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Intelligent User-Preferred Reroutes Using Digital Data Communication

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Abstract

In flight operations in the National Airspace System, flight crews often request trajectory changes from air traffic control (ATC) using voice communications to better achieve the operator's preferred business objectives with a more optimal trajectory. The Traffic Aware Strategic Aircrew Requests (TASAR) concept developed by NASA significantly enhances this procedure by providing flight crews with automation in the flight deck that continually scans for and recommends fuel- and time-saving trajectory optimizations. The recommendations are based on a broad suite of information on the aircraft and the dynamic operating environment, thus making requests more "intelligent." To facilitate increasingly complex requests that align more closely with the optimal trajectory, and to reduce the flight crew and controller workload associated with submitting and reviewing trajectory modification requests over the radio, the proposed Digital TASAR concept makes use of emerging data communications infrastructure and associated automation to permit digital requests in a timely and efficient manner. This report describes a Digital TASAR concept of operations, the enabling technology, and the potential benefits of equipping with the capability to aircraft operators and air traffic controllers.

1. Introduction

Research into optimizing flight paths of civil transport aircraft conducted by the National Aeronautics and Space Administration (NASA) produced an operational concept known as Traffic Aware Strategic Aircrew Requests (TASAR) [1-4]. This near-term concept provides the flight crew with cockpit automation that leverages a growing number of information sources both within and external to the flight deck to make trajectory optimization recommendations[1] while enroute [5-7]. These suggestions can then be used by the flight crew to make trajectory modification requests to air traffic control (ATC) that may be more readily approved, since the requests account for information that may otherwise preclude ATC acceptance (e.g., traffic conflicts, convective weather).

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 the carriers for regular use in operations. In 2016, both Alaska Airlines and Virgin America committed to working with NASA on the venture, and after their subsequent merger, that NASA work continued with Alaska Airlines. An operational evaluation was conducted at Alaska Airlines with three TASAR-equipped B-737-900ER aircraft [8, 9]. These operational trials validated the concept and anticipated benefits [10] for TASAR, and demonstrated that a growth path existed for future applications of airborne trajectory management technology.

To enable immediate technology adoption, the "Basic TASAR" concept (i.e., TASAR as originally evaluated by Alaska Airlines) employs traditional voice communications between pilots and controllers for making trajectory modification requests and receiving the approved re-clearance to fly the requested trajectory. Thus, certain limitations were purposefully imposed on the procedures and optimization algorithms to facilitate verbal requests (e.g., keeping them short, easy to understand, and low workload for pilots and controllers). These limitations included the use of named (i.e., published) waypoints and adding at most two "off route" waypoints prior to reconnecting to the current route. Operational guidance for pilots included limiting trajectory modification requests to once per ATC sector and issuing the request when the controller's workload is low. Even with these limitations, the opportunities for using TASAR were found

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[1] TASAR automation provides recommended optimal solutions in three operating dimensions: lateral, vertical or combination lateral/vertical and provides fuel and time outcomes for each solution. It is at the flight crew's discretion to choose which solution they would like to request from ATC.

to be prevalent such that implementation of the Basic TASAR concept in the current National Airspace System (NAS) demonstrates sufficient value to support an airline business case for installation of required avionics and flight crew training.

Researchers at NASA are investigating means to relax these self-imposed limitations by expanding the TASAR concept to employ the Federal Aviation Administration (FAA) Digital Data Communications (Data Comm) capability between the aircraft and ATC for the request and re-clearance process. ATC Data Comm is a component of the Next Generation Air Transportation System (NextGen) modernization program, and the rollout of Initial Enroute Services is currently underway. Data Comm, in combination with graphical displays and user interfaces for the pilots and controllers, could provide two key enhancements to the Basic TASAR concept: lifting the limitations artificially imposed to accommodate the voice communications environment, and reducing the susceptibility to error of voice communications in the route-change request process. Simplifying the procedures of making complex requests is expected to increase the benefits obtained from Basic TASAR. The enhanced "Digital TASAR" concept and technology described in this document offers a means for TASAR users to leverage Data Comm, thereby obtaining early operating benefits of Data Comm and substantially improved operating benefits of TASAR.

2. Background

In the early 2000s, NASA began development of a concept for airborne trajectory management based on the ability of a given aircraft to manage all aspects of its trajectory autonomously without reliance on ground-based ATC. By distributing key trajectory functions to the aircraft, autonomous Airborne Trajectory Management (ABTM) intends to improve the existing capacity and scalability of the Air Traffic Management (ATM) system and to provide users with greater flexibility to manage and optimize their flights according to their individual business preferences [11-13]. As part of this research effort, NASA developed a prototype cockpit-based software tool called the Autonomous Operations Planner (AOP) [14-19]. Its purpose was to provide the trajectory management functions of conflict detection, resolution, and prevention; constraint compliance; and coordination with other vehicles. For more than a decade, AOP was refined and matured through multiple batch experiments and piloted simulations [20-25].

In 2012, NASA formulated TASAR as an innovative strategy for triggering the long-term changes needed in cockpit technology and pilot culture to achieve airborne autonomy in the NAS [1]. To accomplish these changes, TASAR applies AOP's trajectory management algorithms in a cockpit-based system for trajectory optimization. The TASAR system shifted the focus of AOP away from conflict detection and resolution towards flight path optimization[2] as a viable first step to increase the level of user autonomy in the NAS. TASAR is for advisory-only use and designed for current-day operations. The TASAR research and development activity completed in 2019, having developed the Traffic Aware Planner software (the Basic TASAR technology) to Technology Readiness Level 7[3] by testing it in airline revenue-service operations [10]. TASAR is currently undergoing commercialization by industry.

NASA recognizes that further research must be conducted to achieve the full benefits of ABTM, which enables a greater level of operational autonomy (i.e., more allowances for user preferences) in flight operations for all airspace user classes [26]. Cotton, et al., describe a practical roadmap consisting of five steps to achieve airborne operational autonomy:

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[2] Note: Even though the focus of TASAR shifted from conflict detection and resolution to flight path optimization, the trajectory modification recommendations provided by TASAR are de-conflicted from known airspace hazards, including traffic.

[3] Note: Technology Readiness Level is a NASA-developed scale ranging from 1 to 9 used to measure the maturity of a technology. The definition of TRL 7 is a system prototype demonstration in an operational environment, meaning that a high-fidelity prototype or engineering unit that adequately addresses all critical scaling issues is built and functions in the actual operational environment and platform [44].

1) Basic TASAR. Uses automation to compute optimized lateral and vertical trajectory change requests via voice exchange between pilots and controllers.
2) Digital TASAR. Replaces the voice exchange of the trajectory request and re-clearance of Basic TASAR with Data Comm in order to permit the use of more flexible, complex, and lengthier trajectory definitions for greater savings; facilitates simpler request procedures by reducing pilot and controller workload, as well as frequency congestion; and eliminates sources of error and misunderstanding.
3) Four-dimensional (4D) TASAR. Extends the optimization dimensions of Basic and Digital TASAR to include the speed/time dimension[4] to consider time-of-arrival clearances in optimization routine.
4) Strategic Airborne Trajectory Management. Integrates the Digital and 4D TASAR capabilities with ATC automation to provide user authority to update the strategic trajectory in downstream ATC control sectors.
5) 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 ATC approval.

TASAR is enabled in part by the emergence of the “connected aircraft” [27], an industry-led initiative in which systems onboard and off the aircraft are digitally connected to each other, enabling substantial flows of information. However, the initial implementation of TASAR (i.e. Basic TASAR) was developed prior to the implementation of digital connectivity between pilots and ATC. This imposed certain necessary limitations on the software’s trajectory optimization algorithms to ensure the solutions could be requested of ATC by voice. Basic TASAR therefore represents a starting point on a roadmap of applications that mature as connectivity expands to include communications between pilots and ATC. The second application on this roadmap is Digital TASAR, the subject of this report.

2.1 Basic TASAR

The purpose of Basic TASAR is to advise the flight crew of potential modifications of the aircraft’s trajectory to best achieve the airline’s specific business model. By avoiding airspace hazards such as traffic and weather, and conforming to known airspace constraints, Basic TASAR should result in greater approvability of requests by ATC and therefore increased benefits than without the technology. The NASA prototype implementation of the Basic TASAR concept uses a powerful trajectory optimization tool called the pattern-based genetic algorithm (PBGA) [28] 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 should have a greater likelihood of being approved by ATC when requested by the pilot. The software is controlled through an interface on a tablet-based Electronic Flight Bag (EFB) platform and connected through an Aircraft Interface Device to on-board avionics and to in-flight connectivity systems for external data.

The Basic TASAR concept is predicated on there being enough ATC flexibility in the enroute 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 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 flight time, fuel burn, or total cost of the flight in accordance with the business model of the airline. Which one of these three

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[4] Note: This functionality may be best used in conjunction with Digital TASAR.

optimization objectives is used at any given time 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. The technology has two modes of operation—automatic mode and manual mode. Automatic mode requires little flight crew interaction. The flight crew configures the technology at start-up (e.g., setting the optimization objective) and the software periodically probes for opportunities to optimize the current trajectory [2]. Trajectory optimization solutions are presented to the flight crew, along with their fuel/time outcomes, and are updated regularly. Manual mode requires a more active role by the flight crew. If the flight crew identifies a need or desire to modify the current trajectory, they enter a desired trajectory modification into the software interface, and it probes the desired change for conflicts with known hazards and constraints, and displays the fuel/time outcomes to the flight crew.

In either automatic or manual mode, once a trajectory modification is deemed acceptable by the flight crew, they use existing voice procedures to make the trajectory change request. When a request to ATC is made, no reference to TASAR capability is required, since no special consideration by ATC is being requested. The pilot proceeds in accordance with ATC’s response [2].

2.2 Digital TASAR

Voice communications with ATC limit the complexity of trajectory changes that can be practically communicated between pilots and controllers. Most ad hoc requests made in the absence of Basic TASAR 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 readback/hear back issues or data input on airborne and ground systems. Basic TASAR imposed artificial constraints on generated solutions to facilitate unambiguous and efficient voice communications with ATC.

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 replaces the voice mechanism for the flight crew requesting the trajectory modification and the response by ATC. There is no change in roles and responsibilities for trajectory-change authority or separation of aircraft in Digital TASAR, which enables the certification and operational approval requirements to remain similar to Basic TASAR.

The transition from voice communication to Data Comm has implications on the nature of the change requests and the efficiency of the flight. By using Data Comm, coupled with possible software improvements in the aircraft’s Flight Management System (FMS) and the ATC Center Enroute Automation Modernization (ERAM) software, increasingly complex trajectory modification requests may be permitted. Digital TASAR trajectory change requests can contain multiple new waypoints, and the waypoints may be named, coded, or defined by latitude/longitude coordinates rather than being restricted to only named waypoints. Since the change requests will be complex, the controller will be more reliant on automation to perform conflict probing and a graphical display of the modified trajectory to assess the requested change obtained via Data Comm. The increased use of automation should greatly simplify the process of request and approval, making it more likely that approved trajectory modifications will occur on a more frequent basis and in busier airspace than would otherwise occur.

Furthermore, the use of Data Comm is foreseen to eliminate errors and misunderstanding between pilots and controllers. Throughout this entire process of trajectory generation, assessment, communication, approval, re-clearance and execution in the aircraft FMS, there is no manual entry of route descriptions and therefore, no opportunity for introducing error into the process through that mechanism.

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 [29, 30]. Initial Enroute Data Comm Services were operational in two enroute Air Route Traffic Control Centers in early 2020 and are scheduled to be operational in all Centers by June of 2021 [29, 31]. 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 [32]. However, full Enroute Data Comm Services, scheduled to be available for the NAS in 2023 [29], permit a number of change request messages of greater complexity [30, 33]. Data messages used in Digital TASAR will be fully compliant with existing domestic and international standards, but there must also be graphical interfaces displaying the proposed and re-cleared trajectories for both the pilots and controllers. Such displays are already in place, but there must be a certified translation from the digital to graphical formats in place for process integrity.

Digital TASAR also permits digital data exchange between the flight deck and the Airline Operations Center (AOC) beyond current capabilities of Aircraft Communications Addressing and Reporting System (ACARS) data communications. Aspects of the airline operation regarding airport resources, crew resources, and connection information can all be incorporated into a more advanced set of optimization objectives for use in the Digital TASAR technology[5]. This link could also be used to provide trajectory change concurrence from an airline dispatcher on a TASAR proposed routing that is sufficiently altered to require dispatch review[6]. A detailed treatment of these aspects of air/ground digital data communications for flight and airline efficiency is beyond the scope of this report. However, NASA created a candidate concept of operations for Multi-Agent Air/Ground Integrated Coordination between flight deck and dispatch technologies for trajectory optimization that explores this facet of Digital TASAR in more depth [34].

3. Use Cases for Employing Data Comm in Trajectory Optimization

This section provides use case scenarios that demonstrate the multi-faceted benefits of Digital TASAR operations. Five operational scenarios are presented that each highlight different practical applications and benefits of the Digital TASAR concept.

3.1 Scenario 1: Wind-Conformal Time-Saving Trajectory Optimization

A Digital TASAR-equipped aircraft has just departed Seattle heading to Atlanta (KATL). The flight left the gate 12 minutes late due to a required maintenance repair prior to departure. Wind conditions dictated takeoff to the north, which resulted in the aircraft spending more time on the departure procedure heading north and not proceeding towards KATL. The AOC determines that even though the flight is estimated to arrive late, 85 percent of connecting passengers in KATL will still have adequate time to make their connections and the rest can make other connecting flights within three hours. The aircraft turnaround time is not an issue due to its scheduled time on the ground being adequate to absorb the delay, but the pilots' scheduled next leg to Florida in a different aircraft would depart late due to their minimum turnaround time. The cost consequence of the second late departure is considered, and a new flight-optimization objective

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[5] Throughout the remainder of the report, the term "Digital TASAR technology" will be used to describe the flight-deck automation system that implements the Digital TASAR concept. This technology will leverage, and build upon, capabilities demonstrated in the Traffic Aware Planner, but will feature enhancements and design changes that distinguish it as a new capability.

[6] Based on consultations with dispatcher and flight crew subject matter experts, AOC concurrence is typically required if any of the following criteria are met:

a) the lateral path modification is greater than 100nmi from the active route
b) the vertical modification has an altitude deviation of more than 4,000 feet from the planned cruise altitude
c) the flight arrives 15 minutes earlier or later than the planned arrival time

for the Digital TASAR technology is provided to the dispatcher to be sent to the Atlanta-bound flight changing it from minimizing trip cost (i.e. flight operating cost balancing time and fuel) to minimum flight time. The dispatcher at the AOC sends the new objective to the flight crew along with a higher cost index to be used in the FMS and the Digital TASAR technology in an effort to reduce the flight delay. The crew enters the new parameters into the Digital TASAR technology.

Nearing the top of climb, the crew sees that the tool has found a new solution based on an updated wind forecast that places the jet stream slightly south of the location used by the dispatcher's flight planning software two hours before departure. The recommended trajectory adds six miles over the ground but results in 35 fewer wind miles, due to a higher tailwind component. The Digital TASAR display indicates five-minute savings without requiring any change in speed. Seeing the advantage of the change, the pilot presses the "request to ATC" button on the Digital TASAR technology interface. The trajectory change request is routed to Seattle Center as a Data Comm route request message. The new trajectory is displayed to the controller as an overlay to the existing cleared route and the ERAM analysis of the proposed change confirms that there will be no traffic conflict within the established time horizon. The controller accepts the request and sends the Data Comm message "cleared as requested" back to the flight. This message is received in the cockpit, automatically checked for authenticity, and loaded into the FMS as the new cleared route. This trajectory modification satisfies the greater objectives of the airline without having to burn any additional fuel beyond the original plan before the delay occurred.

3.2 Scenario 2: Trajectory Optimization that Joins New Arrival Procedure

A flight from Newark to Phoenix (KPHX) has just crossed the Ohio River. The flight crew begins to see a broken line of thunderstorms ahead on the airborne weather radar. An area of scattered convective activity had been forecast before the flight departed, so additional fuel for possible weather deviations was added. As the aircraft reaches 60 nautical miles from the weather, the pilots determine a 20 degree left turn will keep the aircraft clear of the weather in accordance with company policy and minimize turbulence. The flight crew requests this deviation from the planned route and air traffic control approves it. Shortly after the aircraft is established on the vector, more weather is observed on the airborne radar that requires the pilots to continue on the new heading for an additional 20 minutes[7].

The aircraft is instructed to proceed direct to EAGUL, a fix on an arrival procedure into KPHX, once clear of the weather. As the aircraft emerges from the weather, the Digital TASAR technology computes a trajectory modification to the right of the direct route, closer to the original route that was filed because of the stronger headwind to the south. This change rejoins the flight plan on the same arrival route, but comes in from Gallup (GUP), a different transition fix located north of EAGUL. Information obtained by the Digital TASAR technology regarding arrival sector loading from the FAA's Time-Based Flow Management (TBFM) technology shows that this trajectory modification will not overload the northern fix[8]. Seeing that 6 minutes 30 seconds can be saved on the northern trajectory to GUP, the crew requests this change from ATC with a route change Controller-Pilot Data Link Communication (CPDLC) Data Comm message. ERAM confirms the availability of the requested trajectory and the controller approves it with a re-clearance message back to the airplane's FMS. The new route is executed in the FMS and the flight is able to save both time and fuel. The Digital TASAR technology notifies the AOC that the aircraft has been cleared for an updated trajectory. The dispatcher (or automation) at the AOC updates the arrival time and fuel for that flight.

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[7] Note: While flight crews have access to weather data obtained from ground-based radar sources, they are often not permitted to make tactical decisions using this information since the update rate of ground-based weather products is not sufficient for real-time decisions.

[8] Note: Digital TASAR access to TBFM information via airborne SWIM (a promised capability) is assumed in this scenario. This data is not required. However, it would increase the likelihood of ATC acceptance of this type of trajectory optimization request.

3.3 Scenario 3: Trajectory Optimization Considering Arrival Fix Balancing

A flight from Cleveland to San Francisco (KSFO) has just entered the Denver Center airspace when ATC issues a traffic advisory message about increased traffic volume arriving at KSFO. Due to arrival fix congestion, the advisory requires that some aircraft be re-routed to arrive over the less congested Point Reyes arrival fix rather than the usual Modesto Arrival. A route change message is sent from ATC to the flight via CPDLC that maintains the aircraft's current trajectory until well into the Oakland Center's airspace, where it diverges sharply to the right to arrive into KSFO from the north. The change is accepted by the crew and the flight continues toward KSFO. The new trajectory automatically goes to the Digital TASAR technology, which analyzes alternative routings and comes up with a solution more direct to the airport. The crew anticipates this routing will not be approved by ATC due to flow constraints so they change the limit waypoint[9] to Point Reyes to ensure that fix is included in the solutions. The Digital TASAR technology then recalculates from present position to Point Reyes and finds a trajectory saving four minutes over the one sent from ATC, still meeting the "fix balancing" objective and remaining clear of traffic through the Denver Center airspace.

The trajectory is requested through CPDLC to Denver Center and forwarded to the Salt Lake and Oakland Centers. Verified by ERAM as an acceptable entry to the Standard Terminal Arrival Route (STAR) over Point Reyes, the request is approved, and the re-clearance is sent to the flight. Thus, the penalty of a commonly used ATC re-route is cut in half by allowing the Digital TASAR technology to optimize the routing to the new arrival fix required for ATC to load-balance the arrival fixes.

3.4 Scenario 4: Trajectory Optimization Considering Expected Runway Assignment

A flight from Boston to Los Angeles (KLAX) is passing through Indianapolis Center's airspace. The flight plan specifies a significantly more northerly route than usual due to traffic congestion and weather blocking a significant portion of the airspace over the central United States. However, an hour into the flight, ATC advises the aircraft via voice communication that the airspace previously being avoided due to traffic congestion and weather has just become available. ATC offers the aircraft an updated routing direct to the waypoint DNERO, a transition fix for the ANJLL Arrival into KLAX.

The crew recognizes that the suggested route cuts off much of the currently northerly route, saving air miles. They enter "direct" to DNERO into Digital TASAR using manual mode, and it calculates that they would arrive 15 minutes later and under minimum fuel. Investigating the Digital TASAR solution, the flight crew realizes that the more direct route had a stronger headwind component than the current more northerly route. Had they accepted the offer, the strong headwinds may have ultimately required a diversion for fuel. The flight crew declines the offer from ATC and continues on their original routing from the flight plan.

Later in the flight, the flight crew notices that the airport has been re-configured to an unusual wind pattern at KLAX. They see that this wind is expected to remain through their arrival period, so they update the Digital TASAR technology to expect an arrival to the opposite runway. The system returns a new optimized trajectory that goes slightly south but connects to DERBB, which is on a new STAR for that runway. The modified trajectory saves 5 minutes and costs 400 pounds of fuel. Since they are running behind schedule due to the northern routing, they request this trajectory from ATC through Digital TASAR. The request is approved, and the flight is cleared to follow the Digital TASAR plan.

3.5 Scenario 5: Cumulative Savings over Multiple Small Trajectory Optimizations

A flight from Orlando to San Francisco (KSFO) has received an optimized flight plan from its AOC that contains considerable ATC preferred routing, in other words, numerous small or moderate turns throughout the flight. The airline's flight planning software contains ATC preferred-routing constraints used when generating flight plans, and the pre-departure clearance reflects this rather inefficient routing. Throughout

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[9] Note: The limit waypoint is defined as the last waypoint on the active route that trajectory modification solutions can rejoin the active route.

the flight, Digital TASAR advises the crew of six opportunities to cut the corner of the turns in places that can be easily accommodated by radar controllers without the need for extensive inter-Center coordination, since each request is localized to the controller's sector. Each request only saves about 45 to 90 seconds. However, the cumulative effect is to save 5 minutes and 580 pounds of fuel by the time the flight arrives at KSFO. Digital TASAR, through its use of FAA Data Comm, permits flight crews to make frequent small requests during the flight, since frequency congestion and ATC workload are much less concerning compared to a voice environment for requesting, reviewing, and approving/denying requests.

4. Benefits Mechanisms of Digital TASAR

This section describes operational enhancements that will permit achieving lower flight costs and shorter flight times on flights with a Digital TASAR capability over those with Basic TASAR. To quantify the additional benefits of Digital TASAR will require fast time simulations for a large number of flights, comparing Basic TASAR solutions to Digital TASAR solutions. Human-In-the-Loop (HITL) simulations would also be valuable in determining parameters for frequency of use by pilots and acceptability to controllers that would otherwise have to be estimated for use in the fast-time simulations.

The benefits derived from the benefit mechanisms described in this section would be in addition to those provided by Basic TASAR (e.g., time and fuel savings from dynamically updated, in-flight optimization of the flight plan; early accrual of benefits as each aircraft is equipped; and reducing the number of requests that are un-approvable due to conflicts [3]).

4.1 Increased Wind Optimization

The ability of the Digital TASAR technology to create solutions that are more "wind-conforming" adds benefits beyond Basic TASAR. The improved wind conformance results from two changes to the existing optimization logic: (1) the removal of the "two off-route waypoint" limit imposed on the Basic TASAR system, and (2) the ability to use latitude/longitude coordinates for waypoint definition rather than the nearest named waypoints that may not be where the best wind solution exists. Such solutions may be described by a very large number of waypoints that conform much more closely to the actual best wind route using the most recent wind forecast.

As the equipage levels of Digital TASAR increase across airline fleets, traffic congestion on the "best wind route" is a potential issue. However, each aircraft's optimal trajectory is a unique combination of origin and destination airports, and airline business preferences. Additionally, the "best wind route" is also temporal in nature as wind patterns are constantly changing. Thus, aircraft of the same airline that have identical optimization objectives for hourly flights between the same departure and arrival airports will have different optimal trajectories. TASAR naturally separates flights to a much greater degree than flying on charted preferred routes by allowing efficient use of existing airspace capacity. Digital TASAR maximizes this benefit, as it is not constrained to use named waypoints. Section 6.1 proposes research to investigate this potential issue.

4.2 Flight Crew Procedure Simplification

Through its simplified procedures, Digital TASAR enables an increase in the frequency of pilot-initiated trajectory change requests without an equivalent workload increase, leading to increased opportunities to accrue larger time and fuel savings compared to Basic TASAR. Simpler procedures are made possible by the system architecture for Digital TASAR (described in Section 5.5) that will permit direct connectivity with the FMS. It is expected that an FMS interface will allow Digital TASAR solutions to load automatically into the FMS as a Mod Route. After viewing the time and fuel predictions from Digital TASAR for a reasonableness check, a single "Request to ATC" button push by the pilot will send the trajectory modification request as a formatted Data Comm message to the appropriate controller. The ATC response received by the aircraft is routed to the FMS and the Digital TASAR technology. If ATC does not modify the requested trajectory, the flight crew loads and executes the clearance, which completes the exchange in very little elapsed time with no manual data entry and minimal attention required by the flight crew. In short, the procedure is simpler and less error prone, thereby making it more likely to be used by the pilots, in turn increasing the likelihood of increased fuel and time savings. The magnitude of this benefit should be validated through HITL simulations of the Basic TASAR vs. Digital TASAR procedures used in the request/re-clearance process.

4.3 Controller Procedure Simplification

Controller vetting of the solutions provided by the Digital TASAR technology and providing the re-clearances to the aircraft will be simplified by making visual comparisons of the new and old routes on map displays while ERAM checks the requested route for conflicts. The lack of the data entry task will be a powerful motivator for the increased acceptance of TASAR procedures by controllers. An "OK" from the conflict alert automation makes it easy for the controller to review and approve the trajectory request and, with minimal keystroke entries in the CPDLC Data Comm message system, send the new clearance back to the requesting aircraft.

Digital TASAR also leverages Data Comm benefits—namely, the elimination of "read-back/hear-back" errors and reduction of frequency congestion. The use of Data Comm removes these inhibitors to requesting trajectory modifications recommended by the Digital TASAR technology. Additionally, while the automation is exchanging digital information, humans have shared situation awareness obtained through simple graphical representations, eliminating manual entry of route and altitude profile definitions, which is both time consuming and error prone.

5. Recommendations for Technology Implementation

Based on the use cases discussed in Section 3, this section discusses several technical recommendations for implementing the Digital TASAR concept. FAA Data Comm messages appropriate for Digital TASAR are reviewed, recommendations are made for changes to the data sources, optimization algorithm, and human-machine interface exercised in the operational evaluation of Basic TASAR, a reference system architecture is proposed, and operational procedures are presented.

5.1 Data Comm Messages Appropriate for Digital TASAR

The FAA Data Comm program supports two versions of CPDLC: The Future Air Navigation System (FANS) 1/A and the Aeronautical Telecommunications Network (ATN) Build 2 (B2). FANS 1/A is an ACARS-based implementation that provides direct data link communication between the flight crew and the controller via avionics and ground systems [30]. ATN is an internationally approved standard for an inter-network architecture allowing digital data exchange between ground, air-ground, and avionics subnetworks for the safety of air navigation and for the regular, efficient, and economic operation of ATM systems [30]. For domestic enroute operations, the FAA is planning to accommodate both FANS 1/A and ATN B2 for the initial operating capability of both Initial Enroute Data Comm Services, being implemented in 2020, and Full Enroute Data Comm Services, expected in 2023 [29].

The functionality of Digital TASAR described in this paper will be sufficiently supported by existing message sets (shown in Table 1) [30, 33]. More advanced TASAR concepts described in Section 2 (e.g., 4D TASAR) may require additional new message formats, which will be documented in separate concept papers. From left to right in the table are the Data Comm message ID, the intent of the message, message elements (variables are italicized), and the Digital TASAR use case identifying when each message could be used. All messages in Table 1 are supported by both FANS 1/A and ATN B2, except DM119 which is ATN B2 only.

Table 1: Data Comm Messages with Potential for Use in Digital TASAR Procedures

Message ID	Message Intent/Use	Message Element	Digital TASAR Use Case
DM6	Request to fly at the specified level or vertical range	REQUEST *[Level]*	• Request short-term block altitude clearance
DM9	Request for a climb to the specified level or vertical range	REQUEST CLIMB TO [*Level*]	• Request vertical solution (climb). • Facilitates short-term block altitude clearances.
DM10	Request for a descent to the specified level or vertical range	REQUEST DESCENT TO [*Level*]	• Request vertical solution (descent). • Facilitates short-term block altitude clearances.
DM11	Request for a climb/descent to the specified level or vertical range to commence at the specified position	AT [*Position*] REQUEST [*Level*]	• Request vertical solution (climb or descent) starting at a future point (named fix or latitude/longitude) in space. • Facilitates short-term block altitude clearances.
DM13	Request for a climb/descent to the specified level or vertical range to commence at the specified time	AT TIME [*Time*] REQUEST [*Level*]	• Request vertical solution (climb or descent) starting at a future time. • Facilitates short-term block altitude clearances.
DM22R	Request for a direct clearance to the specified position	REQUEST DIRECT TO [*Position*]	• Request a lateral solution if the route change is direct to a downstream fix on the active route.
DM24	Request for the specified route	REQUEST [*Route Clearance*]	• Request a lateral solution if the route has any off-route waypoints. • Request a combination lateral/vertical solution (for lateral solutions that are either direct-to or contain off-route waypoints). • Request a lateral or combination solution that contains time constraints along the active route.
DM119 {ATN B2 Only}	Request for a clearance that when the first specified position is reached, the aircraft can proceed directly to the second specified position	AT [*Position*] REQUEST DIRECT TO [*Position*]	• Request a lateral route change starting at a point on the active route in the future, if the route change is to a downstream fix on the active route.

5.2 Modifications to Existing Data Sources

The Basic TASAR technology uses several data sources to perform trajectory optimization, including static databases (e.g., navigation database), real-time on-board data sources obtained via ARINC 834 (e.g., aircraft state data, ADS-B IN traffic), and real-time off-board data sources obtained via in-flight internet (e.g., winds aloft, Special Use Airspace activation schedule, convective weather polygons, etc.). This section discusses potential changes to input data sources that would provide additional benefits for a Digital TASAR technology.

5.2.1 Higher Fidelity Wind Data

The Basic TASAR technology employed in the Alaska Airlines operational evaluation used the National Oceanic and Atmospheric Administration (NOAA) Rapid Refresh (RAP) model for its wind data source. Specifically, it used the prediction for "current" winds. Updated hourly, the gridded wind model data has a resolution and covers much of North America. NOAA also offers higher resolution products, as well as forecast data for additional epochs beyond the current winds.

Whereas Basic TASAR would not benefit as much from higher fidelity winds with faster update rates because its solutions are restricted to only two published waypoints, Digital TASAR is free of that limitation and therefore can leverage the better wind data in optimizing the aircraft's trajectory. A 13-km RAP product is available every hour at 1-hour data intervals that covers North America, and a 3-km High-Resolution Rapid Refresh (HRRR) product is available every hour at 15-minute data intervals for a 16-hour time period [35] that only covers the conterminous United States. Edwards, et al. performed an analysis of wind forecast model data for the 13-km RAP product and the 3-km HRRR product [36]. The analysis determined that both models had adequate average forecast performance for forecast short-term look ahead times of less than 6 hours (which is an appropriate forecast horizon for domestic transcontinental flights), with HRRR providing slightly better performance than RAP.

It is hypothesized that higher resolution wind files obtained at sub-hourly periods, fused to integrate current and forecast data, and modifications to the optimization algorithm to accept these wind forecast products will allow the optimization engine of a Digital TASAR technology to find increasingly wind-optimal routes.

5.2.2 Additional Terminal Navigation Procedural Data

The Basic TASAR technology uses an installed derivative of the ARINC 424 navigation database to find named fixes in the airspace when computing optimized reroutes. In a Data Comm environment, the requirement that trajectory solutions use only named fixes no longer exists. Even though the need for named waypoints is obviated, the ARINC 424 navigation database could prove beneficial for the Digital TASAR technology if additional terminal navigation procedural data (e.g., STAR data) was included in the Digital TASAR technology navigation database. For example, including the STAR information contained within the ARINC 424 database would allow the Digital TASAR technology to exercise the ability to join an arrival route different than the one currently assigned, which is permitted by Data Comm message DM24. However, in order to ensure that the correct STAR is used, the Digital TASAR technology would require information about the expected runway at the destination airport because some STARs may only be used for certain runways. This information could be obtained from the Digital Automated Terminal Information Service if the airfield is equipped to provide that service, or it could be inferred from the surface winds at the destination airport. Additionally, including information for the Standard Instrument Departures and approach procedures in the Digital TASAR technology navigation database would allow the trajectory generator in the Digital TASAR technology to make more precise and accurate predictions of fuel and time over a greater portion of the whole trajectory.

5.2.3 Air Traffic Control Operational Data

The Digital TASAR concept does not require any real-time information from ATC systems to function and produce benefits beyond the ability to receive Data Comm clearances. However, benefits may be improved by including additional data such as dynamic sector boundaries, forecasts for sector loading, arrival fix loading, and aircraft-specific arrival delay. As presented in the use cases in Section 3, access to these data permit the Digital TASAR technology to compute solutions that account for these constraints and therefore have a higher chance of being approved by ATC. Furthermore, the workload for all parties may be reduced by minimizing the number of requests that are un-approvable due to conflicts or the number of requests that may cause a flow management issue in the future. ATC data may be delivered to the aircraft via the System Wide Information Management (SWIM) system, for which the FAA envisions using in-flight internet to deliver relevant information to a flight [37].

5.3 Modifications to the Route Optimization Algorithms

The Basic TASAR concept assumes that voice communication serves as the mechanism to request reroutes. The use of voice communication does not impose any changes to current request procedures of the flight crew and controller. However, because of this operational environment assumption, the PBGA used by the prototype Basic TASAR technology was purposefully constrained from using its full potential to find optimal trajectory solutions. This section discusses proposed beneficial changes to the PBGA resulting from the shift from a voice-communication environment to one that enables the Digital TASAR concept.

5.3.1 Remove Voice-Communication Constraints

The Basic TASAR technology included the following two artificial constraints on the trajectory optimization algorithm to accommodate the voice-request environment: (1) trajectory solutions computed by the PBGA were constrained to a maximum of two off-route waypoints, and (2) all off-route waypoints were named fixes. By moving to a Data Comm operational environment, the need for these constraints is obviated.

5.3.1.1 Use of Additional Waypoints

With the switch from voice communications to Data Comm, the PBGA supporting the Digital TASAR technology can be upgraded to include geometric patterns with more than two off-route waypoints. Several implementation mechanisms exist that permit additional off-route waypoints, such as modifying the parameters of the PBGA or including additional patterns that permit additional off-route waypoints. In a Data Comm environment, the number of waypoints permitted in a route clearance request (specified in DM24) is 128 waypoints, which is typically greater than the number of waypoints in most commercial transport routes (typically 30-40 enroute waypoints that include the destination airport STAR). Data Comm provides more than enough waypoint capacity to specify highly detailed trajectory modification recommendations that yield maximum benefit. However, producing an algorithm capable of generating that detail with reasonable computations may be challenging. It is likely that nearly the same benefit can be achieved with a small subset of the message capacity (e.g., 5-10 additional waypoints), an assumption that would need to be validated through analysis.

5.3.1.2 Use of Latitude-Longitude Defined Waypoints

With respect to the second artificial constraint, a preliminary study conducted in 2013 [38] evaluated three different implementations of the PBGA to determine the impact of limiting the PBGA to named waypoints. The three versions evaluated were the current baseline version of the PBGA, a modified version of the PBGA that did not restrict the solutions to named fixes, and a third version of the PBGA that initially did not restrict the solutions to named fixes, but then forced the off-route waypoints to be at published locations. The preliminary study indicated that routes that were not restricted to named fixes generally saved more time and/or fuel than either of the other algorithms. Furthermore, the study found that the processing time was slightly better for the PBGA that did not constrain the solutions to named fixes. Thus, in a Data Comm environment, it is postulated that removing the artificial constraint of using named fixes would increase the value of the optimizations provided by a Digital TASAR technology and reduce the processing time of the PBGA.

5.3.1.3 Obviate Need for Abeam Waypoints

A secondary benefit is obtained by permitting additional waypoints in Digital TASAR solutions by obviating the need for abeam waypoints in the FMS. Pilots keep track of time and fuel performance as the flight progresses by noting the fuel on board and time as they pass each waypoint. If a trajectory modification removes many waypoints from the original route (e.g., a direct-to clearance), the flight crew may request that the dispatcher create a new flight plan that contains updated predictions of time and fuel at each waypoint, which is a time-consuming process. In lieu of requesting an updated flight plan, flight crews typically use abeam waypoints to retain fuel and time prediction information in the FMS. As the aircraft passes abeam each waypoint from the original route, time and fuel are checked. This method references the original flight plan, which may introduce errors in fuel state or time of arrival depending the magnitude of diversion between the new and original routes.

Since Digital TASAR is permitted to use several waypoints in its solutions, intermediate along-track points spaced at a given interval for time and fuel observations can be created by the Digital TASAR trajectory generator exactly where the abeam waypoints would be placed and included in the trajectory modification request. These intermediate tracking waypoints would be loaded into the FMS upon acceptance of the request from ATC, allowing the FMS to compute fuel and time predictions accurately and reducing dispatcher workload associated with generating an updated flight plan.

5.3.2 Implement New Solution Patterns

To allow for ease of evaluating the trajectory change request by ATC, the Basic TASAR technology assumes that the trajectory modification starts close to the aircraft's current position. The distance from the aircraft's current position to this turn-out point is a predetermined function of the aircraft's groundspeed, estimated to give sufficient time to review, request, receive, and upload the trajectory solution into the aircraft's FMS before the aircraft has flown too far to make the initial turn [38]. However, there are three Data Comm messages (DM11, DM13, and DM119 in Table 1) that allow requests to be made for a change to be initiated farther downstream on the aircraft's trajectory. Two of these messages allow trajectory changes to occur at a given location (specified by either a named fix on the active route, a set of latitude/longitude coordinates on the active route, or a place-bearing-distance waypoint that is on the active route) in either the lateral (DM119) or vertical (DM11) dimensions. The third message (DM13) allows for a change in the vertical dimension to occur at a specified future time, regardless of location.

The aforementioned messages allow route modifications using new geometric patterns to be explored in the Digital TASAR technology's implementation of the PBGA for their efficacy in finding the optimal trajectory. The patterns used by the Basic TASAR technology are designed such that the maneuver rejoins the active route at a named fix prior to a pilot-specified "limit waypoint" in the FMS route, e.g., the initial fix on the arrival procedure. This design feature can be relaxed in the Digital TASAR technology, since Data Comm permits rejoining to any arbitrary point along the leg of the active route (DM24). This provides greater flexibility for the PBGA to determine optimal solutions. Furthermore, by including STAR information in the navigation database that the Digital TASAR technology uses, a new pattern could be explored that would connect to the aircraft's destination, but potentially through a different transition to the assigned STAR, or through a new STAR. Data Comm message DM24 has a field that would permit a new arrival procedure to be requested of ATC via Data Comm. If this functionality in the PBGA were created, this message could be used to request both the route clearance and the new arrival procedure connecting to the destination. The impact of all this is to permit optimization to a rejoin point much closer to destination, potentially increasing the operational benefit.

5.4 Modifications to the Human-Machine Interface

The flight crew fulfills an essential role in the Digital TASAR concept. They ultimately make the decision of whether to optimize the flight and what trajectory modification request they make to ATC. Therefore, the Digital TASAR technology must successfully be integrated into the cockpit environment as a useful tool and be accepted by pilots as an integral part of their decision-making process. These requirements dictate that special attention be paid in this project to human factors that reflect the pilot's interaction with and experience using the Digital TASAR technology.

The flight crew interacts with the Digital TASAR technology through a human-machine interface (HMI). To maximize the pilot's use of Digital TASAR, the HMI should be designed using an iterative, human-centered, design and evaluation process as the technology matures, similar to the approach taken for Basic TASAR. In fact, the design of the Basic TASAR HMI [39] may be a good foundation for designing the Digital TASAR HMI. Air transport pilot subject matter experts (SMEs) consulted on the design of a human-machine interface for a Digital TASAR application and offered several useful perspectives. The design goals were to (1) simplify the request process relative to the Basic TASAR technology by sending and receiving Data Comm messages from the HMI, (2) provide unambiguous presentation of Digital TASAR solutions to the flight crew, and (3) allow the flight crew to cross-reference the optimized route across multiple data sources.

5.4.1 Ability to Send and Receive Data Comm Messages from the HMI

Making the Digital TASAR request process as simple as possible is essential to keeping flight crew workload to a minimum. For this reason, it is advisable for the Digital TASAR technology to send Data Comm messages containing trajectory modification requests directly from the HMI. The function could take the form of a “Request to ATC” button on the HMI. A press of this button would select the proper message for the request, format the message, and transmit the message to the certified avionics, where the flight crew would review the message before transmitting it to the proper ATC recipient. Additionally, the HMI should receive and display Data Comm messages from ATC. These capabilities enable the flight crew to complete all necessary steps for making a digital route request from a single HMI, eliminating the need for time consuming and error prone transcription between systems.

5.4.2 Unambiguous Display of Digital TASAR Solutions

Based on SME feedback, one of the most important considerations for Digital TASAR HMI design is the need to avoid overloading the flight crew with information. To prevent too frequent solutions from distracting the crew from their normal duties, a threshold benefit should be selectable, below which the solution would be suppressed. The possibility of more complex trajectory recommendations with Digital TASAR necessitates the need for a user to identify key information at a glance. Viewing and easily differentiating between the FMS active route, the Digital TASAR technology optimized trajectory, and an amended route clearance from ATC is necessary and a priority. Digital TASAR will likely lead to more complex route requests, which makes immediately understanding the difference between the active route and the proposed optimized route even more important than in Basic TASAR. Being able to view this routing overlaid on external information such as weather radar, wind fields, turbulence areas, and SIGMETS will give the flight crew a complete picture of the impact of the new route in an efficient and easily understood format.

Displaying route requests textually in addition to graphically will not likely be routinely done, but alphanumeric descriptions may be accessible if desired in order to cross-reference between multiple applications on the EFB. When the waypoints are defined by latitude/longitude coordinates and there are dozens of them describing a trajectory, they should be identified on the map as simple codes (e.g. A1) rather than their full numeric values. A vertical display of the altitude profile would also be helpful on route requests that include multiple altitude changes. As in Basic TASAR, a key informational element for a Digital TASAR HMI to select among separate optimized route options is the projected benefit of each optimized route in terms of fuel and/or time saved.

5.4.3 Ability to Cross-Reference

SME feedback also stressed the importance of cross-referencing optimized routes with other information available in the flight deck. Allowing the crew to cross-reference potential optimized routes across multiple data sources will build confidence and facilitate decisions that are more informed. The ability for the flight crew to overlay an optimized trajectory recommendation on supplemental weather applications was identified as a particularly useful function. In an EFB-based Digital TASAR technology, this could be achieved through a “copy/paste” functionality between applications. Displaying which data sources are contributing to an optimized route would also be helpful in the event that a source becomes unavailable and the flight crew needed to reference other available data sources in the flight deck.

5.5 System Architecture

The Digital TASAR technology implementation uses and builds upon the existing software components of the Basic TASAR technology. Similar to Basic TASAR, a system architecture that uses an EFB hosting the Digital TASAR technology is highly desired. The form of Digital TASAR solutions and procedures for conducting Digital TASAR operations (discussed in Section 5.6) require that the Digital TASAR technology seamlessly interoperate with the certified avionics. Recent industry advancements allow EFB applications to interface directly with the aircraft's FMS [40]. These interfaces will allow the Digital TASAR technology to receive additional information from the aircraft compared to the Basic TASAR technology implementation. More importantly, these interfaces are a conduit to deliver data to the FMS directly from the Digital TASAR technology.

A high-level definition of the components of a Digital TASAR technology follows. Figure 1 provides a schematic that illustrates component connectivity.

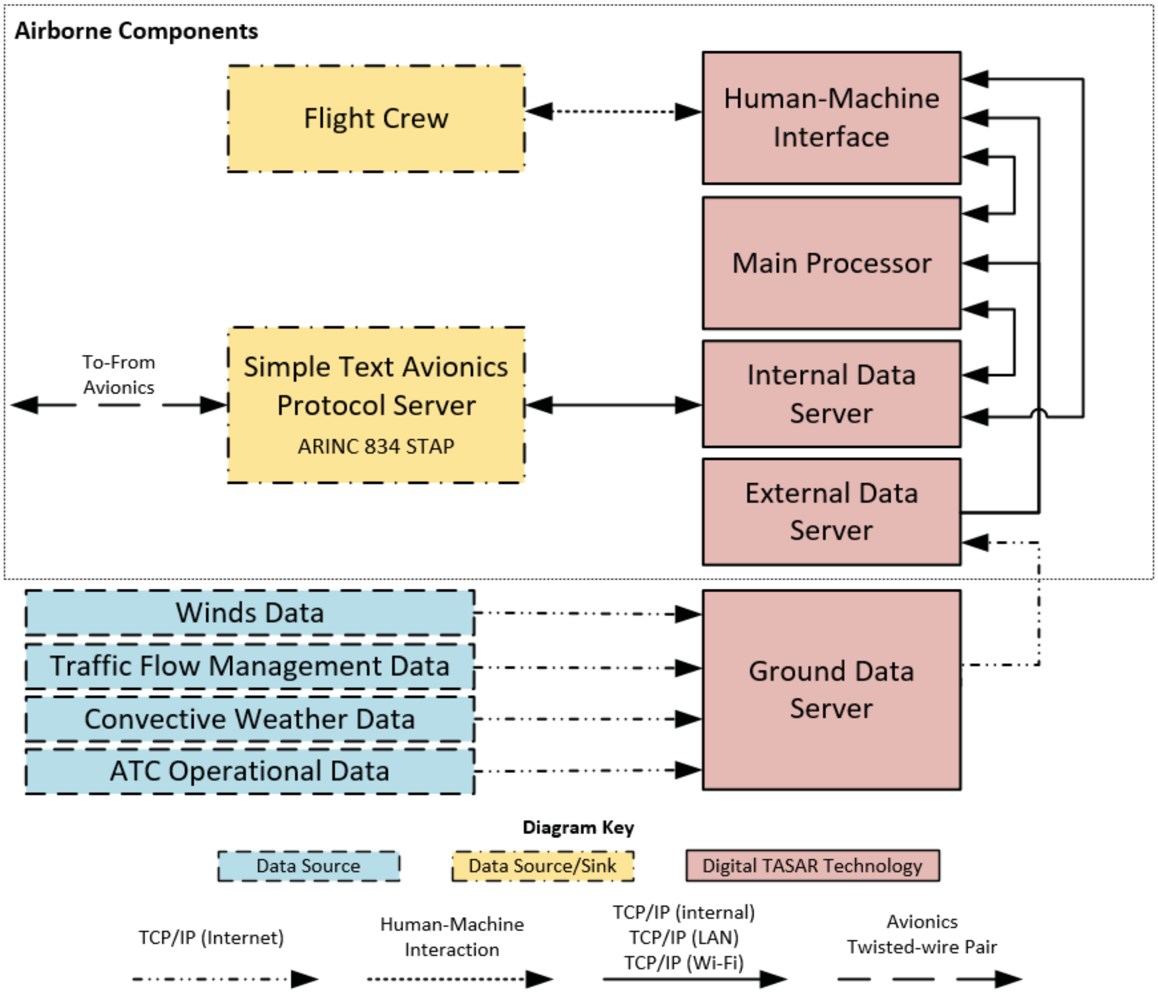

Figure 1. Digital TASAR Technology Reference System Architecture

5.5.1 *Main Processor*

The Main Processor accepts and reads all data inputs and performs all processing necessary to generate optimized conflict-free trajectory-change solutions and responds to pilot inputs from the HMI. It consists of a trajectory generator that computes feasible candidate trajectory solutions that meet any speed or altitude constraints present on the active route, a conflict probe that searches for conflicts along those candidate trajectory solutions, and the PBGA that performs the optimization function. The Digital TASAR Main Processor will incorporate the changes described in Section 5.3.

5.5.2 *Human-Machine Interface*

The HMI enables interaction between the flight crew and the automation. It accepts all pilot-entered information and sends it to the Main Processor. It also displays the most optimal trajectory solutions, time and fuel outcomes for each trajectory solution, conflict information, and additional information regarding the internal state of the system. The Digital TASAR implementation of the HMI will incorporate the modifications described in Section 5.4.

5.5.3 Internal Data Server

The Internal Data Server is a new component for Digital TASAR that does not exist in the Basic TASAR technology. It serves as an interface between the onboard components of the Digital TASAR technology and the aircraft's certified avionics, making use of emerging EFB-FMS interoperability capabilities such as those described in [40]. The Internal Data Server is the only software component that communicates with certified avionics in the Digital TASAR technology system. This design benefits both certification and cybersecurity. The Internal Data Server provides a reasonableness filter for all data flowing to and from the Digital TASAR technology, which increases the integrity of the system. Furthermore, it serves as a cybersecurity barrier between the aircraft's installed equipage and the digital paths into the technology ecosystem without the inherent assurance and reliability (e.g., connections providing data to the External Data Server described in Section 5.5.4). The Internal Data Server ingests an ARINC 834 data feed from an Aircraft Interface Device (AID) and relays the data to the Main Processor. It also receives trajectory data from the HMI for a pilot-selected trajectory change request (i.e., a route definition for a selected trajectory solution), formats the selected trajectory data into the appropriate format (i.e., the proper Data Comm message) and sends it to the AID, where it will be routed to the aircraft's FMS and ultimately to ATC.

5.5.4 External Data Server

The External Data Server is an interface between the airborne components of the Digital TASAR technology and data that originates external to the aircraft. It handles the downloading, decrypting, decompressing, and formatting of winds aloft, convective weather, Special Use Airspace (SUA), and ATC operational data obtained from the Ground Data Server. It will periodically check to see if updated data exists on the Ground Data Server, and if so, download it to the aircraft. Once downloaded to the aircraft, the EDS provides data to the Main Processor and HMI. The Digital TASAR External Data Server will incorporate the changes described in Section 5.2, including higher fidelity winds data and ATC operational data.

5.5.5 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 uplinking a subset of data to the aircraft alleviates excessive use of the bandwidth of 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 Digital TASAR technology with winds aloft data, convective weather data [41], Significant Meteorological (SIGMET) data (convective and turbulence), and SUA data appropriate to the route of flight. It will also provide ATC operational data 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.

5.6 Operational Procedures

Once the Digital TASAR technology provides the flight crew a route optimization solution that provides an operating benefit and the flight crew selects it for further consideration, they would begin by reviewing it to understand the change from the active route. This step would include a cross reference of any additional airspace information or weather information not available to the Digital TASAR technology, such as pilot reported turbulence. A route change that requires significant deviation from the originally planned altitude, route of flight or destination arrival time may require concurrence from a flight dispatcher in the AOC. Once a decision is made to make a request, the flight crew would send the route request to the AOC via ACARS for review if necessary. Once AOC concurrence is received (if required), the flight crew sends the route to ATC via Data Comm for review. ATC would then approve without changes, approve with an amendment, or disapprove (reject) the request. It is possible that a request could go unanswered by ATC for an extended period or new data could be received by the flight crew that invalidates the original request. In those cases, the crew would have an opportunity to select “reject” in the FMS and withdraw the request to ATC.

- ATC Approve without Modification: If the request were approved without changes, the flight crew would load the clearance into the FMS, accept it through CPDLC, and then execute the clearance in the FMS.
- ATC Approve with Modification: If ATC responds with a modified clearance, the flight crew would treat this as a new clearance and determine its acceptability, given the aircraft’s performance limits, current fuel load, proximity to weather hazards, and other considerations. If the flight crew accepts the modified route, they would accept it via Data Comm, and then execute the route in the FMS. If they cannot accept the new clearance, they would Reject it with reasons via Data Comm and erase it from the FMS.
- ATC Reject: A rejected route request would end the process until it is desired to request another route clearance.

An illustration of the workflow for making a Digital TASAR route request is shown in Figure 2.

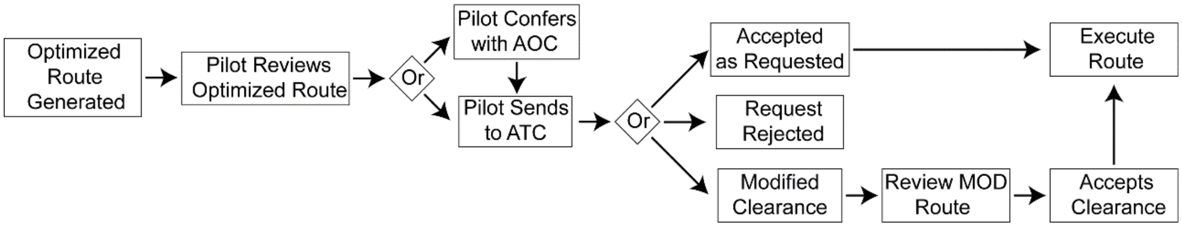

Figure 2: Trajectory Modification Requests Workflow using Data Comm

6. Future Research

Many applications of the Digital TASAR system will benefit from further research to refine the technical design, verify actual cost savings are sufficient to offset the implementation costs, and ensure practicality in operational use. This section describes these future applications, including simplified procedures for complex requests, multiple step climbs, the use of short-term block altitude clearances, and consideration of sector and fix load balancing during the creation of optimal solutions.

6.1 Validate Simplified Procedures for Complex Requests

Digital TASAR provides simplified procedures for making complex route-change requests, as discussed in Sections 4.2 and 4.3. Validating this premise will require HITL experiments using a simulated traffic and ATC environment. Metrics of interest include the acceptability rate from ATC for the increased number of requests and the ability of ATC to examine the requests for acceptability in a timely manner. A HITL simulation should also be used to validate the HMI associated with request/re-clearance using Data Comm and graphical display of the route requests for pilot and controller approval. This includes both the accuracy of the digital/graphical translation of the trajectory description and the acceptability of the graphical display to both pilots and controllers when approving the trajectory modification recommended by the Digital TASAR technology.

Additionally, as more aircraft are equipped with a Digital TASAR technology, several aircraft may attempt to optimize their routes at the same time through the same airspace as noted in Section 4.1. Batch simulations featuring scenarios that consider anticipated traffic density in the next 10 years should be conducted to determine whether and how often this phenomenon occurs, and what types of adverse interactions arise between simultaneous requests. HITL simulations should examine the impact on pilot and ATC workload in simultaneous, conflicting request scenarios and assess the acceptability of generating and executing amendments where the original requests could not be accommodated due to the request interdependencies.

6.2 Assess Impact of Requesting Short-Term Block Altitude Clearances

An aircraft's optimum altitude profile minimizes total costs related to the aircraft operating along a given route. Important factors in its calculation are the aircraft weight and outside air temperature. Aircraft in the NAS are normally assigned a single altitude. This limitation makes the aircraft fly above or below its optimal altitude most of the time. In both oceanic and domestic airspace, ATC procedures allow for a "cruise" clearance, which authorizes an aircraft to fly at any altitude between the minimum IFR altitude and the cleared altitude and to descend to land at the destination [42]. A "block altitude" clearance can also be used permitting flight at any altitude between the upper and lower altitudes defining the block [42]. Aircraft on overwater flights use this type of clearance to set an optimal engine thrust and slowly climb as the aircraft burns fuel and gets lighter, which allows the aircraft to maintain an optimal altitude for the duration of the clearance. This type of clearance is normally impractical in the NAS because of traffic congestion and inter-facility agreements requiring handoffs at specific altitudes. In low-density environments, Digital TASAR could be used to request short-term block altitude clearances between two waypoints, thereby reducing the unnecessary fuel burn of climb thrust required for step altitude changes. The block altitude clearance would end at the waypoint where the aircraft would be established at the new altitude. In preference to using multiple step climbs, this clearance would contain several short-term block altitude clearances. The aircraft's vertical profile would mimic a cruise clearance over a longer duration, but the climbs would be established at agreed flight levels at specific waypoints and use specific blocks of altitudes for cruise-climbs between waypoints. Research should be performed to show the effects on fuel burn due to climbing in this fashion. Additionally, research should be performed to show the effects of climbing in this fashion on workload, procedures, and off-nominal situations. Research should also investigate the procedural impacts of ATC assigning blocks of airspace in complex traffic scenarios and its effects on Traffic Flow Management (TFM).

6.3 Assess Impact of Incorporating Arrival Procedures in Enroute Optimization

Optimized lateral routings that use all available airspace to the destination, including airspace reserved for published arrival procedures, will not only more fully optimize the individual flights but may help optimize arrival traffic flows. Digital TASAR technology can be provided with information on which STARs and runways are being used at the destination airport as well as sector loading and loading over transition fixes. Using that information, an optimized route can be calculated using all transition fixes for a particular STAR or selecting another STAR if it creates a more optimal route and is not overloaded. With this procedure, aircraft will essentially balance the loads over these fixes themselves as Digital TASAR becomes more widely used. Research should investigate what percentage of Digital TASAR-equipped aircraft is needed to see benefits in sector and arrival fix balancing. Additionally, research should assess impacts to ATC automation and controller's acceptance of the operation (i.e., self-balancing traffic flows) resulting from this capability.

6.4 Investigate Inclusion of Airspeed in the Trajectory Request

Using Data Comm to make trajectory change requests opens an additional capability for consideration: including the preferred airspeed in the trajectory description. The inclusion of airspeed will add an additional degree of freedom to the optimization algorithms for generating time and fuel savings, while also enhancing responsiveness to "time of crossing" constraints and arrival time requests. TFM procedures used by ATC are based upon managing crossing times at fixes on the route to establish optimal aircraft flow rates. Incorporating airspeed in the optimization solution can enable finding the most fuel-efficient route and altitude to meet an assigned time constraint at a fix. Similarly, airline terminal operations depend upon timing of arrivals and departures at their gates. The global optimization of a group of arriving aircraft can be better achieved through individual control of flight arrival times, with an updated TASAR optimization capability that includes the airspeed flown in its solution. These considerations are the subject of another report on 4D TASAR [43] that is completely devoted to exploring the needs and requirements of this capability.

7. Conclusion

The Digital TASAR concept, where TASAR route-optimization requests are made via Data Comm instead of voice, permits increasingly complex requests to be made using simplified procedures. Not only does it enable increased end user fuel- and time-saving benefits relative to Basic TASAR, Digital TASAR provides an exemplary use case for integrating advanced airborne route optimization technology with ATC systems designed for evaluating user requests. It provides airlines with an opportunity to capitalize on a communications link already installed on the majority of their fleets while providing the FAA with a technology that demonstrates the value of their investment in the ground automation to support Data Comm. Furthermore, Digital TASAR is expected to reduce the workload of flight crews and controllers when making and approving trajectory modification requests. It may also provide increased system-level predictability by providing ground-based automation systems with a highly detailed trajectory change request, allowing those systems to create more accurate and precise predictions of time enroute.

Digital TASAR is an enabler of future advances in air/ground trajectory coordination for more efficient traffic flow management in both regular and irregular flight operations. It is an essential steppingstone on the roadmap to Airborne Trajectory Management, a concept for greater autonomy in aviation operations to benefit both flight operators and ground service providers, and subsequent concepts along the roadmap will leverage and build upon the capabilities described in this report.

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14. ABSTRACT

Flight crews often request trajectory changes from air traffic control using voice communications to achieve the operator's preferred business objectives with a more optimal trajectory. The TASAR concept developed by NASA significantly enhances this procedure by providing flight crews with automation that recommends fuel- and time-saving trajectory optimizations. To facilitate complex requests that align more closely with the optimal trajectory, and to reduce flight crew and controller workload, the proposed Digital TASAR concept discussed in this report makes use of Data Comm infrastructure and associated automation to permit digital requests in a timely and efficient manner.

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