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Strategic Airborne Trajectory Management

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Acronym List

4D	Four-Dimensional
ABRR	AirBorne ReRoutes
ABTM	AirBorne Trajectory Management
ACARS	Aircraft Communications Addressing and Reporting System
ANSP	Air Navigation Service Provider
AOC	Airline Operations Center
ARTCC	Air Route Traffic Control Center (“Center”)
ATCSCC	Air Traffic Control System Command Center
CDM Net	Collaborative Decision Making Network
CDM	Collaborative Decision Making
CTOP	Collaborative Trajectory Options Program
Data Comm	Digital Data Communications
EFB	Electronic Flight Bag
ERAM	En Route Automation Modernization
FAA	Federal Aviation Administration
FL	Flight Level
FMS	Flight Management System
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NextGen	Next Generation Air Transportation System
RAD	Route Amendment Dialogue
RTA	Required Time of Arrival
RTC	Relative Trajectory Cost
SATM	Strategic Airborne Trajectory Management
STAR	Standard Terminal Arrival Route
SWIM	System-Wide Information Management
TASAR	Traffic Aware Strategic Aircrew Requests
TBFM	Time-Based Flow Management
TBO	Trajectory-Based Operations
TFDM	Terminal Flight Data Management
TFM	Traffic Flow Management
TFMS	Traffic Flow Management System
TMU	Traffic Management Unit
TOS	Trajectory Option Set
TRACON	Terminal Radar Approach Control

Abstract

In current operations, an airline creates cost-optimized flight plans for each of its flights to the extent possible while conforming to constraints imposed in the airspace by the air navigation service provider. In flight, a flight crew executes that flight plan while also responding to tactical changes issued by radar controllers in response to the dynamic airspace environment. Flight crews may try to optimize their plan using more timely winds and weather data. In previous research, the National Aeronautics and Space Administration created a concept known as Traffic Aware Strategic Aircrew Requests that uses flight deck automation to optimize the flight trajectory en route based on winds aloft while filtering out trajectories that conflict with special use airspace, hazardous weather, or nearby traffic. That concept and technology has been adopted commercially in its original form in which the recommended trajectory changes and the re-clearance are made using conventional voice communications between the pilots and radar controllers. Subsequent suggested improvements include using Data Comm for the request and re-clearance process and the addition of the time/speed dimension to the optimization software. In the Strategic Airborne Trajectory Management concept discussed in this report, direct automation-to-automation data communications are proposed between the flight deck and the air navigation service provider to streamline the request and re-clearance process. This concept is expected to greatly expand the use of en route optimized trajectories by the equipped aircraft and significantly reduce the workload associated with this process on both pilots and radar controllers.

1. Introduction

Research into en route flight path optimization for civil transport aircraft conducted by the National Aeronautics and Space Administration (NASA) has created a suite of operational concepts known as Airborne Trajectory Management (ABTM) [1]. ABTM increasingly shifts more of the trajectory determination function to the cockpit. It uses real-time environmental and operational information to find opportunities for flight optimization, and works with the Air Navigation Service Provider (ANSP) to implement those modifications. Each step in the implementation of ABTM builds upon the previous step and provides additional functionality that permits increased benefits for airspace users. The ABTM concepts provide fuel and time savings by using current wind information, weather information, traffic conditions, and ANSP operational constraints to define a modified trajectory in real time and change the active route in the Flight Management System (FMS) to follow the updated trajectory. This is enabled in part by the emergence of the “connected aircraft” [2], an industry-led initiative in which the aircraft is digitally connected to off-board systems, enabling new and substantial flows of information.

The Traffic Aware Strategic Aircrew Requests (TASAR) concept [3–5] is the first implementation step of ABTM. This near-term concept provides the flight crew with cockpit automation that uses a growing number of information sources both within and external to the flight deck to make trajectory optimization recommendations [6–8]. The fuel and time outcomes are shown for each recommendation, and these suggestions can then be used by the flight crew to make trajectory modification requests to the ANSP that may be more readily approved, since the requests consider information that may otherwise preclude ANSP acceptance (e.g., traffic conflicts, convective weather, and special use airspace).

In 2013, NASA solicited interest from U.S. airlines to collaborate in the development of TASAR to accelerate technology transfer to industry and subsequent adoption by airlines. In 2016, both Alaska Airlines and Virgin America committed to working with NASA on the venture. After their subsequent merger, that work continued with Alaska Airlines. An operational evaluation was conducted with three TASAR-equipped aircraft [9, 10]. These operational trials validated the concept and anticipated benefits [11] for TASAR while demonstrating that a growth path existed for future ABTM concepts.

The operational evaluation of TASAR revealed that radar controllers were more likely to approve a trajectory modification when the change covered a relatively near-term portion of the flight rather than the balance of the flight to destination. A likely reason for fewer strategic[1] approvals lies in the difficulty of coordinating the proposed change with each of the affected downstream Air Route Traffic Control Center (ARTCC, or "Center") facilities. Furthermore, agreed-upon constraints for routing between adjacent Centers, as well as between Center and Terminal Radar Approach Control (TRACON) facilities, complicates the coordination process by artificially constraining the route modification to an inefficient human-centric control paradigm. Successive steps in the ABTM Roadmap, described in Section 2, are intended to streamline the request, review, and coordination processes by using communication mechanisms and automation tools in the cockpit and in ANSP facilities.

The most efficient mechanism to make and coordinate trajectory modification requests would be a digital communication link between flight deck automation, Airline Operations Center (AOC) automation, and ANSP automation. Understanding that many technical, procedural, and institutional barriers exist to realizing the full potential of that architecture, the Federal Aviation Administration (FAA) has used Collaborative Decision Making (CDM) for many years to facilitate airline/ANSP coordination. The operator of the flight (nominally the AOC) is able to submit a Trajectory Option Set (TOS) either pre-departure or en route for a given aircraft to traffic managers at Center facilities using the Route Amendment Dialogue (RAD) feature in the Traffic Flow Management System (TFMS) automation platform. The Airborne Reroute (ABRR) capability built into TFMS expands upon this CDM process, and permits a trajectory option chosen for implementation by a traffic manager to be sent directly from TFMS to the active sector radar controller using the En Route Automation Management (ERAM) automation [12, 13].

The ABRR capability and modern digital communication mechanisms provide a pathway to implement a concept known as Strategic Airborne Trajectory Management (SATM). The SATM concept combines previous ABTM steps with a direct connection between ground and air automation systems, including enhanced airborne knowledge of necessary ANSP constraints, which allows a user to update the strategic trajectory in downstream ANSP control sectors. In the SATM concept, strategic trajectory management is a shared function of the flight crew, the AOC, and the ANSP. Each entity uses automation to limit human involvement in the process to a minimum. The SATM concept empowers the flight crew to request trajectory changes proposed by the optimization software and direct the automation to change the active flight plan in both the ANSP automation and the aircraft's FMS throughout the flight.

In Section 2 of this report, ABTM concepts preceding SATM are provided for background context. The SATM concept is defined in Section 3, and a use case scenario is presented in Section 4. A comprehensive description of the equipment, systems, and procedures that could be used to implement SATM, both in the aircraft and in the ANSP facilities, are provided in Sections 5 and 6.

In Section 7, the incremental benefits of trajectory optimization that would accrue to aircraft operators from this step are described, along with the benefit to the government from greatly improved ANSP processes

[1] Within the context of this paper, the term "strategic" means both a longer time into the future of the flight plan and the nature of the air traffic constraints affecting that longer trajectory.

employing new information from the user community. During the preparation of this report, interviews with airline stakeholders, as well as FAA air traffic controller, traffic manager, and automation subject matter experts were held. Synergies and potential roadblocks to implementation were identified during these discussions. Section 8 describes these potential barriers to be overcome. Finally, Section 9 presents conclusions and recommendations for further research and collaboration to implement the SATM concept.

2. Background

Over the last two decades, the use of automation in the management of air transport operations has proceeded along two semi-independent, parallel paths: one within the FAA and one within NASA. The FAA path focuses on the pursuit of TBO by streamlining the use of flight data in traffic flow management. Core ANSP automation platforms, such as ERAM, TFMS, Terminal Flight Data Manager (TFDM), and Time Based Flow Management (TBFM) [14] assist human decision makers that provide traffic control and traffic flow management services. These automation platforms leverage shared data via the System Wide Information Management (SWIM) [15] service. Each automation system was each created independently in separate domains and is not easily integrated with each other (for example, each automation platform has its own trajectory predictor that is inconsistent with the others). However, the FAA is attempting to integrate them so that they might assist controllers and traffic flow managers more efficiently and effectively.

The second path, explored by NASA, involves using the most current wind, weather, and other operational information to optimize an aircraft's trajectory in real time throughout the flight while conforming to constraints in the airspace. These concepts and their enabling automation platforms, primarily developed for use by airspace users, have been implemented in both airborne [3, 16] and ground-based applications [17] in operations at major domestic airlines [9, 10, 18]. Automation systems used by the airlines have sought to optimize flight planning, more effectively orchestrate the various parts of their operations, and continually assess and optimize the flight trajectories of active flights for fuel, time, and cost savings [19].

Very limited connectivity exists between these air-ground and ANSP/ user automation systems. The FAA's Digital Data Communications (Data Comm) program establishes the standards for air-ground communications to be used in exchanges between pilots and controllers, but it is only partially implemented and mainly used for pre-departure clearances in the domestic airspace. When Full En route Services are available at all Centers[2], Data Comm is anticipated to supplant the voice communications (Voice Comm) now used between these entities. CDM provides information exchange between airline dispatchers and FAA traffic flow managers, but it is not a part of any control system. Aircraft Access to SWIM [20] provides traffic, weather, and system operations data to the flight deck, but very few concepts have been proposed to employ these data in operational concepts. NASA has proposed an air-ground communication mechanism for coordinating reroutes between the flight crew and dispatchers [21] beyond the capabilities of the Aircraft Communications Addressing and Reporting System (ACARS), but this system is not operational and is does not have bi-directional communication with any ANSP automation. Since no direct connection exists between flight deck trajectory management automation and ANSP ground automation platforms, this concept intends to create that connection for the benefit of the airspace users and the ANSP.

NASA's ABTM Roadmap has focused on automating the airborne element to find and implement an optimum flight path from the aircraft's present position to its destination. The steps in that Roadmap are listed below, and subsequently described in further detail as background information for the proposed end-state SATM concept, which uses direct, digital connections between air and ground automation to submit, review, and implement trajectory modifications.

[2] Full Enroute Data Comm Services are scheduled to be available at all Center facilities in 2023 [27].

- Basic TASAR. Uses flight deck automation to compute optimized lateral and vertical trajectory changes to be requested via voice exchange between pilots and controllers.
- Digital TASAR. Replaces the voice exchange for trajectory request and re-clearance of Basic TASAR with FAA Data Comm permitting the use of more flexible, complex, and lengthier trajectory definitions for greater savings; to facilitate simpler and faster request procedures by reducing pilot and controller workload as well as frequency congestion; and to eliminate sources of error and misunderstanding.
- Four-dimensional (4D) TASAR. Extends the optimization dimensions of Basic and Digital TASAR to include the speed/time dimension to consider time of arrival constraints in the optimization routine and permit along-path speed optimization in the absence of time constraints.
- Strategic Airborne Trajectory Management. Integrates the Digital and 4D TASAR capabilities with ANSP automation to provide user authority to update the strategic trajectory in downstream ANSP control sectors automatically, removing the time- and workload-intensive coordination process with downstream ANSP facilities.
- Full Airborne Trajectory Management. Extends Strategic Airborne Trajectory Management to include airborne separation responsibility in the current sector and the authority to make tactical trajectory changes without prior ANSP approval, by operating under Autonomous Flight Rules [16].

Previous research has described upgrades to the Basic TASAR capabilities: 1) to overcome the inefficiencies in Voice Comm with the ANSP by using Data Comm [22], and 2) to incorporate ANSP time constraints used in traffic flow management into the optimized trajectory “solutions” generated in the cockpit [23]. The fourth step of ABTM, SATM, proposes that aircraft automation communicate directly with ANSP automation to coordinate approval of an optimized solution that is acceptable to the ANSP all the way to destination without requiring the lengthy and often impractical manual processes of coordination within and among Center facilities. Recognizing that there are significant issues to be addressed before fully automated connectivity between flight deck and ANSP automation systems may be realized, an initial implementation of SATM that uses the current ACARS link between the flight deck and the AOC, the CDM link between the AOC and the ANSP, and the ABRR capability in TFMS may be possible.

2.1 Basic TASAR

The purpose of Basic TASAR is to advise the flight crew of potential lateral and vertical modifications to the aircraft’s current trajectory to achieve fuel and time savings. By avoiding known airspace hazards such as traffic and weather, as well as conforming to known airspace constraints, Basic TASAR provides recommendations that are more likely to be approved by the ANSP, increasing the realized benefits beyond that of flights without the technology. The NASA prototype implementation of the Basic TASAR concept, the Traffic Aware Planner, uses a combination of a powerful trajectory optimization algorithm called the pattern-based genetic algorithm [24], a trajectory generator [25] and a conflict probe [26] to produce optimized trajectory modification recommendations. This technology uses data internal to the aircraft (e.g., current state and route data, traffic state data, aircraft performance model, and navigation database) and data obtained from external sources via in-flight internet (e.g., current winds aloft, convective weather hazards, and special use airspace activation schedules) in its real-time trajectory computations. The proposed trajectory modifications shown to the flight crew for consideration are de-conflicted from known hazards, and therefore have a greater likelihood of being approved by the ANSP when requested by the flight crew.

The Basic TASAR concept is predicated on there being enough flexibility in the en route airspace that flight crews can routinely request, and generally receive, approval for changes to their active trajectory when verbally making the request to the controller. This flexibility is routinely used now by pilots for both flight safety and efficiency in seeking out less turbulent altitudes, to avoid icing conditions, to deviate around convective weather hazards, and to seek shortcuts or winds that are more advantageous. Basic TASAR is designed to make use of this flexibility for optimizing the flight by reducing the fuel burn and/or flight time of the flight in accordance with the business model of the airline. The optimization objective used at any given time during the flight is a pilot selectable function, and may be changed based on the flight's evolving circumstances (e.g., unexpected delay due to weather).

The Basic TASAR technology provides the flight crew with advisory information on trajectory-change options, thereby enhancing their decision-making process. Once a trajectory modification is deemed acceptable by the flight crew, they use existing voice procedures to make the trajectory change request[3]. When a request to the ANSP is made, no reference to TASAR capability is required, since no special consideration (i.e., operational credit) from the active sector radar controller is being requested.

If a request is complex (i.e., involves a change to the trajectory that affects multiple Centers), the active sector radar controller may need to receive concurrence from the traffic manager before approving the request. Once the active sector radar controller has reviewed the request, he or she will provide one of three clearances to the flight deck – accepted as requested, accepted with modifications, or rejected. The pilot proceeds in accordance with the active sector radar controller's response [4], and the controller updates the aircraft's flight plan in the ERAM system. A block diagram is presented in Figure 1 that describes the location of the various technologies involved in a Basic TASAR operation, as well as human-human, human-automation, and automation-to-automation interactions. Note that there is no connectivity between airborne and ground-based automation platforms.

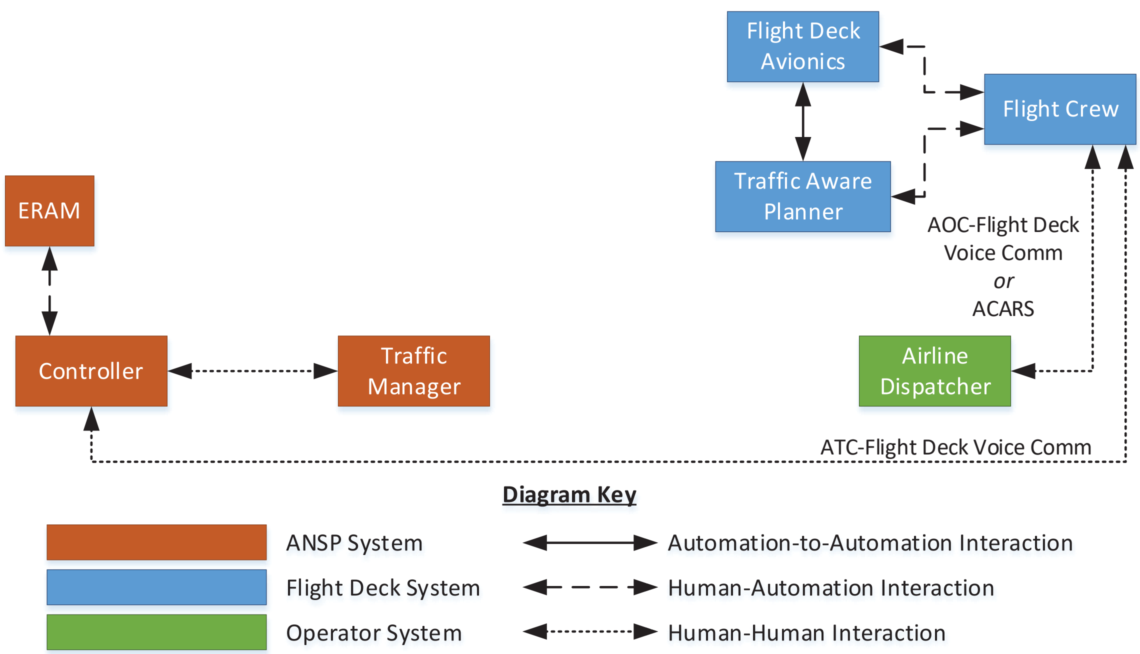

Figure 1: Basic TASAR Interaction Diagram

Today's Voice Comm environment limits the complexity of trajectory changes that can be practically communicated between pilots and the ANSP. Most ad hoc requests made in the absence of Basic TASAR

[3] Some requests may require concurrence from dispatchers at the AOC before the request is made. Standard practice for requesting dispatch concurrence occurs when the flight deviates from the original flight plan by 100 nautical miles laterally, 4000 feet vertically, or will arrive more than 15 minutes earlier or later than the estimated time of arrival. This coordination may be conducted using either ACARS or a voice communication system.

are altitude changes or a request to be cleared "direct" to a downstream waypoint on the active route. Any requests more complex than these are generally workload prohibitive on all parties and prone to errors due to voice read back/hear back issues or keyboard data input on airborne and ground systems. Therefore, the Basic TASAR technology imposes artificial constraints on generated solutions to facilitate unambiguous and efficient Voice Comm between the flight crew and the ANSP.

2.2 Digital TASAR

To achieve greater levels of user operational autonomy, increase operational efficiency, and make efficient use of existing airspace capacity, a need exists to be able to request complex trajectory modifications using simple procedures. The second step of the ABTM roadmap, Digital TASAR, directly satisfies this need. In the Digital TASAR concept, FAA Data Comm [27, 28] replaces the voice mechanism for the flight crew requesting the trajectory modification and the response by the ANSP. There is no change in roles and responsibilities for trajectory-change authority or separation of aircraft in Digital TASAR.

The transition from Voice Comm to Data Comm has implications on the nature and complexity of the change requests. By using Data Comm, coupled with possible software improvements in the aircraft's FMS and the Center ERAM software, complex trajectory modification requests are possible. Digital TASAR trajectory change requests can contain several off-path waypoints, and the waypoints may be named, coded, or defined by latitude/longitude coordinates. Since the change requests will be complex, the controller may be more reliant on automation to perform conflict probing. A graphical display of the modified trajectory may be used to visually assess the requested change obtained via Data Comm. Digital requests and increased use of automation during the approval process should simplify the request and approval process, making it more likely that approved trajectory modifications will occur on a more frequent basis and in busier airspace than would otherwise occur. For more information regarding Digital TASAR, refer to [22].

A block diagram that describes the location of the various technologies involved in a Digital TASAR operation, as well as human-human, human-automation, and automation-to-automation interactions is presented in Figure 2. In this step of the ABTM roadmap, connectivity exists between the Data Comm avionics on the flight deck and the Data Comm functionality in ERAM. However, significant human-to-human interaction is required to request, review, and approve any trajectory modification request.

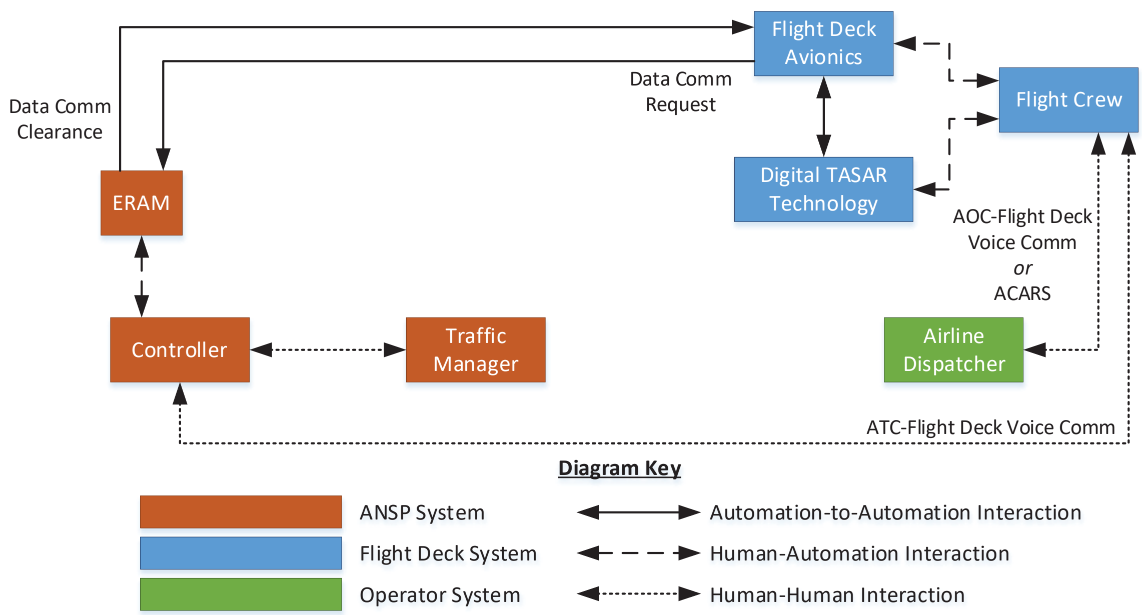

Figure 2: Digital TASAR Interaction Diagram

2.3 Four-Dimensional TASAR

In addition to considering the lateral and vertical dimensions of the flight trajectory when optimizing to the chosen time, fuel, or cost saving objective, 4D TASAR includes aircraft speed in the optimization algorithm. This enables the creation of trajectory solutions in three dimensions plus time at points along track and the speed flown between waypoints. Thus, for example, if saving fuel is the objective, finding a better wind route could be combined with an airspeed reduction along the new trajectory, enabling a simultaneous solution for best fuel while also meeting a time objective at the destination (usually a scheduled arrival time) for efficient use of airline ground resources or for traffic flow management. This capability could also enable tight coupling of traffic flow constraints with the individual optimization objective of each flight, creating both flight and ANSP efficiencies simultaneously.

The FAA, as part of its Next Generation Air Transportation System (NextGen) Program, is implementing technologies across the National Airspace System (NAS) that enable time-based flow management. These technologies are expected to increase the predictability of the NAS and improve the use of the existing system capacity [14]. A basic premise of time-based flow management is that time-based metering is used in conjunction with scheduling tools to optimize the flow of aircraft as they depart and approach congested airspace and airports [29]. As a result, each aircraft may have a scheduled time of arrival at certain points along its trajectory from the ANSP. While these automation tools are not yet routinely used by controllers, it is intended that they be used increasingly in the future to establish regular flows to the runways and would be compatible with aircraft use of the Required Time of Arrival (RTA) feature in existing FMS units. Currently, controllers issue speed control instructions to aircraft to have them cross the constrained fixes at scheduled times of arrival issued by the TBFM automation platform. The use of RTA has been demonstrated to improve the time-crossing accuracy and precision [30–33]. In addition, these RTAs usually end at a gateway fix for a terminal arrival at an agreed-upon interval, which may or may not be needed. By assigning an RTA to a fix inside the TRACON arrival airspace (provided by the TRACON), the aircraft can program its vertical profile and descent speed to meet that restriction and optimize fuel burn.

The 4D TASAR concept considers time of arrival constraints in its trajectory optimization to provide compatibility with time-based flow management concepts. The 4D TASAR technology will have the capability to receive and apply such constraints to its active route and to generate advisories that optimize the objective while meeting all known constraints, including time of arrival constraints. Solutions produced by the 4D TASAR technology will have a time (or speed) component, as well as the lateral and/or vertical path changes to ensure that the time constraint is met. In the absence of any time constraints on the route, the inclusion of a time or speed solution enables continual optimization in speed as well as lateral and vertical flight path. These solutions will be presented to the flight crew, who can use a combination of Data Comm messages (leveraging Digital TASAR capabilities) to request the trajectory modification, and, likewise, the ANSP can respond to the request with a Data Comm message. For more information regarding the 4D TASAR concept, refer to [23].

A block diagram is presented in Figure 3 that describes the location of the various technologies involved in a 4D TASAR operation, as well as human-human, human-automation, and automation-to-automation interactions. In this step of the ABTM roadmap, more information (e.g., time of arrival constraints) is transmitted to the flight deck from ground-based automation platforms (namely, ERAM via TBFM) via a Data Comm message, where it is ingested by the 4D TASAR technology. However, significant human-to-human interaction is still required to request, review, and approve any trajectory modification request.

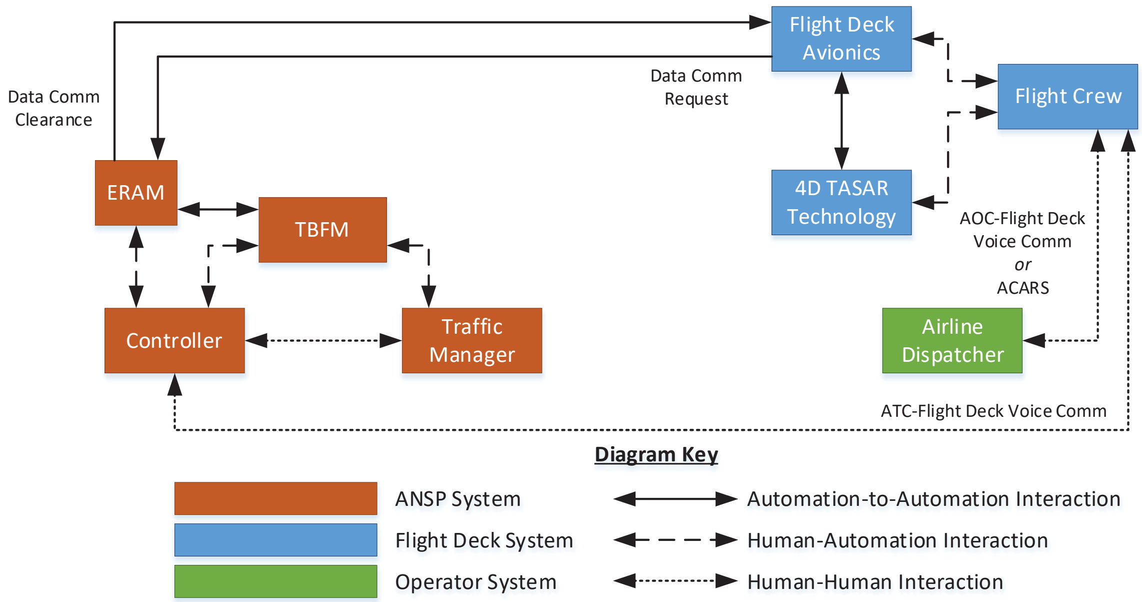

Figure 3: 4D TASAR Interaction Diagram

3. Strategic Airborne Trajectory Management Definition

As discussed in Section 2, the first three steps in the ABTM roadmap focus on bringing automation to the flight deck to allow flight crews to perform intelligent, dynamic, digital trajectory optimization. Basic TASAR introduces the concept of using airborne automation to recommend trajectory modifications of this nature to the flight crew for request to the active sector radar controller via Voice Comm. Digital TASAR uses FAA Data Comm to facilitate increasingly complex trajectory requests digitally using simplified procedures. Finally, 4D TASAR begins the process of incorporating system-level constraints into the en route trajectory optimization function. In each of these operational concepts, there is still significant human-human coordination required to review, coordinate, and implement the requested trajectory modification. Furthermore, air and ground automation platforms are not directly connected to one another, causing inefficient and workload-intensive human-human and human-automation interactions.

In the SATM concept, direct machine-to-machine data communications are proposed between the airborne trajectory optimizer and ANSP automation platforms to accomplish two goals. The first goal is to provide an information-rich set of dynamic constraints to the flight deck automation, such that the optimization capability may generate trajectory modification requests that have a high likelihood of approval from the ANSP. The second goal is to automate the request and re-clearance process as much as practical by employing automated agents that vet trajectory modification solutions before they are presented to human operators. By accomplishing these two goals, the SATM concept is expected to greatly expand the use of en route optimized trajectories by the equipped aircraft while significantly reducing the workload associated with this process on both pilots and controllers. Furthermore, expanding the use of en route optimized trajectories will lead to an increase in the realized fuel and time savings for each equipped aircraft, resulting in significant operating cost reductions for an airline.

3.1 Key Enablers for the SATM Concept

The suite of ABTM concepts require sequential implementation of each step of the roadmap. This stepwise implementation provides an opportunity for two key enablers of the SATM concept to manifest. The first enabler is an evolution of the NAS towards increased use of automation. The second enabler is an ability to gain operational experience through use of each step of the ABTM roadmap, leading to confidence in the performance of the operational system.

3.1.1 Increased Use of Automation for TFM Functions

The NAS is evolving toward greater use of ANSP automation, particularly for Traffic Flow Management (TFM), through the increased use of the TFMS and TBFM tools in the Center facilities. A reduction in the use of manual control processes (e.g., miles-in-trail procedures, speed control, flight vectoring) to achieve TFM objectives will dramatically increase the availability of airspace and flexibility in that airspace to accommodate requests for changes to aircraft trajectories while they are en route. Furthermore, through enabling infrastructure and technologies being developed and fielded by the FAA and industry, such as Data Comm, SWIM, ACARS, and aircraft access to SWIM, a sufficient number of system-level constraints from the ANSP TFM automation can be digitally transmitted to the flight deck, allowing an aircraft to request a highly acceptable trajectory modification. Investments in automation made by the FAA in their NextGen Program demonstrate that tangible steps have been taken to increase the amount of automation used in air traffic automation. This increase in automation is anticipated to occur for the next several years, and the SATM concept will leverage those investments in ANSP automation.

It is important to note that, even with the introduction of advanced automation for TFM, most airspace constraints relate to artifacts of the NAS that come from a manual control paradigm. The organized flows of traffic embodied in Standard Instrument Departures, Standard Terminal Arrival Routes (STARs), and ANSP preferred routes, the shapes and sizes of the control sectors themselves, and their stated “capacity” are all based on human perception of this very dynamic, multi-element traffic picture and the controller’s cognitive ability to manage it safely. For instance, it is true that runway capacity limits an airport’s ultimate throughput, but that constraint alone does not require but a fraction of the preferred routes, boundary-crossing restrictions, speed control and vectoring that define today’s Instrument Flight Rules operations. As air-ground collaborative automation performs increasing TFM functions, system designers must ensure that the automation software and operational procedures are adaptable. The constraints required for manual operations will evolve as increased automation is used, and these constraints will need to be represented in the automation such that the ANSP and airspace users are aware of them. The evolution of airspace constraints will facilitate flexibility in the use of the airspace, supporting the option of a gradual transition toward a fully automated control paradigm.

3.1.2 Operational Experience Leading to System Trust

The ABTM roadmap enables experience to be gained through operational application of each step and allows improvements to be made to the flight deck automation software as insights are gained from that experience. Experience gained using Basic TASAR, Digital TASAR and 4D TASAR may lead to improvements in air-ground automation-to-automation data exchange, as well as provide user and ANSP confidence in the performance of the airborne automation.

As confidence is gained in the validity and acceptability of the trajectory modification requests by the human operators, trust[4] can be built in the operational system. Trust in the operational system (including the flight deck automation, ANSP automation, and network connections) is critical to the realization of the fully automated approval process featured in the end state SATM concept. Developing ANSP and airspace

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[4] Trust, according to Lee and See [46], can be defined “as the attitude that an agent will help achieve an individual’s goals in a situation characterized by uncertainty and vulnerability.” Sheridan and Parasuraman [47] expand this definition in the context of perceived robustness. They characterize trust in automation as demonstrated or promised ability to perform under a variety of circumstances, sense of familiarity, perceived understandability, usefulness of the system to the trusting person, or dependence of the trusting person on the system. The Sheridan and Parasuraman definition is applicable to the use of the term “trust” in this report.

user trust in the system in early implementation phases will minimize potential setbacks and hindrances affecting its adoption into the airspace system, fostering rapid growth toward ubiquitous implementation across the system. It is suggested that this trust may start through operational experience gained during routine flights with the earlier ABTM concepts, but it should be refined through careful system design and authentication procedures to ensure that data exchange occurs without unintended or deliberate corruption.

3.2 Concept Overview

The primary objective of SATM is the ability to update the active flight plan in ANSP automation directly from the aircraft, including full compliance with any TFM constraints that may be in place. This can be achieved once the flight deck and ANSP automation capabilities are integrated into normal operations, and trust has been established (i.e., the key enablers are in place).

The SATM technology, the flight deck automation platform that enables the SATM concept, will generate a TOS that may be submitted to the ANSP at the flight crew's discretion. There are only minimal functional upgrades that must occur to the 4D TASAR technology to implement the SATM concept: namely, the ability to transmit a TOS in addition to a Data Comm request. There will usually be multiple flight plan updates throughout the flight using the SATM technology as environmental conditions change and new information is received onboard the aircraft from weather sources, the airline, and the ANSP. In each flight plan update, the operating constraints are accommodated in the optimized solution that saves the most fuel and time possible on each flight.

Initially, changes to the active flight plan because of the SATM concept will still be made manually by controllers and pilots, even once a digital request exchange mechanism is in place. It is expected that with more data feeds of system level constraints being used by the flight deck automation, the requested flight path will routinely be more acceptable and conflict free than what is being accomplished today. Once the requests reach a consistent level of high approvability, the process for manually approving these requests may become onerous for traffic managers in the Center Traffic Management Unit (TMU) and traffic flow managers at the Air Traffic Control System Command Center (ATCSCC). Widespread implementation of the SATM concept in the fleet may likely lead to an unacceptable workload for these human operators, who receive very few such requests today. This situation may result in denied or ignored requests, removing any benefit to be gained from the use of SATM. Widespread manual approval of SATM requests, while it may increase workload from the ANSP perspective, would also indicate that airspace users are employing the system to their benefit. At this phase of SATM implementation, a transition towards a fully automated approval process should begin.

To alleviate high ANSP workload, assuming that trust has been built in the operational system, the SATM concept proposes to make extensive use of automation and digital connectivity for the approval process, alleviating the workload of human operators. The validation of the proposed TOS against active airspace constraints normally done by the TMU would be performed by ANSP automation, with a data response to the aircraft (and the AOC, if applicable) when the process was complete. No manual entry of trajectory descriptions would be required by the pilots, or any of the controller staff. Controller/pilot interactions in the active sector would not be changed from earlier versions of TASAR. The controller is still responsible for separation, and requests for changes in the active sector transmitted from the SATM would be made using Data Comm. These requests would still be vetted by the active sector radar controller and the response to the aircraft made by return Data Comm message.

Trajectory modifications generated by the SATM technology require minimal attention from the pilots, and none from the active sector radar controller, since these changes are not made in the active controller's sector. By beginning the change in the following sector, it does not interfere with the mental traffic planning of the active sector radar controller. Controllers in the next downstream sector would receive an alert on the flight plan change of the incoming flight.

The first three steps of the ABTM roadmap derive their benefits from flexibility in the use of the airspace permitting changes to be made to the cleared flight path. Manual coordination processes within the ANSP limit that flexibility to relatively short-range changes. The SATM concept is designed to substantially improve that flexibility in the use of the airspace all the way to destination, and to serve as the flight deck's entry point for trajectory negotiation.

4. Use Case Scenario

Many route modification requests are not accepted by air traffic control due to a lack of knowledge of downstream traffic conditions by the current controller, or due to the impact of the amount, or frequency, of requests on workload. This use case scenario demonstrates the impact of data feeds on constructing a route that is acceptable to the ANSP, highlights the importance of having connectivity between various automation platforms to facilitate a streamlined request process, and establishes the need for automation to approve well-informed requests so as not to increase controller workload.

Flight 1222 was scheduled from Newark, New Jersey to Denver, Colorado. Due to a forecasted large convective weather system in the Midwest, accompanied by high traffic volume, a routing was selected from the airline's provided TOS that planned the flight over Bradford, Pennsylvania into Toronto's airspace then over Duluth, Minnesota, Casper, Wyoming, and Steamboat Springs, Colorado for an arrival into Denver from the west. This is shown in Figure 4 as the "Filed Flight Plan" in magenta. The cruise altitude for this route, based on forecasted en route winds, was Flight Level (FL) 320. This flight plan added 45 minutes to the nominal city-pair flight time due to the additional flight miles, and the flight would incur Canadian overflight fees on the leg between Bradford and Duluth.

Once airborne and flying in New York Center's airspace (depicted by the cyan target in Figure 4), the data feeds to SATM indicated that the weather system was not developing as expected and the predicted sector loading was relaxing. The SATM technology provided a routing starting in the next control sector from over Bradford to Detroit, Michigan, then over Nodine, Minnesota, rejoining the filed route at Casper (shown in Figure 4, "SATM Route 1" in cyan). For this lateral path, the en route winds were more optimal at FL360 than at the current cruise altitude of FL320. The combination lateral and vertical flight path modification was predicted to reduce the flight time of the aircraft, keep the aircraft inside United States airspace, and reduce the fuel consumption at the higher cruise altitude. The effect of this optimization was reduced operating costs for that flight. Via Data Comm, this request was sent to ANSP automation from the SATM technology, which approved the request due to the lower sector loading, de-confliction with the weather system, and compliance with known constraints applied to the flight. The amended route clearance was sent back to the aircraft and updated in ANSP automation systems without any human interaction. New York Center handed the aircraft off to Cleveland Center, and the aircraft continued on its new route.

As Flight 1222 approached Bradford, Pennsylvania (depicted by the green target in Figure 4), the SATM technology presented a new route that was further south and more direct to Denver, due to the increasingly favorable sector loading and smaller-than-anticipated convective weather system. This route turned at Detroit and headed southwest over Omaha, Nebraska and into Colorado using Lat/Long waypoints. This route also put the flight on a STAR arriving from the east (shown in Figure 4, "SATM Route 2" in green). The SATM technology predicted that the new routing would save both fuel and time due to the reduction in air miles. The new route was once more sent by the SATM technology to ANSP automation, approved, and executed by the flight crew.

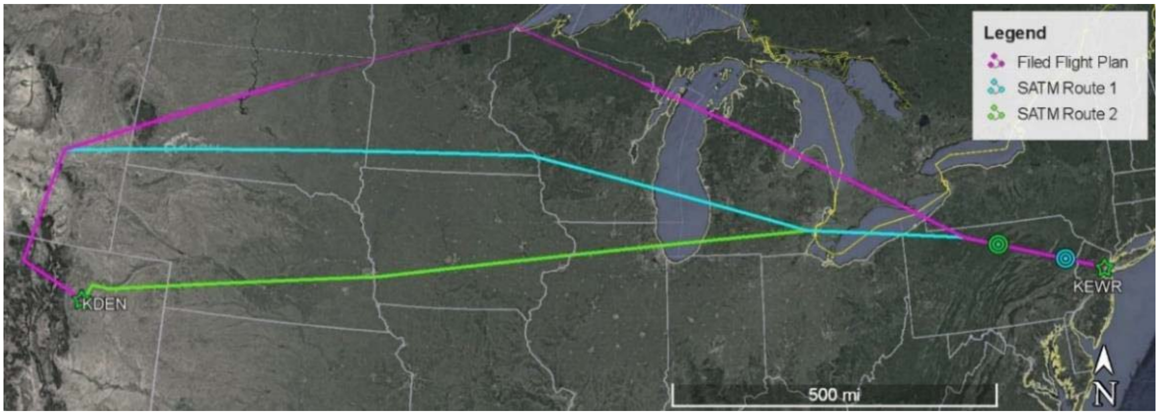

Figure 4: Use Case Filed Flight Plan and Initial SATM Amendments

The crew then saw that they did not need to go over Detroit on the new route, and could save slightly more time if they started towards Omaha immediately. They requested direct-to a lat/long waypoint on the new route using CPDLC to the controller handling their current sector at the point depicted by the purple target in Figure 5, utilizing Digital TASAR functionality (shown in Figure 5, "Digital TASAR Request" in purple). The controller reviewed the request and, seeing no issues, granted them direct-to approval to the lat/long waypoint. The new routing, featuring two SATM route requests and a Digital TASAR route request, saved the flight almost the full 45 minutes of superfluous flight time in the original filed route.

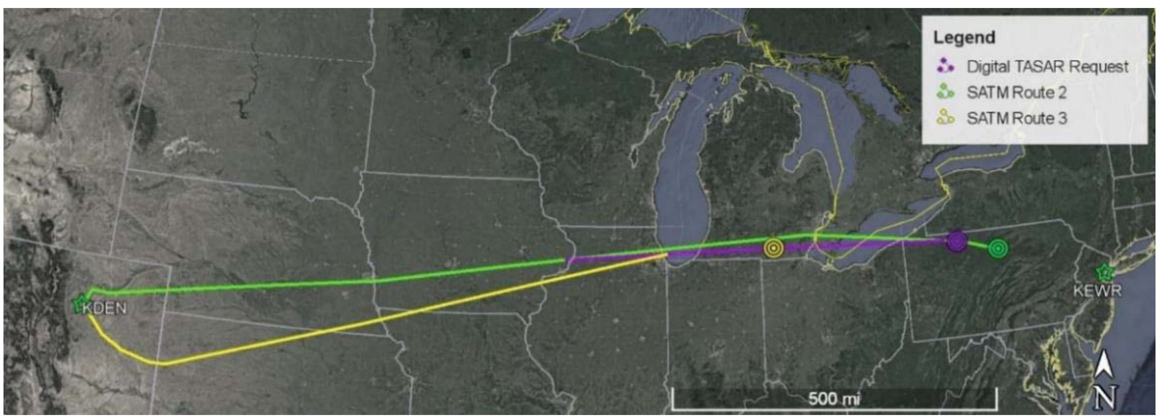

Figure 5: Use Case Digital TASAR and SATM Amendments

As Flight 1222 progressed (depicted by the yellow target in Figure 5), an RTA was created in TBFM at the gateway waypoint on the northeastern arrival into Denver. Metering was put into effect at Denver because of arrival loading from other aircraft requesting a similar shortcut that passed through the northeastern arrival fix[5]. The slower speed required to meet the RTA would cause the aircraft to be 5 minutes late arriving into Denver. The SATM technology presented another route showing that with a slight modification south, the aircraft could fly to the southeastern arrival fix with no time constraint (shown in Figure 5, "SATM Route 3" in yellow). Performing a climb to FL380 in conjunction with the lateral path modification would result in the fuel burn being roughly the same as the current route, and an on-time arrival would be made at Denver. The new route was approved, and the aircraft finished the trip into Denver on time and with significantly less operating cost.

This scenario illustrates the dynamic nature of SATM trajectory planning, taking advantage of changing traffic and environmental conditions. The SATM technology provided the flight in this use case with a

[5] Ensuring system stability and equity when concurrent TOS submissions from multiple parties are made is a critical research topic.

series of optimized trajectories, each saving fuel and/or time. The flight was able to respond proactively to changing constraints, and utilized multiple mechanisms to either request a trajectory modification from the active sector radar controller or submit a modified trajectory directly into ANSP automation.

5. SATM Technical Implementation Considerations

This section discusses technical implementation considerations for the SATM concept. An overview of the technology ecosystem is presented. Required airborne equipment, including SATM technology components and example architecture alternatives is discussed. Finally, ground-based ANSP systems, AOC systems, and communications infrastructure supporting SATM implementation are described.

5.1 Technology Ecosystem Overview

The SATM concept leverages a number of automation platforms, both airborne and ground-based, in operation. Each of these automation tools interact digitally with other automation tools, and some require interactions with human operators. Since TASAR-like route amendment requests may still be made using the SATM technology, the ecosystem in which the SATM technology resides, presented in Figure 6, employs several of the same systems and communication mechanisms used in prior ABTM steps. The largest difference in the SATM system from previous ABTM steps is the inclusion of AOC automation and communication links that facilitate the direct communication of a TOS between the SATM technology on the flight deck and the TFMS automation at the ANSP.

Each technology system presented in Figure 6 (e.g., SATM Technology, AOC Automation, and TFMS) is comprised of multiple automation platforms with functionality that may or may not be integrated within itself. For example, the "AOC Automation" box represents automation platforms that perform flight planning, flight monitoring, communication, and TOS generation. In current-day operations, these functional systems are not integrated with one another; data exchanges between systems rely on humans.

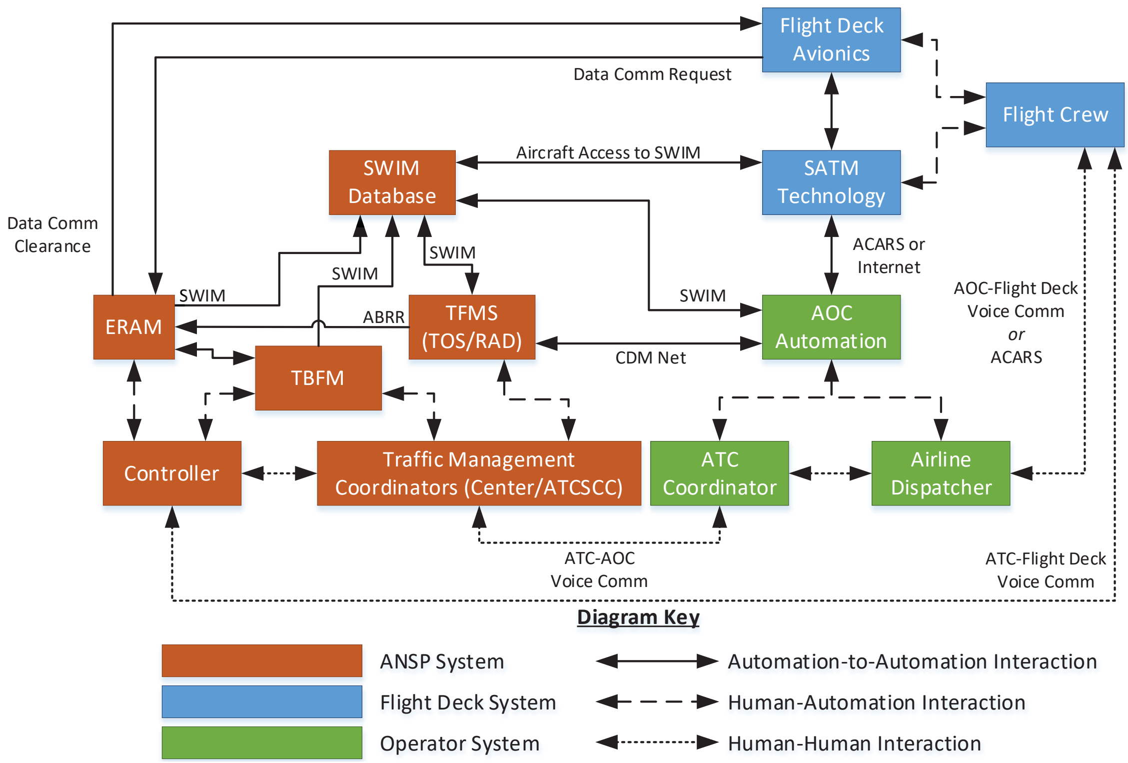

Figure 6: SATM Technology Ecosystem

5.2 Flight Deck Systems

The first set of equipment discussed are the systems onboard the aircraft that create an environment to conduct SATM operations. This section provides an overview of the flight deck systems used, how they are connected to each other, and modifications made to them to enable the SATM concept.

5.2.1 Avionics

The complexity of SATM solutions, the requirement to maintain cognizance of all constraints that the aircraft is subjected to, and the ability to utilize Data Comm for making requests or ACARS for submitting a TOS necessitates continuous synchronization between the aircraft's certified avionics and the SATM technology. Recent industry advancements allow technologies like the SATM technology to interface directly with the aircraft's avionics suite [34]. These interfaces will allow the SATM technology to receive additional information from the aircraft compared to the Basic TASAR technology implementation. The vast majority of connections between the SATM technology (namely, the Internal Data Server subsystem) and flight deck avionics are read-only; however, there are a few two-way connections.

The SATM technology receives data from certified flight deck avionics (e.g., the air data computer, the global navigation satellite system, the flight management system general output bus and the inertial reference system) regarding the operating state of the aircraft. These data provide an accurate, up-to-date depiction of what the aircraft is doing and sensing, and are used in the trajectory generation function within the Main Processor (described in Section 5.2.2.1). The SATM technology also receives the intended flight path of the aircraft from the FMS. The intent data, provided in three dimensions (latitude, longitude, and altitude) parameterized by time, are used by the trajectory optimization function of the Main Processor to compute predicted fuel and time savings of all optimized trajectory solutions.

Additionally, the SATM technology receives data from avionics that perform surveillance functions to detect nearby traffic (e.g., automatic dependent surveillance - broadcast). These data are used by the conflict probe in the Main Processor to ensure that computed optimized trajectories are free of nearby traffic conflicts. Finally, the SATM technology reads data from, and writes data to, avionics that perform communication functions (e.g., the Communications Management System, which facilitates transmission and reception of Data Comm and ACARS messages). These interfaces provide a conduit to transmit Data Comm requests or ACARS TOS submissions from certified avionics and to receive re-clearances from the ANSP and route them appropriately to the cockpit equipment.

5.2.2 Notional SATM Technology Components

The SATM technology implementation uses and builds upon the existing software components of the Basic, Digital, and 4D TASAR technologies. The SATM technology is notionally comprised of five subsystems: the Main Processor, the Human-Machine Interface, the Internal Data Server, the External Data Server, and the Ground Data Server. Depending on the configuration of the implemented system, functionality from certain components may be combined.

5.2.2.1 Main Processor

The Main Processor accepts and reads all data inputs, performs all processing necessary to generate optimized conflict-free trajectory-change solutions that are compliant with known traffic management initiatives, and responds to pilot inputs from the Human-Machine Interface. It consists of a trajectory optimizer that generates candidate solutions, a probe that searches for conflicts along those candidate solutions, and a trajectory generator that computes a trajectory based on the intent information for the candidate solutions that also meets constraints present on the active route.

A key update of the Main Processor for SATM is the ability to provide a TOS in addition to the TASAR-like trajectory modification recommendations. A SATM-generated TOS may consist of all types of trajectory modifications present in 4D TASAR (lateral, vertical, speed, or combination lateral/vertical/speed) combined into a single TOS (i.e., the TOS consists of an optimized solution in each operating dimension, plus a combination solution), or there may be other combinations of trajectory solutions that could comprise a TOS. If there are subsets of trajectory modifications that would still provide savings (e.g., only the Lateral and Combo solutions provide savings), these will be computed and passed in as a TOS. The trajectory optimizer will ensure that all off-path maneuvers for all trajectory options in a TOS will start in the next downstream sector to maximize the probability of controller acceptance, since potential conflicts in the current sector are avoided. Finally, the trajectory optimizer and conflict probe must be provided with increased information for better environmental situation awareness (e.g., increased information regarding the state of the NAS).

5.2.2.2 Human-Machine Interface

The Human-Machine Interface enables interaction between the flight crew and the automation. Similar to the Basic TASAR technology, it accepts all user-entered information and sends it to the Main Processor. It also displays the most optimal trajectory solutions (one in the lateral dimension, one in the vertical dimension, one in the speed dimension, and one combination of lateral/vertical/speed maneuvers), fuel and time outcomes for each trajectory solution, conflict information, and additional information regarding connectivity to data sources and the internal state of the system to the user.

For a SATM implementation, the Human-Machine Interface will present a graphical display of the solutions, constraints and environmental factors to facilitate the flight crew assessment of the solution options (either a TASAR-like trajectory modification recommendation or a TOS). The Human-Machine Interface will host all necessary controls to create, manipulate and communicate the chosen trajectory modification or TOS to the airline and the ANSP. The Human-Machine Interface will provide awareness to the flight crew of whether they are reviewing TASAR-like recommendations for request or a TOS submission, and will allow the pilot access to subset solutions that would be included in the TOS. The Human-Machine Interface will also permit the flight crew to submit all solutions as a prioritized TOS to the ANSP with a single button push.

5.2.2.3 Internal Data Server

The Internal Data Server is an interface between the onboard components of the SATM technology and the certified avionics, making use of emerging EFB-FMS interoperability capabilities such as those described in [34]. The Internal Data Server is the only software component in the SATM technology system that communicates with certified avionics. This design benefits both certification and cybersecurity considerations. The Internal Data Server provides a data assurance filter for all data flowing to and from the SATM technology, which increases the integrity of the system. Furthermore, it serves as a cybersecurity barrier between the aircraft's installed equipment and the digital paths into the technology ecosystem that lack inherent assurance and reliability. The Internal Data Server ingests a simple text avionics protocol data feed from an Aircraft Interface Device connected to the aircraft's avionics, and relays the data to the Main Processor and the Human-Machine Interface. It also receives trajectory data from the Main Processor for a pilot-selected trajectory change request (i.e., a route definition for a selected trajectory solution), converts the selected trajectory data into the appropriately formatted Data Comm message, and routes it to the aircraft's FMS and ultimately to the ANSP. There are no significant changes expected in the Internal Data Server for a SATM implementation.

5.2.2.4 External Data Server

The External Data Server is an interface between the airborne components of the SATM technology and data that originate external to the aircraft. It handles the downloading, decrypting, decompressing, and formatting of winds aloft data, convective weather data, SUA data, and air traffic control operational data obtained from the Ground Data Server. It will periodically check to see if updated data exist on the Ground Data Server, and if so, download it to the aircraft. For the SATM implementation, the External Data Server must also be able to receive trajectory data from the Main Processor for a pilot-selected trajectory option set submission (i.e., trajectory information for all valid solutions generated by the Main Processor). It will convert that information into the appropriate TOS format and send the TOS for submission to the ANSP.

5.2.2.5 Ground Data Server

The Ground Data Server handles the downloading and processing of large sets of external data obtained via the internet. Centralizing the downloading and processing of large datasets prior to uploading a subset of data to the aircraft alleviates excessive use of the bandwidth shared by in-flight internet systems and the processing power available on avionics where the External Data Server is hosted. In this system architecture, the Ground Data Server provides the SATM technology with winds aloft data, convective weather data, SIGMET data (convective and turbulence), and SUA data relevant to the location of the aircraft and the route of flight. It will also provide several types of air traffic control operational data (e.g., dynamic sector loading, traffic flow management constraints) obtained from SWIM. These data will be compressed and encrypted in order to minimize the file size and protect the contents of the information while it is in transit to the aircraft, respectively. NASA Langley Research Center designed, built, and hosted a prototype Ground Data Server for the Alaska Airlines TASAR operational trial [35]. However, a commercialized Ground Data Server may be owned and operated by an AOC or a third-party service provider. In a SATM implementation, the Ground Data Server will be required to send more information to the flight deck SATM technology in order to provide the Main Processor with an increased set of operational data to apply in the trajectory optimization algorithm.

5.2.3 Potential SATM Technology Architectures

Due to the highly connected nature of the SATM technology ecosystem presented in Figure 6, multiple design alternatives exist with respect to the system architecture of the SATM technology. Each component may be connected to the others using interchangeable mechanisms, meaning that there are various ways to allocate functionality between the aircraft and ground-based systems. This section presents three of these architecture alternatives for implementing the SATM technology that allocate the functional components discussed in Section 5.2.2 differently between airborne and ground-based computing platforms. Several elements are common to all configurations, such as the use of a connected EFB architecture similar to all three of the TASAR technologies.

5.2.3.1 Airborne System Configuration

The first configuration, shown in Figure 7, is an airborne-based design. This configuration does not make use of a Ground Data Server; instead, all relevant information is delivered directly to the External Data Server residing on the aircraft using a high-bandwidth, low-latency internet link. This permits the entire SATM technology to reside in each aircraft. However, this configuration places significant reliance on the in-flight internet link, which raises potential issues with availability, reliability, and cybersecurity.

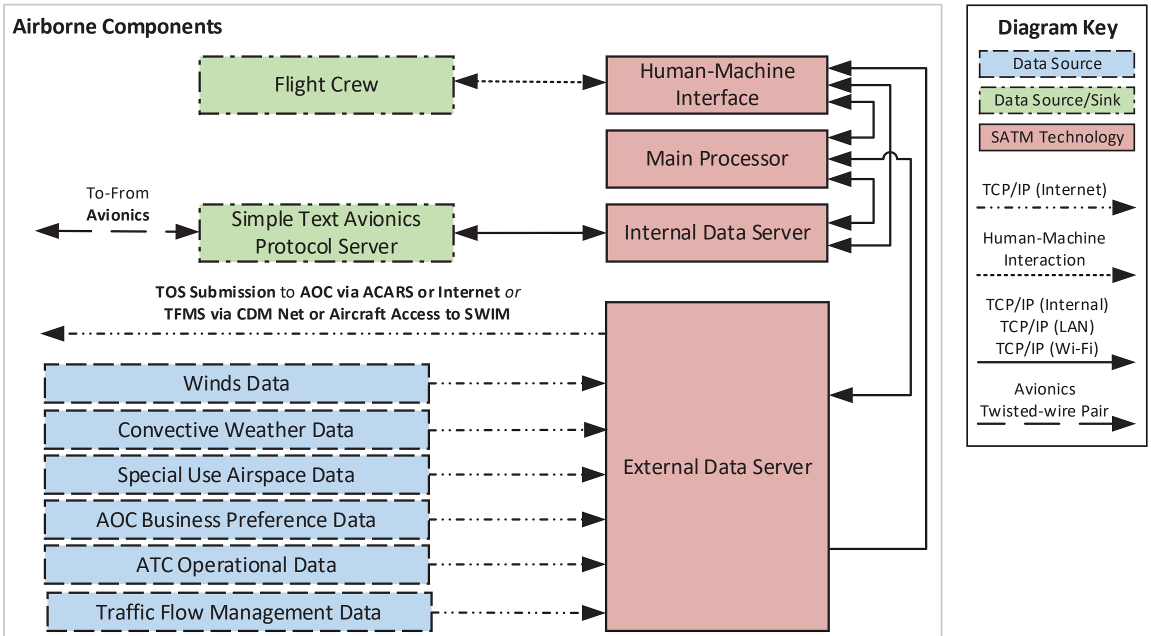

Figure 7: Notional Airborne-Based SATM Technology Configuration

5.2.3.2 Hybrid System Configuration

The second configuration, presented in Figure 8 is a hybrid air-ground design where the majority of the computing power for the SATM technology is located on the flight deck, but significant external data processing occurs on a ground-based system. In this configuration, the Ground Data Server gathers relevant information from SWIM and other ground-based sources, and pre-processes them into a more streamlined form that minimizes in-flight internet bandwidth usage. This configuration was used in the Alaska Airlines operational evaluation of the Basic TASAR technology [3].

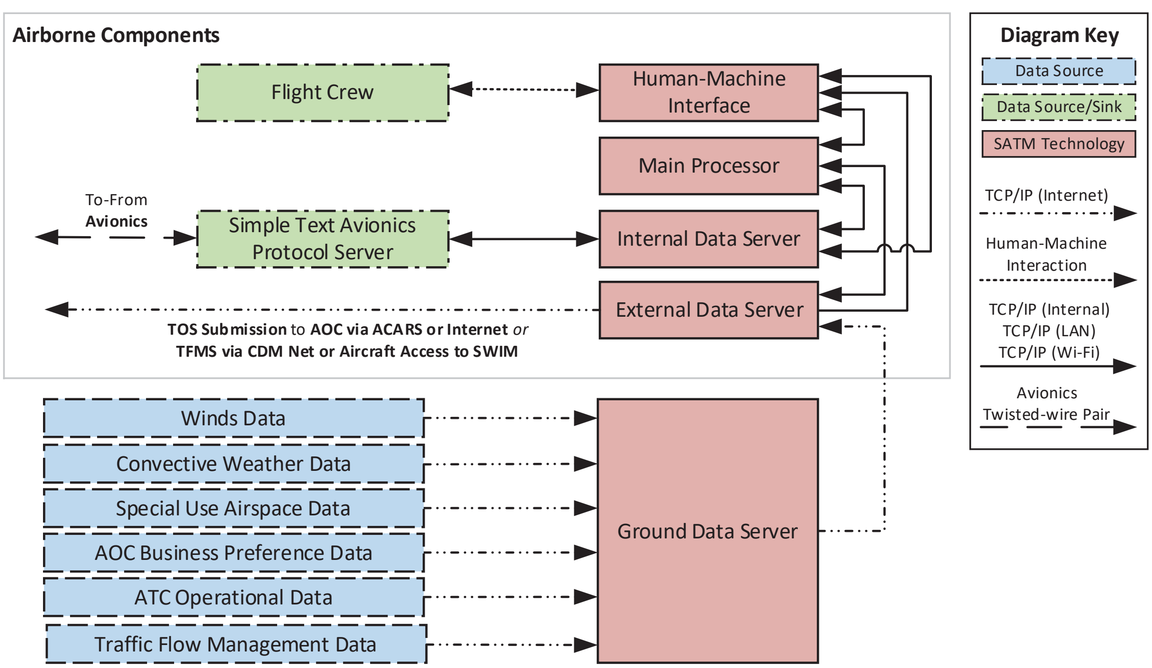

Figure 8: Notional Hybrid Air-Ground SATM Technology Configuration

5.2.3.3 Ground-Based System Configuration

The third configuration, shown in Figure 9, is a ground-based design where the majority of the computing occurs on the ground-based system. The display program on the EFB and an internal data server are the only software components resident on the flight deck. This configuration may be the easiest to implement in operations (minimizing updates to aircraft hardware). However, similar to the airborne configuration described in Section 5.2.3.1, this configuration places significant reliance on the in-flight internet link. There are also cybersecurity concerns associated with streaming aircraft state data from the flight deck to the ground-based server where the main processing is occurring, and data privacy concerns with sending that data outside of the airframe.

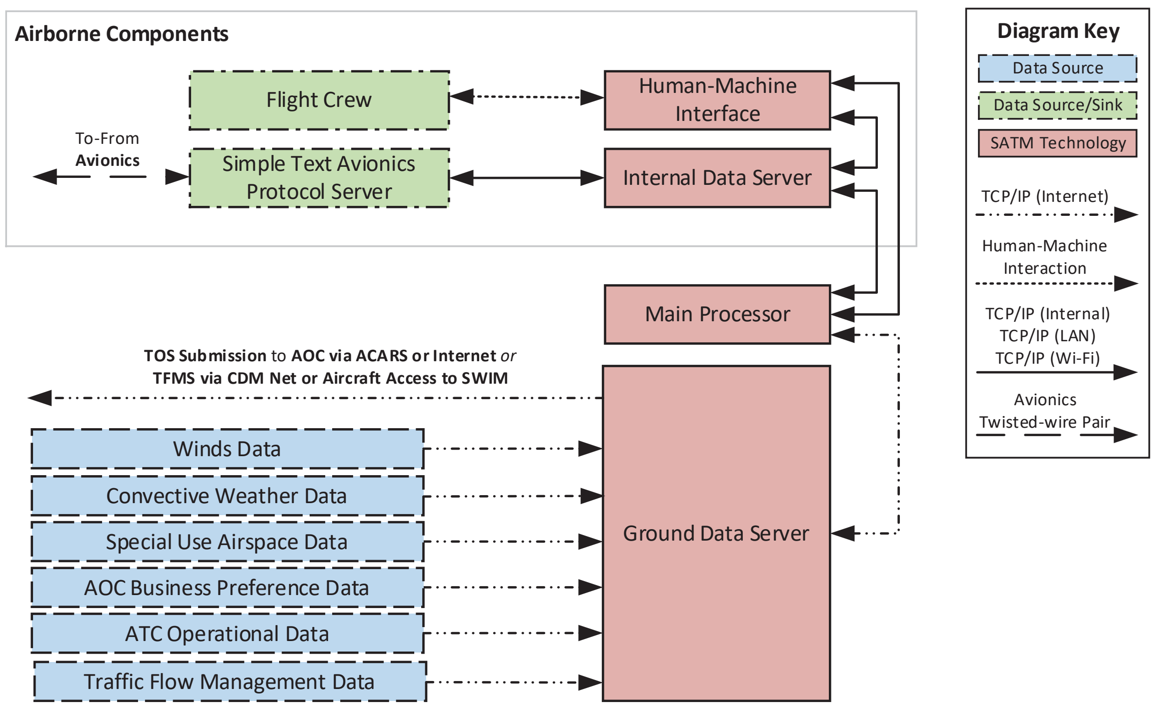

Figure 9: Notional Ground-Based SATM Technology Configuration

5.3 Airline Operator Systems

This section discusses systems located within AOC facilities that create an environment to conduct SATM operations. There are various flight planning, flight monitoring, weather monitoring, and communications systems used by airline dispatchers, and each airline features a different combination of these capabilities. All similar systems at the various AOCs perform the same functions required by regulation, but do so with varying degrees of ease and situational awareness.

The preflight planning function has historically been the focus of dispatchers. Once a flight departs, very little attention is paid to it unless something irregular occurs. In fact, the dispatcher's workload and the manning needs of the dispatch function itself are assessed with this focus in mind. As a result, the dispatcher tools are not optimized to interact easily with many airborne flights simultaneously requesting assistance with trajectory changes simply to optimize their fuel burn and flight time. Typically, a dispatcher's workstation will have three or four monitors to display and process different kinds of information such as weather and traffic, ANSP and NAS system status, internal airline information from relevant departments to support flight monitoring, a flight planning system and a communications control center. Integrating AOC systems is critical to achieving the SATM concept.

5.3.1 Flight Monitoring System

The flight monitoring system at an airline is the main operational system. It contains the schedule of all flights, and receives feeds from all airline and outside entities that affect the accomplishment of that schedule. Examples of these feeds include the aircraft location, flight crew schedule, cabin crew schedules, and crews that operate, service, load and unload those aircraft. The flight monitoring system is typically hosted on the airlines main operations computer, which is a legacy system that performs all the processing. Dispatcher workstations are typically client systems on this mainframe. In current-day operations, airlines make use of a growing number of third party-provided, web-based applications for many airline operational control functions. They are also transitioning from the mainframe architecture to cloud-based computing.

The dispatcher's main application resides in the flight monitoring system. Typically, this application will contain a list of current and future flights for which a dispatcher is responsible. Assessing all information relevant to those flights and planning their operation forms the bulk of the dispatcher's role. Airline and aircraft resources are also available on this application, and may include aircraft flight manuals and bulletins, Minimum Equipment List (MEL), as well as airspace charts and procedures. This application also hosts the ACARS messaging system, allowing the dispatcher to send communications to the aircraft and notifying him or her when a new message appears.

For the SATM system, a new application for handling airborne TOS message requests from aircraft should be resident on this system. This SATM addition should distinguish between those changes that require dispatcher approval and those that are provided for awareness only. This application should also have access to the flight planning system to validate fuel and time outcomes predicted by the SATM technology. Finally, this application should be capable of sending the TOS from the AOC to the TFMS automation platform in the appropriate Center. This action would occur automatically in most situations and with a single button push when dispatcher approval was required.

5.3.2 Flight Planning System

Flight planning systems at airlines are very sophisticated. They use performance data specific to each aircraft, and make use of wind and weather information to find a least wind route among numerous options. Furthermore, they consider ANSP preferred routes and constraints in order to select a route that will be accepted by the ANSP automation when the flight plan is filed. Most airlines do not create their own flight planning systems; they purchase licenses to use systems developed by third-party vendors. Dispatchers almost exclusively use the flight planning system pre-flight, usually several hours before each flight's departure. However, many flight planning systems are capable of running a forward flight plan for an airborne flight if the dispatcher requests it (i.e., generating a flight plan from an aircraft's present position to the destination). The updated flight plan includes updated fuel burn and time of arrival estimates along the route.

For a SATM operation, the forward flight plan functionality will be used by the dispatcher to assess the impacts of trajectories proposed in a TOS. If a TOS request is received via ACARS, the dispatcher must copy and paste the requested route into the flight planning system (the flight monitoring system and flight planning system are generally not well integrated) to create the new plan and asses its fuel and time impact. It is proposed that the new TOS application discussed in Section 5.3.1 would have the connectivity to perform this function automatically, inform other airline systems of the outcome, and transmit the TOS to the TFMS at the ATC Center.

5.3.3 Weather and Traffic System

Nearly all weather sensing comes from government owned systems and processed weather products may be accessed publicly. Additionally, airspace traffic information is accessible publicly through web-based applications. However, most airlines have contracts with private data service providers that tailor their products to the airlines' specific needs. For example, WSI Fusion is a subscription service combining many weather products with the Aircraft Situation Display (ASD) feed from the FAA. This application displays all airborne traffic along with the weather on a common map display, providing a high degree of situational awareness for dispatchers for real time conditions. However, many of these systems do not permit viewing projected and forecast future conditions at varying time horizons (several do for weather, but not for traffic conditions), and few of them provide data to other systems to allow en route flight path optimization. Furthermore, typical dispatcher workload does not permit much time for assessing future opportunities for savings on individual flights. Since the dispatcher does not necessarily have the automation tools, or time available, to perform per-flight optimization, the SATM concept allocates that role to the flight crew and flight deck automation.

5.3.4 Collaborative Decision Making System

Dispatcher communications with pilots, other operational centers within the company, and the ANSP have traditionally occur via phone calls and radio calls on ARINC frequencies. Communication displays at the dispatcher workstation typically still contain equipment for working in this way, but an increasing amount of messaging is performed digitally using other software applications. For example, all airline messages sent to TFMS currently go through a subscription-based private secure service of ARINC called CDM Net using a custom-built user interface. These messages include flight plans and swap messages sent during ground or airspace delay programs, among others, including TOS messages.

Additionally, there are allowances in the SWIM standard to permit transmitting these messages through a subscription-based private secure SWIM channel. This is the FAA's preferred method for receiving airborne TOS messages, subsequently to be routed from TFMS through ABRR to ERAM. Airlines communicating TOS messages this way must apply for the SWIM services they wish to access and be thoroughly vetted for cybersecurity protection before being granted access. As a result, the use of this channel by airlines has been slow in implementation, but is critical to achieve the full airborne TOS capability required for SATM to work through the dispatch channel.

5.4 Air Navigation Service Provider Systems

The last set of equipment discussed are the systems located within ANSP facilities that create an environment to conduct SATM operations. This section presents FAA automation equipment used during a SATM operation, connections between the automation platforms that enable the SATM concept, and new connections that must be established to realize the concept.

5.4.1 Traffic Flow Management System

The TFMS automation platform is a NAS-wide system for planning and implementing strategic and tactical traffic management initiatives to mitigate demand/capacity imbalances. TFMS is operational in all Center facilities, and provides a variety of flight and flow information, including flight-plan data, departure and arrival times, flight cancellations, flow-constraint areas or flow-evaluation areas, ground stops, and strategic playbook reroutes [14].

TFMS facilitates CDM through its Collaborative Trajectory Options Program (CTOP) functionality, which is a strategic flow management tool that uses both ground delay and reroute capability to solve a constrained resource problem (i.e., demand for a runway exceeds the capacity). A significant benefit of a CTOP is its ability to incorporate a TOS instead of the unilateral application of a single flight plan. Each trajectory option is accompanied by a Relative Trajectory Cost (RTC), which expresses the preferences of flight operators for assigned delay that they would take in the current flight plan before triggering an alternate route [36]. A TOS is typically used only in conjunction with a CTOP; however, there is a planned capability for an operator of a flight (nominally the AOC) to submit a TOS for an airborne flight into TFMS in the absence of a CTOP [37].

The SATM concept makes extensive use of TFMS capabilities, namely the ability to submit a TOS generated by flight deck automation to TFMS via existing and/or new communication channels. Once a TOS has been submitted to TFMS, it is presented to a traffic manager at a Center facility, who reviews it on the RAD. The Traffic Manager does not receive any notification that a new TOS has been submitted for a given aircraft; however, if a flight is affected by a CTOP, the Traffic Manager will generally review the RAD as part of their normal duties to see if the operator has filed a TOS. The SATM proposal includes a new software application in TFMS to automatically check the acceptability of received trajectory change requests and forward the acceptable ones to ERAM. Once the Traffic Manager chooses to implement one of the acceptable TOS options, he or she can use TFMS functionality in the RAD to deliver the updated flight plan to the radar controller. The ABRR capability for en route trajectory modifications sends the trajectory option chosen for implementation directly from TFMS to the radar controller's ERAM computer [12, 13]. Once the active sector radar controller receives the updated flight plan, he or she will review it and issue a route clearance to the affected aircraft.

5.4.2 Time-Based Flow Management

The TBFM automation platform enables routine time-based merging, spacing, and metering operations for aircraft departing from and arriving to congested airspace and airports [29]. TBFM is operational in all Center and major TRACON facilities; however, it is not yet routinely used by the TMU and radar controllers. It provides scheduled times of arrival at select waypoints for each aircraft being metered, and those times may be expressed as a constraint on that aircraft's trajectory. The capabilities of TBFM are expected to improve the efficiency of the NAS by increasing predictability and improving the use of the existing system capacity [14].

In the SATM Concept, the TBFM automation will provide traffic flow management constraints, expressed as time of arrival control instructions (e.g., RTA), to the SATM technology on the flight deck, the TFMS automation platform, or both systems. TBFM is connected to the TFMS platform through SWIM [38], and the two automation platforms share data.

5.4.3 En Route Automation Modernization

The ERAM system is the core automation platform of the ANSP. ERAM processes flight and surveillance data, provides communications and generates display data to radar controllers. The ERAM system is installed at all 20 Center facilities, and is connected to automation at all major TRACONs and Air Traffic Control Tower facilities, as well as the Air Traffic Control System Command Center. ERAM allows controllers to share and coordinate information seamlessly between Center facilities. ERAM improves flight plan processing and enables automatic transitions between sectors and Centers, even when aircraft divert from their planned course [39].

In the SATM Concept, ERAM serves as the radar controller's interface to provide command and control instructions to the SATM technology-equipped aircraft. The ABRR capability in TFMS allows a selected trajectory modification from a TOS to be sent directly to the active sector radar controller who is responsible for the aircraft that is affected by the modification. The controller is notified that a trajectory modification is present for that aircraft via a symbol on the controller's traffic display. This notification persists within a Center facility, meaning that if the controller who originally receives the request from TFMS cannot provide the trajectory modification instruction in a timely manner, the controller in the next downstream sector in that Center also receives the trajectory modification notification. A conflict detection capability within ERAM provides the controller with automation that assists in reviewing the safety of the proposed trajectory modification. The active sector radar controller will use another ERAM capability, Data Comm, to deliver the trajectory modification clearance to the flight deck. Finally, the active sector controller will update the aircraft's flight plan within ERAM based on the trajectory modification clearance.

5.5 Communication Infrastructure

This section discusses communication infrastructure used to enable the SATM concept. Each communication channel's applicability and use case for SATM operations is discussed, and recommendations for additional channels or authorizations are presented. Common concerns for each of these communication mechanisms include the latency, reliability, availability, bandwidth, and security of the link. Each of these factors must be investigated for each link used in an implemented SATM system.

5.5.1 In-Flight Internet

Historically, the aviation industry relied on government entities to provide the communication infrastructure to support all aviation operations. Today, airlines provide their passengers with internet connectivity through third party service providers, similar to an internet service provider on the ground. In recent years, processing and storage capabilities located on the aircraft have augmented traditional in-flight networking avionics, and created an ecosystem for "connected aviation" [2]. The Basic TASAR concept was a pioneer application of connected aviation. For the first time, on-board avionics data were fused with ground-based data obtained via in-flight internet.

The SATM concept is expected to extend the concept of air-ground data fusion and provide an increased amount of data to the flight deck for the SATM technology to consider when generating a TOS or route modification recommendation. Furthermore, air-ground integration and coordination between the flight deck and AOC (such as the Multi-Agent Air-Ground Integrated Coordination concept presented in [21]) may permit a low-latency, high-bandwidth mechanism to obtain operator consensus for a TOS prior to submitting it to TFMS for implementation consideration. No modifications to the in-flight internet system are required to enable the SATM concept; however, new internet-based connections may be required to augment point-to-point communication between flight deck and AOC automation platforms.

5.5.2 System-Wide Information Management

The SWIM system is the digital data-sharing backbone of NextGen with infrastructure that enables Air Traffic Management-related information sharing among diverse qualified systems. In the past, connecting two ANSP automation systems required a fixed network connection and custom, point-to-point, application-level data interfaces. The FAA identified a need to reduce the high degree of interdependence among systems and move away from the proliferation of unique, point-to-point application interfaces; therefore, the SWIM system sets forth a standard for information sharing in the NAS that provides users with relevant and commonly understandable information [40]. SWIM is also capable of accepting user information for input to NAS automation systems and serves as the pathway for SATM-generated change requests into ANSP automation.

For the SATM concept, SWIM provides a rich data set to use in the SATM technology optimization. No modifications to SWIM standards are required to enable the SATM concept. The SATM technology can receive information from ANSP automation platforms (e.g., TFMS, TBFM, ERAM) via SWIM from two mechanisms – either through the Ground Data Server discussed in Section 5.2.2 or through Aircraft Access to SWIM [20]. These data from SWIM may provide the SATM technology with situation awareness regarding air traffic operations and weather. Furthermore, the SWIM communication mechanism may be used to submit a TOS from the AOC or the aircraft to TFMS.

5.5.3 Aircraft Communication Addressing and Reporting System

ACARS is a legacy air-to-ground data communication mechanism that exchanges information between aircraft and their operators (e.g., the AOC) through a third-party service provider. Typical air-to-ground transmissions include requests for weather/winds updates, requests for terminal conditions, requests for clearances or flight plan amendments, automated position reports, and text messaging. Ground-to-air traffic may include pre-departure flight clearances, flight plan information, connecting flight information, text messaging, regularly scheduled weather updates, and responses to any requests that may have originated onboard the aircraft [41].

For the SATM concept, ACARS may be used to send a given TOS from the SATM avionics on the flight deck to AOC automation. This communication mechanism is used today to permit the flight crew to send a trajectory modification to the AOC for review by, and to obtain concurrence from, a dispatcher. It is assumed that no modifications to ACARS are required because of the SATM concept. This assumption should be verified as the SATM concept is implemented.

5.5.4 Collaborative Decision Making Network

The CDM Network (CDM Net) refers to the communications network that links the AOC, Centers, the ATCSCC, and the TFMS automation [42]. The CDM Net capability allows for two-way data exchange of real-time information enabling the distribution of Aircraft Situation Display to Industry data as well as the timely transmission of CDM information and time-critical operational activities. The CDM Net also supports data exchange for delay programs, traffic flow management data, and collaborative rerouting (i.e., TOS) data.

For the SATM concept, CDM Net serves as a potential mechanism to submit a TOS from the AOC to TFMS for airborne flights. This is currently only available on the ground, so a modification to CDM Net is required to enable the SATM concept to use this communication mechanism.

5.5.5 Digital Data Communications

Data Comm is a component of NextGen. Many modern commercial transport aircraft are currently equipped with the avionics necessary to perform Data Comm. However, the FAA's ground portion of Data Comm is being implemented in stepwise fashion, with the only completed step currently being an application in airport control towers, known as the Tower Data Link System, which provides pre-departure clearance information to the flight deck via Data Comm [27, 28]. Initial En Route Data Comm Services were operational in two Air Route Traffic Control Centers in early 2020 and are scheduled to be operational in all Centers by June of 2021 [27, 43]. In this initial phase, the only change request messages the FAA ground system can accept from aircraft are for an altitude change or a "direct" to a downstream waypoint on the active route [44]. However, Full En Route Data Comm Services, scheduled to be available throughout the NAS in 2023 [27], permits a number of change request messages of greater complexity [28, 45]. Data messages used in SATM will be fully compliant with existing domestic and international standards.

6. Notional Operational Procedures

Due to the potential for a highly connected technology ecosystem such as the one presented in Figure 6, a number of operational procedures may enable the SATM concept. This section discusses three example sets of operational procedures that implement the SATM concept, with a gradual increase in the use of automation for decision processes. Increased automation will allow rapid execution of the request, ultimately allowing many more requests to be made in a given period. In any of the three examples, the pilot may always make a direct TASAR request using Voice Comm or Data Comm, which will force human action to evaluate and approve the request.

Figure 10 highlights the basic flow of information, which is common to all operational procedures discussed in this section. In basic terms, the information flows from the SATM technology on the flight deck to the ANSP, with checks for acceptability along the way. The aircraft will need access to multiple data sources that provide enough information to develop a TOS that has a high probability of acceptance by the ANSP. These data sources are shared among all automation platforms in the system, such that a common operational understanding is attained. This trajectory may be sent to the AOC for review, acceptance, and packaging in the correct format before it is transmitted to the TFMS. It is envisioned that once the aircraft has a direct link into TFMS via SWIM and enough data sources that an additional check is no longer required, the AOC approval step could be eliminated and the TOS request is entered directly into the TFMS by the SATM technology onboard the aircraft. Any re-clearance would still be provided to the AOC for information to be distributed throughout the airline.

Once the TOS arrives in TFMS, a traffic manager will evaluate the request for their reasonableness and may choose to select a trajectory in the TOS for implementation. The selected trajectory will be sent to the active sector controller using the TFMS ABRR capability. The active sector controller will confirm that the new route does not cause any conflicts in the sector, and will send the new clearance to the aircraft. At any time in this process prior to sending the new clearance, the trajectory may be rejected by any of the agencies and a denied or unable message sent back to the aircraft. All evaluation and decision-making processes described in this paragraph may be performed by human action or gradually replaced by automation as described in the following sub-sections and the flowcharts in Appendices A, B, and C.

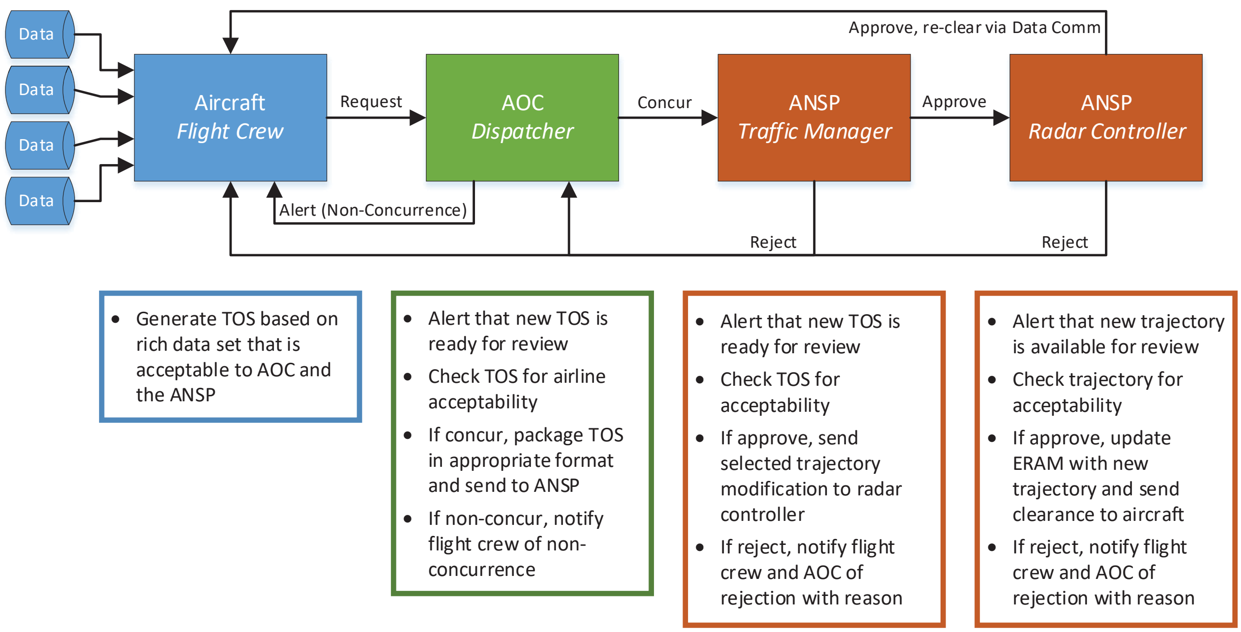

Figure 10: Basic Information Flow for a SATM Operation

6.1 SATM Operational Procedures, Example 1

In the first example implementation, described using the flowchart (Figure 11) in Appendix A, the flight crew will receive a set of trajectory modification recommendations from the SATM technology that may include more than one optimized flight path. If the flight crew desires to implement any of these modifications, and they are acceptable to the crew, they will submit the request into the system. The SATM technology will format the trajectory requests as a TOS and assign a RTC to each trajectory contained in the TOS[6]. The RTC provides a ranking of desirability of the trajectories by the flight crew. This TOS is then sent to the AOC via ACARS or a secure internet connection.

The airline dispatcher at the AOC will be alerted that a TOS is available from the aircraft, and will review it for acceptability. If the dispatcher concurs with the TOS, it will be submitted into TFMS via the CDM Net or SWIM. If the dispatcher does not agree with the proposed trajectory modifications, the aircraft would be contacted, and further clarification would be discussed.

Once the TOS is submitted into TFMS, it would appear as an option in the RAD. The traffic manager receives an alert that a route change request has been received via TOS. The traffic manager uses the RAD to check whether the request can be approved. If so, the route with the lowest RTC that is acceptable is selected. The Traffic Manager changes the active route for the flight in the TFMS and uses the ABRR capability to send the updated flight plan to the ERAM automation in each affected Center and to the radar controller actively working the flight. The radar controller evaluates the new routing and either accepts it as is, accepts it with modifications that meet the current airspace environment, or rejects it due to safety concerns. If accepted by the radar controller, the updated flight path clearance is sent from the controller to the aircraft via Data Comm. The flight crew receives the new routing, and loads it into the FMS for review. If the routing is acceptable, the flight crew confirms acceptance of the new routing via Data Comm and executes it in the FMS. If the routing is unacceptable, the flight crew will reject the routing with reasons submitted back to the controller via Data Comm, and clear the FMS of the uploaded route.

6.2 SATM Operational Procedures, Example 2

Many of the factors that the AOC and the ANSP consider when accepting a TOS have already been addressed by the SATM system onboard the aircraft using the data feeds available to it. For example, fuel, time, weather, sector loading, and assigned RTAs have already been incorporated into the requested TOS. As confidence and trust in the system grows, more of the decision making from AOC and the ANSP can be made by automation. Example 2 demonstrates an increased use of automation by replacing the human review/approval process at the AOC with an automated service.

In this example implementation, described using the flowchart (Figure 12) in Appendix B, the flight crew receives a set of trajectory modification recommendations from the SATM technology. Like Example 1, the flight crew uses the SATM technology to submit a formatted TOS and assigned RTCs to the AOC via ACARS or a secure internet connection. This is received and reviewed automatically by automation at the AOC that has been developed to make sure that the TOS meets all company objectives and requirements. The major difference between Example 1 and Example 2 occurs at this step of the procedure—if all operational requirements are satisfied, the TOS is sent on automatically to TFMS via CDM Net without the need for human intervention. If the requirement check was not met, the TOS is not sent on and a message is sent to the aircraft to contact Dispatch.

Once the TOS is received in TFMS, automation will check the new trajectories against all restrictions required from the ANSP for compliance. If successful, the automation will pick the trajectory with the lowest RTC and send the trajectory to ERAM via ABRR. The active sector radar controller receives the new trajectory from ERAM via the TFMS ABRR capability. Unless there is an overriding safety issue, the active sector radar controller will send the requested trajectory clearance to the aircraft via Data Comm. The operational procedures immediately following transmission of trajectory clearance from the radar controller to the aircraft are identical to that in Example 1.

[6] Note: The rationale behind prioritization and selection of acceptable route change requests in a SATM-generated TOS relative to RTC is a critical research area topic for the SATM concept.

6.3 SATM Operational Procedures, Example 3

As SATM continues to use all the data sources and decision processes that the AOC and ANSP systems use, it is believed that checks on the TOS will become redundant and not necessary. As confidence in the reliability of the SATM TOS requests increases, eventually it will be accepted that any TOS request coming from SATM will be acceptable to both the AOC and the ANSP and no further checks would need to be made except for non-normal situations affecting the active sector radar controller issuing the clearance. Example 3 of the SATM Operational Procedures considers an airspace system with widespread trust in SATM TOS requests outside of off-nominal or otherwise unforeseeable situations.

In the final implementation example, described using the flowchart (Figure 13) in Appendix C, the flight crew submits the formatted and ranked TOS directly into TFMS via a SWIM link. This bypasses the AOC entirely. TFMS and ANSP automation receive the TOS and, if necessary, review it for acceptability before picking the trajectory in the TOS with the lowest RTC that meets the constraints imposed on the aircraft. ANSP automation will send the trajectory from TFMS to ERAM using the ABRR capability, and the active sector radar controller sends the new clearance to the aircraft via Data Comm. The operational procedures immediately following transmission of trajectory clearance from the radar controller to the aircraft are identical to that in Example 1. As stated earlier, anytime the flight crew feels human involvement is necessary, they can request the TOS via a TASAR request, which forces human action in the AOC and the ANSP.

7. Anticipated Benefits

Basic TASAR, Digital TASAR, and 4D TASAR are all steps in the roadmap that rely on a process of request, review, and re-clearance taking place between the pilot and the active sector radar controller. Each of the aforementioned steps along the roadmap alter the trajectory change request exchange from Voice Comm to Data Comm, and incorporate more information in the trajectory solution, decreasing the reasons for rejection.

However, human-to-human exchange and review processes still take place throughout each of the earliest, capability-enhancing steps in the ABTM roadmap. As trajectory modification requests get longer and more complex, the manual acceptability review processes may become more onerous, resulting in rejection of requests despite acceptability from an airspace and traffic standpoint. The following examples provide a reason that an “approvable” trajectory change request (based on conflict probing and system constraints) may not be approved, or at least be seriously delayed in obtaining approval:

- <u>Length and complexity of trajectory modification request.</u> The length and complexity of the request may present an impediment to timely approval. Digital TASAR permits a trajectory modification that contains many waypoints, each potentially with an altitude and/or times component. Additionally, Data Comm permits the use of Lat/Long to define a desired waypoint position. However, when spelled out in alphanumeric format, such requests appear very formidable and not easily approvable by a controller considering his or her nominal workload.

- <u>Coordination with other sectors or Center facilities.</u> When the request traverses several sectors or perhaps several Centers, the radar controller will have to coordinate with others before he or she can approve the request, even when it is “easily approvable”. This coordination task may be passed to the active sector data controller or to the TMU. Involving others, while relieving the radar controller of the workload, will likely slow down the process. Depending on the workload of those individuals, an acceptable request may still not be approved.

The SATM concept presented in this report is designed to support transition to a fully automated approval process, thereby minimizing the aforementioned factors. The SATM concept greatly increases the likelihood of approval of strategic trajectory optimization requests by the ANSP by incorporating a large quantity of operational data into the trajectory optimization process. Through an increased use of automation, it also introduces the ability of the Air Traffic Management system to process a significantly higher number of requests originating from the flight deck.

Ultimately, streamlining the approval process will cause aircraft to realize more of the cost saving benefits of the preceding TASAR concepts. The SATM concept itself does not introduce new benefit mechanisms to reduce operating costs for airspace users. Instead, the SATM concept focuses on realizing as much of the benefits of Basic, Digital, and 4D TASAR as practical. SATM monetary benefits, therefore, are directly measured by the improvement in percentage of requests approved over those using Basic, Digital, and 4D TASAR alone. It is anticipated that this improvement may be significant, and will increase proportionally to the amount of automation used in the approval process (i.e., more automation in the approval process will lead to higher monetary benefits).

An additional benefit accrues to the ANSP by relieving the workforce of the burden of manually reviewing and approving or rejecting every change request proposed by SATM. The process should become as automatic, seamless, and routine as the initial filing of flight plans is today. However, until the necessary software modifications are made in ANSP automation platforms to accept this process, a set of initial operating procedures for SATM makes route change requests as a TOS and uses TMU personnel in the approval process. This is still expected to provide a benefit through more regular approval of requests containing 4D constraints or other TFM attributes as well as gain trust in the system over the request of these through the radar controller in the active sector.

8. Issues Remaining and Next Steps

The investigation of the SATM concept, intended to extend the optimization capability of ABTM all the way to destination using a completely automated process among the responsible entities, has uncovered many issues that must be addressed to enable implementation. The issues arise because the automation systems used in each of the three controlling locations – the aircraft, the AOC and the ANSP facilities – have all been developed independently and without this intended function having been considered. However, despite the issues, the concept has been verbally supported at a high level by all stakeholder parties. This section presents research and development topics organized by location – the aircraft, the AOC and the ANSP facility.

8.1 Aircraft

Since the SATM technology has not yet been implemented, the requirements and system design have not yet been formalized. This creates an opportunity to conduct research and development to ensure that a flexible and extensible system has been designed, prototyped, and tested before major investments have been made in flight deck automation. Requirement considerations for the SATM technology include:

- NAS system status information, including combined sectors and projected sector loading as well as TFM constraints, must be available to SATM software via aircraft access to SWIM.
- Sector boundary maps, updated dynamically as changes are made, must be made available digitally for use in SATM software.

- Data on the rate of acceptance of operational trajectory change requests must be automatically recorded by airlines that have implemented Basic TASAR and Digital TASAR for use in the development of SATM air-ground machine communications.
- Logic must be developed for SATM to differentiate between trajectory change requests that should go directly to the active sector radar controller (i.e., a TASAR request) from those that should be sent through TFMS for vetting and approval (i.e., a TOS submission).
- Logic must be developed to determine if a TOS submission can be made directly to TFMS via SWIM, or if it is required to route through the AOC first via ACARS or in-flight internet.
- Research must be conducted to define the process by which the fuel and time outcomes for a given flight are converted to an RTC. Parameters that affect direct operating costs, schedule considerations, and other factors should be included in this conversion computation.

8.2 Airline Operations Center

Changes to AOC automation must be made in many disparate systems, as there is no standardization among airlines for this function. There are also numerous third party vendors involved from whom these systems have been acquired. Accordingly, it is best to state these issues as requirements that permit each airline to make necessary changes in their own systems. Requirement considerations for AOC automation include:

- AOC automation platforms must be integrated such that data can be transferred between the flight monitoring system, the flight planning system, the weather and traffic system, the CDM system, and other entities without the need for significant human intervention.
- AOC data communications infrastructure used for the SATM function must meet all ANSP automation system requirements for performance, integrity, and connectivity.
- New software must be created in the airline operational computer systems to check the validity of route change requests received from airborne aircraft and to determine their acceptability from the standpoints of fuel reserves and hazardous weather avoidance. If found acceptable, such requests should automatically be routed through CDM Net or SWIM to the TFMS automation platform and to the dispatcher having jurisdiction over that flight for updating the flight record. This software system would automatically perform a function that historically takes a significant amount of time to perform manually due to dispatcher workload.
- Standard data formats for trajectory exchanges must be agreed upon as an industry and used in all AOC automation systems that communicate either with aircraft or with the ANSP.

8.3 ANSP Facilities

Historically, changes in Center automation are implemented very slowly. Even within the traffic management function of the ANSP, the TFMS, TBFM, and TFDM automation platforms were each developed independently with their own trajectory modelers. This system design creates inconsistent predictions for the same flights within each platform that hampers efficient delivery of TFM services. Since it will take time before the SATM objective of fully automatic vetting and approval of trajectory change requests is realized, this list of issues contains both the near term, manual control needs as well as requirements to enable the end-state system. Requirement considerations for ANSP automation include:

- A software modification in TFMS must be created to provide an alert to the traffic manager when a new TOS appears in the RAD. Presently, no alert or message is given to the traffic manager in the TMU that there is a new TOS request for a given aircraft. Careful attention must be taken when designing this system, since this alert may overwhelm a human operator when several flights are making TOS submissions (or a single flight is making multiple TOS submissions frequently).

- Center TMUs must be briefed and trained on their new responsibility to review and approve flight plan change requests from airborne flights or their airline's AOC generated by SATM. Manual evaluation of a TOS may require a full-time "on scope" position (i.e., a dedicated position to evaluate TOS submissions), which would require a significant culture change to implement.
- The approval function for en route trajectory modifications must be automated. Once there are many aircraft making trajectory change requests through TFMS, the burden on the traffic manager will become too great to be handled in a manual fashion. Furthermore, because the SATM technology in its end-state implementation will have access to all ANSP system status information, including traffic, weather constraints, and TMIs, there is a high probability of acceptance of the TOS as submitted.
- The ANSP trajectory approving automation must be created to validate trajectory change requests comparing them to active constraints in the system, including severe weather re-routes and TMIs. If found acceptable, this trajectory approving software will route the TOS as a route change through ABRR to ERAM for dissemination to the controller and all downstream sectors.
- The ANSP trajectory approving automation must be resilient to and robust against system saturation when several aircraft are making simultaneous requests (or a few aircraft are making many requests). Furthermore, the approval automation must ensure that requests are considered equitably across multiple submitters, and that multiple simultaneous submissions will be deconflicted against each other as much as practical, causing increased rejections.
- The software to approve trajectory change requests, send new routes to all downstream sectors and aircraft using direct air-ground and internal communications, must be designed and implemented with high regard for reliability, integrity, security, and availability.
- The best location for the ANSP route approving automation must be determined, whether it is in TFMS, TBFM, ERAM, or a third-party system.
- As the use of automation increases for approving trajectory modifications, ANSP personnel must be trained on the automation systems. Automated trajectory modification approval for en route flights represents a major cultural shift from today in the way Center controllers conduct operations, and it will not be an instant transformation.
- Mitigation of remaining issues with automation platforms and operational procedures will necessitate frequent meetings between NASA researchers and FAA automation and operations personnel.

9. Conclusion

Previously described improvements to the Basic TASAR airborne trajectory optimization system include the use of Data Comm to simplify the request and re-clearance process and speed/time optimization to complete the system's capability to find the best trajectory, even in the presence of constraints in the airspace. Parallel developments in ANSP automation have led to the creation of controller tools for surface, terminal, and en route air traffic management. These developments, and discussions with airline industry and FAA personnel, have highlighted the remaining impediment to realization of the Airborne Trajectory Management objective. TASAR's lack of information on system-level routing and traffic management needs could result in most full-route optimization requests being denied because of onerous coordination demands on controllers and traffic managers to approve requests that are, from an airspace standpoint, approvable routes. The Strategic Airborne Traffic Management system is designed to address that issue.

The SATM technology seeks to overcome this remaining limitation by using current traffic flow management and sector loading information to ensure compatibility in requested trajectory changes. The concept also proposes new automation routines in both AOCs and the FAA's TFMS to review and approve trajectory change requests at machine speed, making the optimum use of physically available airspace a reality without workload-intensive, manual coordination procedures. By freeing controllers from the review and coordination process, the SATM technology may communicate directly with FAA automation. This permits multiple, rapid trajectory changes to be made for hundreds of aircraft simultaneously, in response to an ever-changing flight and operational environment.

Ground and airborne automation platforms to host this new capability are already in place, and the communications pathways among them are in place and operational. The application software for the SATM technology and the AOC and TFMS route approval automation must be created through new joint development efforts. Achieving this technical capability necessitates a coordinated development process among NASA, industry, and the FAA to add these improvements to existing systems on a joint timetable. Experience in the trajectory coordination process may be gained using manual procedures in TMUs for early adopters, but the focus should be on developing an automatic capability for the review and approval process such that the SATM concept becomes ubiquitous in operations. The payoff in flight efficiency and more efficient use of ANSP facilities through this novel use of the airspace is expected to be unprecedented. This cooperative trajectory negotiation process between airborne and ground-based automation will enable continuous optimization of flights while adapting to all real world, evolving anomalous behavior of weather and NAS aviation systems.

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Appendix A. SATM Operational Procedures Flowchart, Example 1

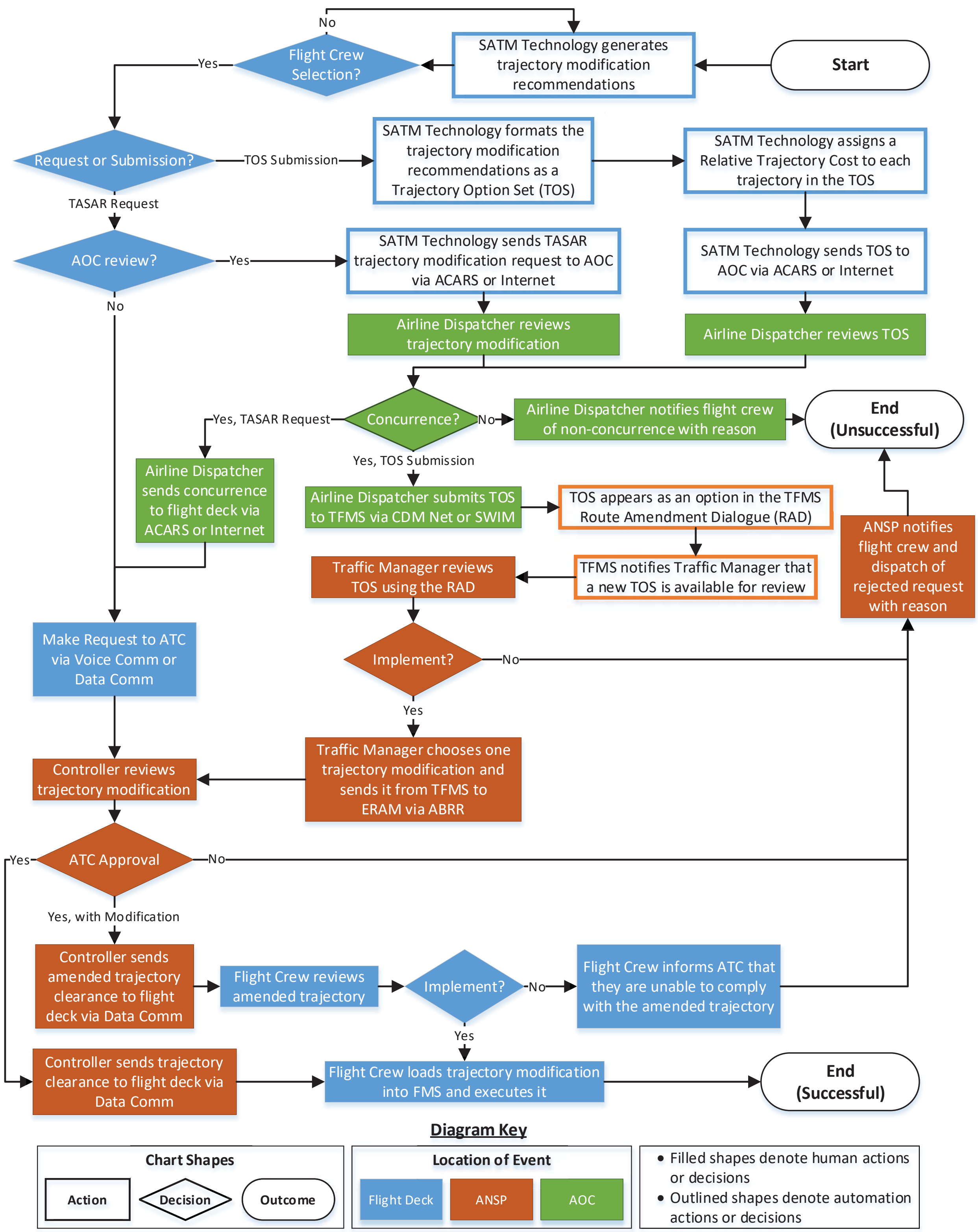

Figure 11: SATM Operational Procedures Flowchart, Example 1

Appendix B. SATM Operational Procedures Flowchart, Example 2

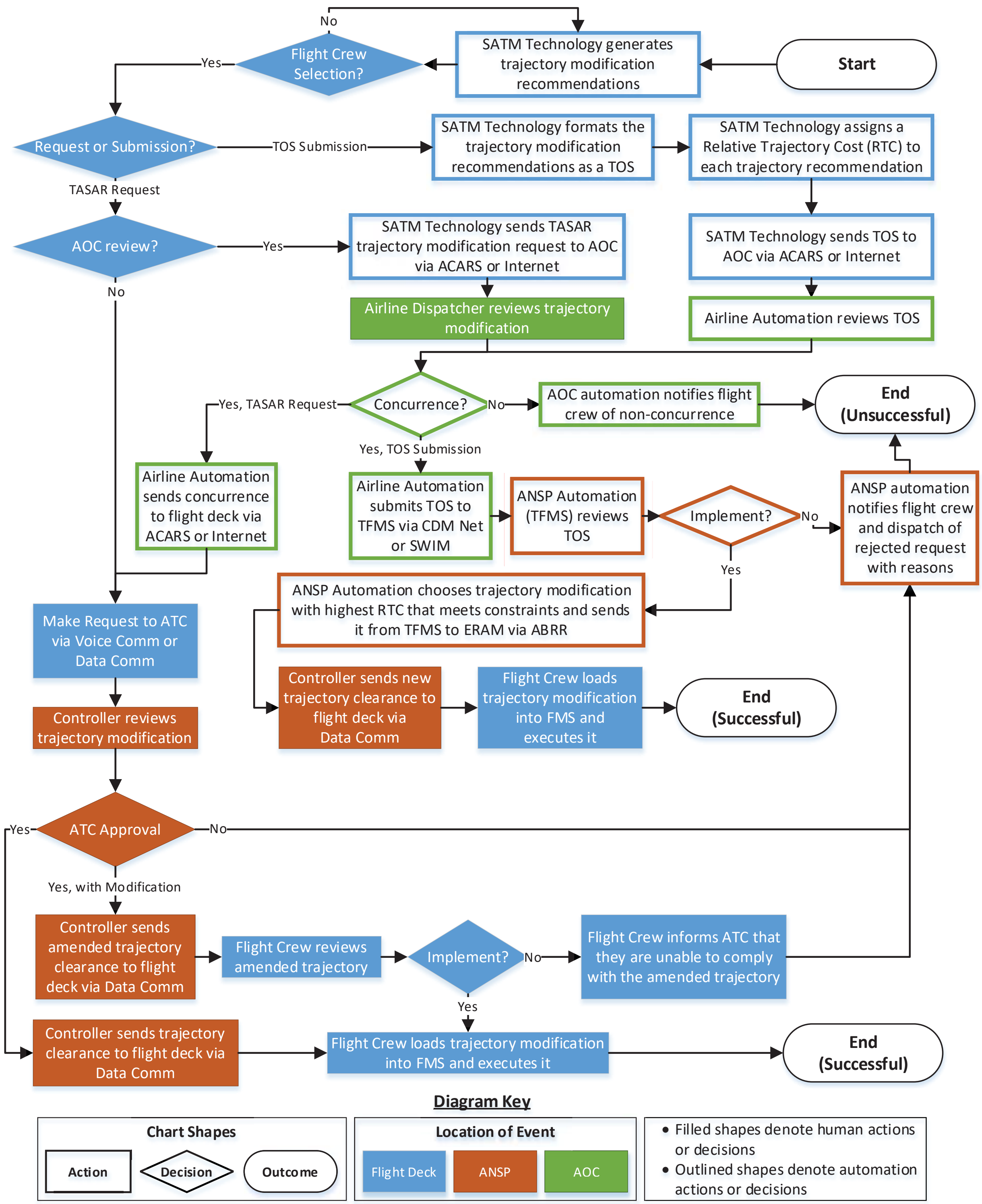

Figure 12: SATM Operational Procedures Flowchart, Example 2

Appendix C. SATM Operational Procedures Flowchart, Example 3

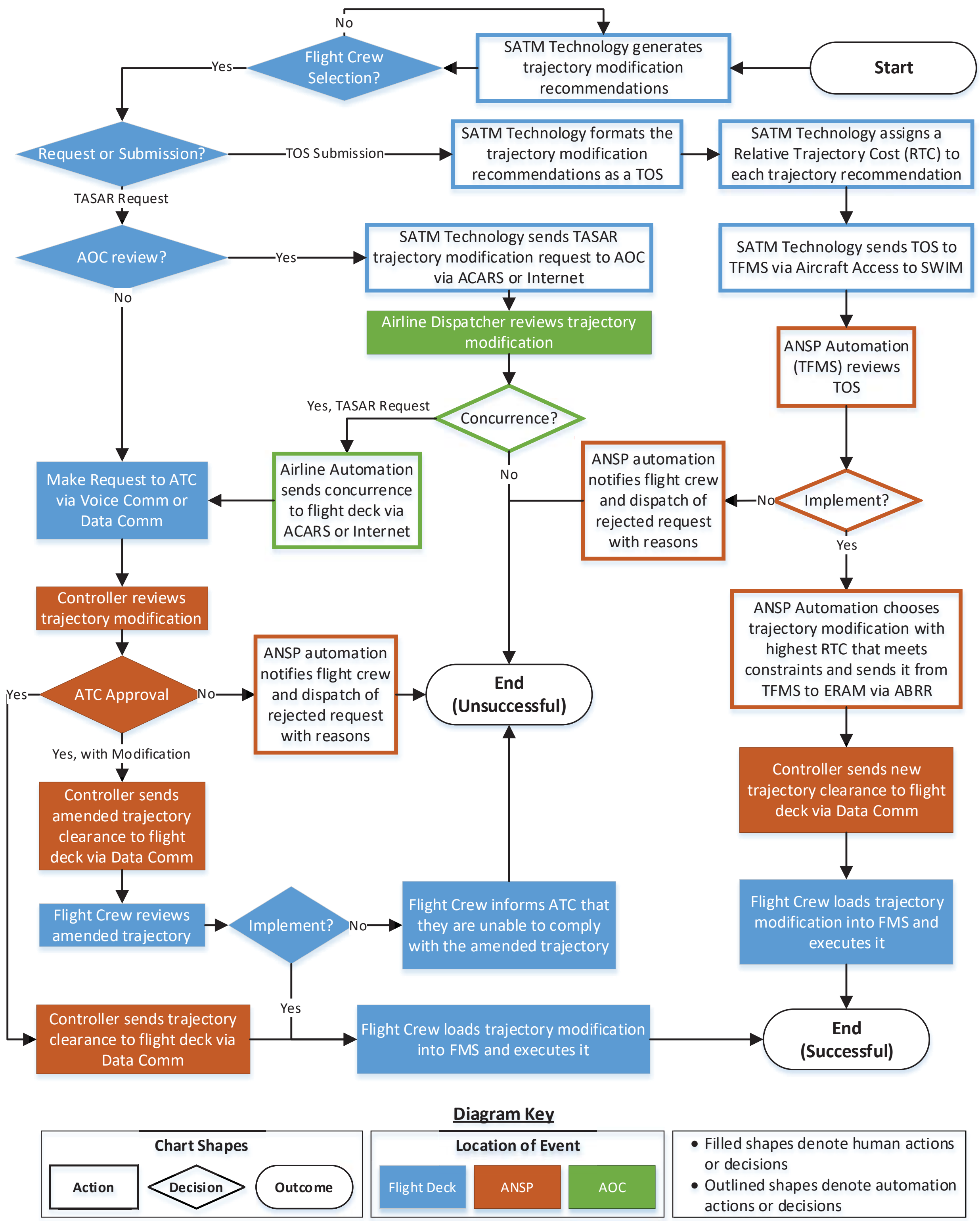

Figure 13: SATM Operational Procedures Flowchart, Example 3

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14. ABSTRACT

Flight crews often request trajectory changes from air traffic control to achieve the operator's business objectives with a more optimal trajectory. NASA's TASAR concept significantly enhances this procedure by providing flight crews with automation that recommends fuel- and time-saving trajectory modifications. The Strategic Airborne Trajectory Management concept extends TASAR, using direct automation-to-automation data communications between the flight deck and the air navigation service provider to streamline the request and re-clearance process.

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