and Embry Riddle Aeronautical University (ERAU), to promote NextGen capabilities and accelerate their implementation into the National Airspace System (NAS). In this demonstration, consortium member Ensco, Inc. generated convective weather forecast using their version of the weather research and forecast (WRF) model. The forecast areas of convection were depicted as 3-D polygons on the ERAM D-side display. These polygons moved in space and time according to the forecast. The ERAM Conflict Probe was modified so that the trial plan trajectories would be "weather aware". In this sense, the weather areas were treated as special use airspace and the trial plan trajectories would "light up" indicating there was a conflict with a hazardous weather area. This highlighting of the trajectories was distinct from the mechanism currently used to highlight traffic conflicts. The demonstration met with mixed reviews. Controllers and TMU representatives commented that having a hazardous weather area depicted on the D-side would certainly improve weather situational awareness and improve coordination between the sectors and the TMU. On the other hand, some commented that the sector controllers should not re-route aircraft around weather using the weather hazard area depicted on the D-side display. Instead, the TMU should communicate weather re-route information to the sectors for implementation.

Regarding weather avoidance fields (WAFs), recent research has centered on the definition of convective WAFs. In an April 2009 presentation to the Joint Program Development Office (JPDO) Environmental Information working group, Jack May, former director of the National Weather Service's Aviation Weather Center proposed a working definition of a 3-D Convective Hazard Volume. Rich DeLaura and others at MIT Lincoln Laboratory have defined convective WAFs based on a convective weather avoidance model (CWAM) as a probability of pilot deviation around convective weather [5] [6]. The CWAM is based on statistics from NEXRAD radars and aircraft flight trajectories near convective weather [9].

The paper we published in the ATCA 2009 conference proceedings [8] described the concept of integrating weather into ATC automation decision support tools (DSTs) as one that should be trajectory-based. That is, to define weather as a
grid-based “trajectory-aware” object. The idea being that weather-aware DSTs would be applicable to not only En Route systems such as En Route Automation Modernization (ERAM) system, but to terminal, oceanic and traffic flow as well. The summary of our recommendations for the integration of trajectory based gridded weather were:

1) be applicable to multiple weather phenomena a) convective activity, b) Icing, c) Ceiling and Visibility hazards, d) Turbulence and e) volcanic ash
2) be applicable to multiple ATC domains including TFM, Oceanic, En Route, Terminal, Oceanic and Surface - thus supporting the NextGen Weather ConOps "common weather picture" concept
3) be modulated according to aircraft characteristics and mission
4) be adaptable to products evolving from ATM-Weather integration research by Mitre, MIT Lincoln Labs, NCAR or others (e.g., Consolidated Storm Prediction for Aviation (CoSPA) weather avoidance field) [10]
5) require a minimum training of ATC Controllers – do not want controllers to be meteorologists
6) be implementable, certifiable and deployable by 2015 – the timeframe for NextGen Weather Processor Initial Operating Capability (IOC).

1.2 Purpose for Undertaking Research

With an understanding of the research and prior work as described above, the concept of integrating a grid-based weather avoidance field into our ERAM DST presented some challenges to how we currently provide tactical and strategic conflicts between aircraft, between aircraft to ground and aircraft to airspace. Thus, we needed to evaluate the impacts to our current conflict algorithms if we were to include 4-D gridded WAFs as another object to probe for conflicts. The use of a grid-based approach to conflict evaluation dictates an entirely new method and technique; one in which all WAFs are integrated into a single grid, and the trajectory conflict processing is done against that grid instead of against each individual WAF.

For this year’s research, we built upon the work described in last year’s ATCA Paper by defining a grid-based convective WAF that could be represented within ATC automation that aircraft trajectories would be aware of. Generally, a WAF scores the hazard level associated with current and short term forecast weather (e.g., convective, turbulence, icing, etc. within a 30 minute time window)

2. Approach

The approach to this year’s research comprised five components:
1) Generation of 4-D research-level convective WAF data;
2) Retrieval of net-enabled weather data based on Corridor Integrated Weather System (CIWS) derived products using a System Wide Information Management (SWIM) service;
3) Creation a set of sample flight plans and trajectories using jet, turboprop and piston type aircraft types;
4) Development of a conflict detection service between WAFs and aircraft trajectories; and
5) Visualization of the interaction of source weather products, the resulting weather avoidance field, aircraft trajectories and aircraft-WAF conflicts.

2.1 Four Dimensional (4-D) WAF Data

For the purpose of trajectory integration, we postulate that a WAF be applicable to not only convective weather, but to other forms of potentially hazardous weather such as turbulence, icing, ash, ceiling/visibility. Thus, when considering a convective WAF definition as described in reference [5], how does one assign a probability of deviation to a WAF that can represent varying forms of hazardous weather (e.g., turbulence, icing, hail, etc.) as evaluated by pilots of varying experience flying aircraft of varying capabilities and missions subject to individual or company operating rules?

In order to modify our conflict probes from a trajectory-polyhedron based evaluation to a grid-based trajectory-WAF evaluation, we needed a gridded 4-D WAF product. A 4-D WAF product includes the severity level and is defined horizontally by latitude/longitude, vertically by Echo Tops and temporally by source system (i.e. CIWS) forecast time updates. Since gridded 4-D WAF fields were not available when the project began, ENSCO was consulted to generate prototype 3-D WAF data sets using CWIS Echo Tops (ET) and Vertically Integrated Liquid (VIL) in 1 km x 1 km resolution products [8]. Examples of VIL and ET products are shown in Figures 2a and 2b. These are examples and not the data used in the work described here.
We needed CIWS data for a sample day in the Denver region that had experienced convective activity. The Denver area was the area of choice as our prototype trajectory service included adaptation data similar to that used in the Denver area. To obtain the sample CIWS data, we turned to MIT Lincoln Labs for assistance. While Lincoln Labs researched sample data, we started to build a framework to “digitize” the Denver area airspace of interest as well as to develop a grid-based aircraft-to-WAF conflict service. We chose to limit the conflict look-ahead time to 30 minutes since beyond that time weather forecast uncertainties would need to be modeled. Thus, we required the WAF data set to include a current time data plus six additional forecast data sets where each data set corresponds to a 5 min future forecast. Since the CIWS VIL and ET products were 1 km x 1 km resolution, the resulting WAF data would also be 1 km x 1 km resolution. MIT Lincoln Labs graciously provided a sample data set shown in Figure 3 that included gridded VIL and ET in netCDF4 format. In addition to the VIL and ET data, Lincoln Labs also provided a prototype CoSPA convective WAF data set which we plan to integrate in the next phase of the project. An example of the combined WAF, ET data set is depicted in figure 4. This is a ¼ scale portable network graphics (PNG) image of the entire CIWS region with the hazard value plotted in subset area with an orange border that roughly corresponds to the area covered by the Denver ARTCC airspace. The Figure 4 map projection is different from the one in Figure 3. The red areas have both high VIL and ET and are thus most likely to be avoided by all aircraft. The blue areas have lower VIL and ET values that some aircraft may choose to penetrate. The gray areas have much lower VIL and ET values and thus are less likely to present an obstacle to air traffic.
The process used to create the 3-D WAF was to consider a given grid cell and to extend the grid cell’s WAF value from the surface up to and including the altitude of the grid’s ET value. This array will be stored in netCDF4 format. Figure 5 depicts a Google Earth™ visualization of the 3-D WAF data.

Figure 5. Visualization of 3-D WAF Array (10k x 10k)

2.2 Retrieval of net-enabled weather data based on CIWS SWIM service

This portion of our project was deferred. Instead, we received sample CIWS data files from MIT Lincoln Labs and stored them locally. It would be our preference to retrieve data such as gridded WAF fields using a net centric format such as Weather Information Exchange Model (WXXM) over a NNEW/SWIM service.

2.3 Flight Plan and Trajectory Prediction Service

A simple service was created that either reads in existing flight plans or creates new flight plans and publishes those flight plans to a prototype trajectory prediction service, which converted the flight plans into NAS flight trajectories using a route conversion and trajectory generation algorithm similar to that used in the current en route automation system. See Figure 6.

Figure 6. Flight Plan/Trajectory Service Panel

Examples of a Seattle (SEA) –to- Dallas Ft. Worth (DFW) 4-D trajectory is shown by the blue wall in Figure 7. The trajectory is essentially the converted route with altitude cusps defining trajectory segments. The blue wall extends from the trajectory altitude down to the surface.

Figure 7. 4-D Trajectory

2.4 Aircraft-WAF Conflict Detection (AWCD) Service

The AWCD service and its interaction with other services used on this project is depicted in Figure 8. The AWCD uses the following generalized approach to detection of aircraft trajectory –to- WAF conflicts using a grid-based technique. At this time, the AWCD does not suggest alternate routes around the WAFs.

Figure 8. Aircraft-WAF Conflicts Service Block Diagram

1) Digitize Airspace Containing Aircraft and WAFs

We created a digitized volume of Denver’s Air Route Traffic Control Center (ARTCC) Area of Responsibility
(AOR) plus a 150 nm buffer. However, as a simplification for this project, the digitized volume is rectangular extending in height from MSL to 70,000 ft MSL. The airspace is digitized into an array of grid points where each grid point represents the center of a 1 km ± 1000 ft MSL. The margins described above were for research purposes only and not suggested to be used operationally. The actual buffer margins used operationally by pilots of general aviation or commercial airlines will be in accordance with their own personal weather minimums or company policy respectively. The Aeronautical Information Manual [11] suggests pilots avoid severe thunderstorms by at least 20 nm (i.e., ~ 40 km) laterally and by at least 1000 ft vertically. The margins described above were intended to be used as starting points in defining a pilot/company provided risk preference.

5) Search Algorithm to Determine AC-WAF Conflicts
Once the first order BV test passes, the detailed search algorithm begins using the WAF avoidance margin search domain. Each grid cell that the trajectory passes through is compared against the grid for the appropriate forecast time interval (there are grids at 5 minute intervals that represent time up to 30 minutes into the future). Any grid cell found to be within the WAF avoidance margin of the trajectory cell will cause a conflict to be generated. This algorithm allows different aircraft types or airline preferences to have different avoidance margins; for example, a cargo flight may be allowed to fly closer to a given level WAF than a passenger flight.

2.5 Visualize Aircraft-WAF Conflicts
Google Earth™ - a simple visualization tool, was selected to visualize the WAF, flight plans, trajectories and Aircraft-WAF conflicts. We selected Google Earth™ to avoid significant development and complication of the visualization function. This allowed us to focus on the content of the research that had more significant unknowns and risk. i.e., the WAF itself and the Aircraft-WAF conflict detection service. Google Earth™ has proved itself to be an effective visualization tool for all involved. When the search algorithm finds a WAF cell within the aircraft trajectory WAF buffer region, the trajectory segment for the corresponding trajectory at the time increment under evaluation is highlighted in a color corresponding to the trajectory buffer margin penetration and of the proximate WAF cell value. The output of the conflict service returns the subset of aircraft trajectory segments with a conflict including the value of the conflict (WAF 1-4). See Figure 9.

Figure 9. Aircraft - WAF Conflicts for SEA-DFW flight
3. Conclusion

Our work to date has demonstrated the viability of using a gridded representation of a hazardous weather product that may be published by the 4D weather cube. We have integrated this gridded representation with existing 4D trajectory models to detect conflicts in a way that can be tailored for aircraft types and operator preferences. We currently have used netCDF4 format for the weather products; future work will incorporate net-centric WXXM-based gridded models received from a NNEW/SWIM service when available.

Additionally, we look to the aviation weather science community for continued development of gridded hazardous weather products to be used in trajectory-based integration, that include other weather phenomena, specifically addressing the variability of the weather phenomena hazard, spatial resolution of the gridded representation and the temporal resolution of the product updates.

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Usage of ERAM SWIM for Pre-departure Re-routing

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Introduction

The System Wide Information Management (SWIM) initiative allows users to achieve common situational awareness and, with the addition of other tools that make use of the consistent data made available to them, make optimum use of the airspace. It achieves this by providing the backbone for sharing information throughout the National Airspace System (NAS). SWIM enables new applications and decision support tools to take advantage of current and consistent data on the SWIM infrastructure. Existing and evolving applications and decision support tools lower the FAA’s long-term maintenance costs by transitioning from point-to-point legacy interfaces (with a bevy of interface definitions, typically unique per interface) to use of SWIM for information sharing (by sharing a single, generalized, interface). By building one common interface definition that meets the needs of all users, SWIM reduces FAA expenditures when compared with building many separate, specialized interfaces. Stepping up to using SWIM interfaces is typically not done solely to replace legacy interfaces, but rather to show user benefit by automating some previously manual steps, simplifying some existing process, or adding entirely new functions.

The En Route Automation Modernization (ERAM) system has been accepted by the FAA and is going through the final stages of integration prior to operational use. The SWIM Flight Information Service (FIS) enables the Traffic Flow Management System (TFMS), a national, centralized system, to automate application of pre-departure re-route amendments to flight plans available in ERAM. Applying pre-departure re-route amendments is currently a manual operation performed by a specialist who transfers information from the TFMS into the En Route automation system. The TFMS to ERAM interface is being upgraded incrementally: pre-departure re-route amendments are being automated first, immediately providing benefit to the controllers who manually enter the re-route amendments. Next, active aircraft re-route amendments will be automated, and finally, the method by which TFMS obtains the flight data from the En Route automation system will be upgraded by stepping up to the FIS publish/subscribe interface. Developing this initial ERAM SWIM service has provided opportunities to learn about Progress Software’s FUSE enterprise integration infrastructure and to validate a first operational architecture for ERAM SWIM. FUSE is a product mandated and provided by the FAA for all SWIM Implementing Programs to use.

This paper summarizes lessons learned in building a working, SWIM-based service. This first service constitutes a stepping-stone for expanding the ERAM SWIM Flight Information Service and developing other services (e.g., Track Information Service).
**En Route Automation Modernization Program and Next Generation Air Transportation System (NextGen)**

ERAM replaces the existing en route air traffic control automation system at FAA’s Air Route Traffic Control Centers (ARTCC). ERAM modernizes the en route infrastructure to provide a supportable, open standards-based, system that is the basis for future capabilities and enhancements. ERAM provides existing functionality and new capabilities needed to support NextGen. ERAM has been accepted by FAA at the William J. Hughes Technical Center (WJHTC) and each of the 20 ARTCCs. Initial operational capability has been achieved at some of the ARTCCs, with the remainder in progress. Operational readiness decision is expected, on a per ARTCC basis, starting toward the end of this year and ending in 2011.

**ERAM’s Flight Information Service Initial Usage – Pre-departure Re-route Amendments**

FIS, added as one of the first enhancements to the baseline ERAM system, is one of the first operational SWIM services. FIS provides a mechanism for NAS systems to use ERAM flight data through a SWIM-enabled interface. Authorized users will employ web services to efficiently modify flight data or obtain flight data of interest. The web service ‘update’ operation is used by the service consumer (web services term for “client” - here, an authorized system) to modify ERAM flight data, on a per-flight basis. Each flight is uniquely identified, worldwide.

The FAA has selected pre-departure re-route amendments as the first to utilize SWIM capabilities in the En Route environment. TFMS is the first user of FIS and provides an example of a gradual progression in the transition from legacy interfaces to SWIM provided services. As described in the following sections, first TFMS is using FIS for pre-departure re-routes only. Later, TFMS will add active re-route amendments and finally, TFMS will replace use of a legacy interface for obtaining flight data of interest with subscription to FIS. The initial version of FIS has been developed to enable processing of TFMS-initiated pre-departure re-routes. Pre-departure (i.e., flights which are still on the ground) re-routes are accomplished by TFMS using the FIS update operation to either re-route or protect a portion of the current route.

The pre-departure re-routes provide a more efficient way for Traffic Management Coordinators (TMCs), located in the ARTCCs, to implement re-routes. When there are a large number of re-routes, this approach reduces controller workload by automating data exchange that is largely manual today, and minimizes the likelihood of errors.

Re-routed flights carry an indication visible to en route controllers identifying the flight as part of a traffic management initiative (TMI); this SWIM interface usage benefits both en route and traffic flow personnel.

**“As-Is” Thread**

*Figure 1. “As-Is” Re-route Data Flow, with Legacy HCS shows a notional view of how En Route and TFMS systems interact to apply pre-departure re-routes, prior to ERAM being operational.*
Today, TFMS receives flight information from each of the 20 ARTCCs, via the Host ATM Data Distribution System (HADDS) connected to the Host Computer System (HCS). Even after ERAM is operational, HADDS interface remains the mechanism for TFMS to receive flight information.

Figure 2. "As-Is" Re-route Data Flow, with ERAM

When TFMS decides to re-route a group of flights, typically due to some weather event, TFMS determines the flight plan amendment for each flight and forwards each to the appropriate en route center’s Traffic Management Unit (TMU). “Appropriate” in this context refers to the ARTCC responsible for the specific flight. In the case of pre-departure aircraft, the on-the-ground location of the aircraft unambiguously determines the responsible ARTCC. The TMCs read the re-route...
instructions on the TMU screen, and enter the amendment using an en route controller position, to affect the flight in the en route system one flight at a time. As flight plans are amended in the en route system, the updated flight plan is forwarded to all users, including TFMS, via HADDS. At that point, TFMS can verify that the flight re-route has been implemented. The TMCs may update the remarks with the TMI when a flight is re-routed, but this is not enforced by the automation. Having the TMI indicator visible helps the en route controller understand why an aircraft was re-routed and therefore to avoid reversing the re-route instructions via a subsequent command. Prior to usage of SWIM FIS for pre-departure re-routes, indications of re-routing were manual and not uniformly applied.

“To-Be” Thread

Figure 3. "To Be" Re-route Data Flow, with ERAM’s Initial FIS Capability shows the addition of the Initial FIS capability and the reduction of manual processing it facilitates.

The existing re-route thread requires manually entering (essentially retyping) amendments into the en route system, using the information generated by the TFMS. Avoiding the manual reentry is the first operational benefit yielded by the information sharing in the NAS, utilizing SWIM. Once FIS is deployed in an upcoming ERAM release, and once TFMS steps up to using FIS, the first step towards simplification will have been taken.

TFMS will continue to receive flight information from each of the ARTCCs, via HADDS. Re-routes will be sent as a batch of updates, one update per flight, directly to ERAM’s FIS. The remainder of the flow will be unchanged, for now. As flight plans are amended in the en route system, the updated flight plan is forwarded to all users, including TFMS, still via HADDS. Receipt of the updated flight plan provides verification beyond the web service response message for TFMS to verify that the flight re-route has been implemented.
The pre-departure re-route amendments sent by TFMS directly to FIS will include TMI information for en route controllers’ benefit – no manual reentry by the TMC will be needed, reducing the likelihood of errors and reducing the TMCs’ workload.

To facilitate this thread, and to lay the foundation for sharing en route information NAS-wide, an initial FIS has been developed and is undergoing testing in preparation for release to the field in 2011 / 2012. This initial FIS function demonstrates SWIM capabilities’ use in the NAS and prepares ERAM for success in developing additional SWIM services, which will eventually replace many legacy interfaces.

Once the re-route is accepted by ERAM, the ERAM automation refrains from changing it. The controller sees that the re-route was due to TFMS. There is a re-route indicator on the departure and aircraft lists (as well as in other views). The protected segment portion of the route is shown inside another set of indicators to identify the portion of the route TFMS intends to maintain unchanged. An indication to the controller remains onscreen even if the protected portion of the route is scrolled out of view. The Traffic Management Initiative identifier itself is added in the inter-facility remarks, for display, strip output, and sharing with other users.

The pre-departure re-route capability also enables TFMS cancel re-routes, or to protect a segment of an existing route. If a Traffic Management Initiative is cancelled, TFMS can use FIS to remove the route protection and TMI IDs from affected flights.

**Flight Information Service Implementation**

Though there is only one physical set of SWIM servers, each ARTCC (ERAM) is represented by a separate logical instance of FIS and provides service through separate web service endpoints that securely manage access to that one ARTCC’s flight data. Although TFMS is a consumer (client of) all twenty FIS instances in order to manage traffic flow in the NAS, other clients may only be interested in a single FIS instance corresponding to one ARTCC, or perhaps a few instances. Each client can choose to contact as many FIS instances as applicable to the individual application needs. Providing FIS service on a per-ARTCC basis accommodates both clients with ARTCC-specific interests and clients with national interest.

The physical location of any particular FIS instance does not matter to any client – as long as the response time and availability requirements meet the client’s needs. In the initial deployment of FIS, a single ARTCC has been selected to house the added hardware platforms for ERAM SWIM FIS. All twenty logical FIS instances will reside in this central location, one for each of the ARTCCs. This initial architecture is economical, meets all requirements for the initial FIS, and successfully demonstrates SWIM-enabled ERAM services for the first time.

In this initial implementation of FIS, security is accomplished via router-to-router Virtual Private Network (VPN). With TFMS being the sole client initially, this approach is economical and effective for the initial FIS implementation, providing access control and transport layer encryption. The security implementation is being revisited in the next release as additional clients use FIS, and as additional ERAM SWIM services are provided. Fault tolerance is provided by multiple IP addresses through which the
service consumer can manage its connection in the event of a path failure.

FIS is implemented using commercial products and protocols such as Progress Software’s FUSE enterprise integration infrastructure and web services interactions. FIS is built from modular components which will be re-used for, and extended by, future ERAM SWIM services (e.g., Track Information Service). The FUSE middleware itself includes some open source components from Apache: Mina, Camel, CXF, ActiveMQ and ServiceMix. The FUSE product is mandated and provided by the FAA for all SWIM Implementing Programs to use, with the benefit of enforcing consistency and publish/subscribe interoperability across SWIM Implementing Programs.

The web services paradigm uses Web Service Definition Language (WSDL) to define the system-to-system interface. The initial release of FIS meets the challenge of establishing scalable version identifiers, with clear rules for when and how the versions are updated, how the service users are kept in sync with the updates, and how obsolete versions are deleted. Since the WSDL literally defines the interface, versioning has additional importance over other interface implementations. The messages exchanged are SOAP messages, and transmitted by HTTP over SSL (SSL provided by VPN). Requests and responses are transmitted synchronously.

To illustrate the interface definition more clearly, an example portion of the schema is shown. Example 1 below is a web service request showing how TFMS sends a FIS update to request a TFMS re-route identifying a protected segment. Here, the flight uniquely identified as KL00012458 is updated by TFMS with a new route, including a segment of the route to be protected from change by the automation. The TMI ID value indicates which TMI required the re-route.

**EXAMPLE 1: TFM Re-route with Protected Segment**

```
<soapenv:Envelope xmlns:soapenv="http://schemas.xmlsoap.org/soap/envelope/
  <soapenv:Header />
  <soapenv:Body>
    <urn:flightUpdateRequest>
      <source>TFMS</source>
      <GUFI>KL00012458</GUFI>
      <TMIID>JTMSBSS</TMIID>
      <route>LAX./.COOLI..RENAE..TOMSN</route>
      <protectedSegment>RENAE..TOMSN</protectedSegment>
    </urn:flightUpdateRequest>
  </soapenv:Body>
</soapenv:Envelope>
```

Example 2 shows how TFMS sends a FIS update to cancel a previously applied pre-departure re-route by removing the protected segment. The literal value “Null” is submitted for the TMIID and the protected segment.

**EXAMPLE 2: TFM Re-route Cancellation**

```
<soapenv:Envelope xmlns:soapenv="http://schemas.xmlsoap.org/soap/envelope/
  <soapenv:Header />
  <soapenv:Body>
    <urn:flightUpdateRequest>
      <source>TFMS</source>
      <TMIID>JTMSBSS</TMIID>
      <route>LAX./.COOLI..RENAE..TOMSN</route>
      <protectedSegment>RENAE..TOMSN</protectedSegment>
      <TMIID>JTMSBSS</TMIID>
      <route>LAX./.COOLI..RENAE..TOMSN</route>
      <protectedSegment>RENAE..TOMSN</protectedSegment>
    </urn:flightUpdateRequest>
  </soapenv:Body>
</soapenv:Envelope>
```
Experience, Lessons Learned

ERAM is the largest SWIM Segment 1 Implementing Program and has been, on several occasions, the first to encounter SWIM related process and architectural issues. Our team learned to use Progress Software’s FUSE enterprise integration infrastructure product, and learned to do product configuration in favor of custom code development, whenever possible. The learning curve was, and remains, steep for those new to FUSE. Several problem reports and suggestions for improvement were submitted for Progress Software’s consideration. As problems are corrected, the documentation maintained by Progress Software is updated, thereby benefiting all users of the product; in particular, other SWIM Implementing Programs benefit from the improved product quality and avoid falling into the same pitfalls. For example, FUSE failure modes are still presenting challenges. FUSE documentation on this subject is limited. Our team prototyped and experimented with various cases to observe the results and evaluate them against desired outcomes, to understand the various failure modes; the online user community, the product vendor, and the product source code were used as sources of information, complementing our observations.

The use of FUSE has had a tangible impact on our software development environment. FUSE, along with the other open source products it brings along to satisfy dependencies, roughly doubled the number of Free and Open Source products in our baseline. Reviewing the terms and conditions of licenses for each of the products was a laborious, yet necessary activity.

Working closely with the SWIM Implementing Programs to share experiences and approaches has been helpful; as more programs gear up to both use SWIM services and to provide them, the experience base should be richer, thereby reducing the learning curve for implementing and using services. Working out the end-to-end threads with the programs using services being implemented is invaluable. We have participated in numerous discussions on the details of the data flow, the details of the fields to be exchanged, and the details of the interface definition (encoded in the WSDL). Early integration testing in our labs and at WJHTC found and fixed problems early. Working out the details of interfaces is not unique to SWIM services of course: the ERAM flight data has been extended to accommodate TFMS re-route additions, and will continue to be extended to cover the needs of terminal, tower, surface systems towards the goal of having accurate end-to-end trajectories, of fulfilling the trajectory based operations (TBO) goal of NextGen.
Use of ERAM SWIM for Pre-departure Re-routing constitutes one small step for SWIM, one step closer to achieving NextGen!

**Flight Information Service Next Steps**

The Initial FIS implementation supports the “inbound” thread, i.e., flight data can be created (filed), updated (amended, this is what TFMS uses), and deleted. Only the FIS update will be used operationally by TFMS. The other FIS operations are implemented as proof-of-concept in the initial implementation, and will be used operationally in the future. The next release of FIS, already being engineered, will add support for the “outbound” thread, i.e., flight data will be published to authorized subscribers, thereby moving closer to the eventual replacement of more legacy systems, such as HADDS.

Service consumers will establish a long-running subscription to ERAM Flight data, enabling them to be initialized (if they request it) when the subscription is first established, and allowing them to receive updates as they occur. ERAM publications consist of the changed data elements, rather than complete flight data, whenever any data element of interest changes. The service consumers are provided “selection and filtering” capabilities which enable them to select the set of flights of interest, as well as filter data elements relevant for each of the selected flight. Publications will use JMS messages placed on queues established specifically for each service consumer upon successful processing of their tailored subscription request.

*Figure 4. Planned Re-route Data Flow, with ERAM’s FIS Publication Capability* completes the sequence of data flows shown earlier, replacing HADDS with SWIM-based interface for receiving flight data from ERAM.

The security implementation in the next release of ERAM SWIM services evolves to use of WS-security implementation, including authenticating interactions using x.509 certificates, and altering the approach for transport layer security to use HTTP/SSL and JMS/SSL outside of a VPN. The fault tolerance implementation will be enhanced
by the use of an FAA-provided Domain Name Service (DNS), thereby simplifying service consumers’ implementation. A reference implementation for the SWIM service consumer (client side implementation) will be provided with FIS; it will be available in the same FAA-provided SWIM service registry/repository as the interface documentation, and will change as FIS capabilities expand.

References
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