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Incorporation of Time of Arrival Constraints in a Trajectory Optimization Technology

Matthew C. Underwood
Langley Research Center, Hampton, Virginia

William B. Cotton
Cotton Aviation Enterprises, Inc., Lakeway, Texas

Clay E. Hubbs
All Aspect Aerospace Innovations, LLC, Parker, Colorado

Michael J. Vincent and Sagar KC
Langley Research Center, Hampton, Virginia

David A. Karr
Science Applications International Corporation, Andover, Massachusetts

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National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23681-2199

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Acronym List

4D	Four-Dimensional
ABTM	AirBorne Trajectory Management
ACARS	Aircraft Communications Addressing and Reporting System
ACT RTE	Active Route
ADS-B	Automatic Dependent Surveillance – Broadcast
AID	Aircraft Interface Device
AOC	Airline Operations Center
AOP	Autonomous Operations Planner
ARINC	Aeronautical Radio, Incorporated
ARTCC	Air Route Traffic Control Center
ASM	Available Seat Mile
ATC	Air Traffic Control
ATM	Air Traffic Management
BBTG	Behavior-Based Trajectory Generator
CAS	Calibrated Airspeed
CSP	Constraint Satisfaction Points
Data Comm	Digital Data Communications
EFB	Electronic Flight Bag
ETA	Estimated Time of Arrival
FAA	Federal Aviation Administration
FL	Flight Level
FMS	Flight Management System
HMI	Human-Machine Interface
HRRR	High-Resolution Rapid Refresh
MOD RTE	Modified Route
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
PBGA	Pattern-Based Genetic Algorithm
RAP	Rapid Refresh
RPM	Revenue Passenger Mile
RTA	Required Time of Arrival
RTCA	Radio Technical Commission for Aeronautics
SIGMET	SIGnificant METerological Information
SME	Subject Matter Expert
STA	Scheduled Time of Arrival
SUA	Special Use Airspace
SWIM	System-Wide Information Management
TAP	Traffic Aware Planner
TASAR	Traffic Aware Strategic Aircrew Requests
TBFM	Time-Based Flow Management
TBO	Trajectory Based Operations
TFMS	Traffic Flow Management System
TRACON	Terminal Radar Approach Control
UAS	Unmanned Aircraft System

Abstract

During flight operations in the National Airspace System, flight crews often request trajectory changes from air traffic control using voice communications over the radio 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 based on a broad suite of information on the aircraft and the dynamic operating environment. To achieve system-level traffic flow management objectives while accommodating user business preferences, the Four-Dimensional TASAR concept introduced in this report considers time of arrival constraints and permits speed profile optimization by adding the speed dimension to its trajectory optimization recommendations. This report describes a Four-Dimensional TASAR concept of operations, the enabling technology, and the potential benefits of equipping with the capability provided 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]. 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 [2, 3]. These suggestions may be used by the flight crew to make trajectory modification requests to air traffic control (ATC) that are more readily approvable, 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 Boeing 737-900ER aircraft [4]. These operational trials validated the concept and anticipated benefits [5] for TASAR, and demonstrated that a growth path existed for future applications of airborne trajectory management technology.

The TASAR concept considers information regarding hazards that affect the flight (e.g., convective weather, nearby traffic and special use airspace), airline business considerations (e.g., optimization objective), and published route constraints (e.g., altitude and speed constraints on an arrival procedure) when generating optimized trajectory recommendations. This information is known to the TASAR automation through either automated data exchange or manual data entry by the flight crew. However, many National Airspace System (NAS) traffic flow management constraints (e.g., miles-in-trail, flow constrained areas, time of arrival constraints, etc.) are not commonly made available to aircraft or operators through digital means, and operations that require compliance with these constraints (e.g., time-based metering) are not yet routine. Therefore, the Basic TASAR technology does not consider these types of constraints.

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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.

The Federal Aviation Administration (FAA) is currently implementing technology across the NAS that enables routine time-based metering operations for aircraft departing from and arriving to congested airspace and airports [6]. This technology, known as Time Based Flow Management (TBFM), 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. Enabling infrastructure and technologies being developed and fielded by the FAA, such as Digital Data Communication (Data Comm) [7] and System Wide Information Management (SWIM) [8], allow these constraints to be digitally transmitted to the flight deck. Additionally, current technology like the Aircraft Communications Addressing and Reporting System (ACARS) allows flight crew and dispatchers in the Airline Operations Center (AOC) to relay airline-related information on timing objectives (e.g., gate availability and duty time constraints).

These current and future technologies enable a concept known as Four-Dimensional (4D) TASAR that adds the speed and time dimension to the trajectory optimization software to incorporate ATC and AOC time constraints and objectives when calculating trajectory optimization recommendations. The 4D TASAR technology, in conjunction with Required Time of Arrival (RTA) and Data Comm functionality existing in many modern commercial transport aircraft, creates an opportunity to perform airborne trajectory optimization throughout the flight from departure flow to arrival flow. Airlines may choose to use this functionality to increase the efficiency of their flight operations, or as a mechanism to begin trajectory negotiation with ATC to fly a business-preferred trajectory that has a higher chance of acceptability by the system. The 4D TASAR concept describes a means to consider system-level constraints in a trajectory optimization technology, obtaining immediate operating benefits for adopters of the technology while simultaneously providing system-level benefits to the NAS.

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 perform the traffic separation function 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 [9]. As part of this research effort, NASA developed a prototype cockpit-based software tool called the Autonomous Operations Planner (AOP) [10, 11]. 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 [12–17].

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 (TAP) software (the Basic TASAR technology) to Technology Readiness Level[3] 7 by testing it in airline revenue-service operations. TASAR is currently undergoing commercialization by industry.

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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].

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 [18]. Cotton, et al., describe a practical roadmap consisting of five steps to achieve airborne operational autonomy:

- Basic TASAR. Uses automation to compute optimized lateral and vertical trajectory change requests via voice exchange between pilots and controllers.
- 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; to facilitate simpler 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[4] to consider time of arrival constraints in optimization routine and permit along-path speed optimization.
- 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.
- 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” [19], an industry-led initiative in which systems onboard and off the aircraft are digitally connected to each other, enabling substantial flows of information. Basic TASAR represents a starting point on a roadmap of applications. Digital TASAR [20], the second application on this roadmap, demonstrates maturity of the concept as connectivity expands to include data communications between pilots and ATC. Building upon Digital TASAR, the third application on this roadmap is 4D TASAR, the subject of this report.

2.1 Non-Time Compliant TASAR Concepts

2.1.1 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 combination of a powerful trajectory optimization tool called the pattern-based genetic algorithm (PBGA) [21], a trajectory generator known as the Behavior-Based Trajectory Generator (BBTG) [22] and a conflict probe [23] 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 (AID) to on-board avionics and to in-flight connectivity systems for external data.

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[4] Note: This functionality, while it can be used as a standalone capability, may be best used in conjunction with Digital TASAR.

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 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 [1, 24]. 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 [24].

2.1.2 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 Enroute Automation Modernization software, trajectory modification requests may be complex. 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 trajectory modification approvals will occur on a more frequent basis and in busier airspace than would otherwise occur. For more information regarding Digital TASAR, refer to [20].

2.2 Time-Compliant, 4D TASAR Concept Overview

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 the three dimensions of space 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 a speed reduction along the new trajectory, enabling a simultaneous solution for best fuel while also meeting a time objective at the destination (usually scheduled arrival time) for efficient use of airline ground resources or for traffic flow management. This capability could also enable tight coupling of ATC flow constraints with the individual optimization objective of each flight, creating both flight and ATC efficiencies simultaneously.

The FAA, as part of its NextGen program, is implementing technologies across the NAS that enable time-based flow management, which is expected to increase the predictability of the NAS and improve the use of the existing system capacity [25]. 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 [6]. As a result, each aircraft may have an ATC scheduled time of arrival at certain points along its trajectory. Two FAA automation platforms provide this functionality:

- Traffic Flow Management System (TFMS). An Air Route Traffic Control Center (ARTCC, or "Center") trajectory prediction tool that provides a variety of flight and flow information, including flight-plan data, departure and arrival times, flight cancellations, flow-constraint area or flow-evaluation area, ground stop, and strategic playbook reroutes [25].
- Time Based Flow Management (TBFM). An ARTCC and Terminal Radar Approach Control (TRACON) tool that contains a traffic scheduler for airport arrivals, providing controllers with Scheduled Times of Arrival (STAs) used in metering aircraft to various freeze horizons and terminal metering fixes [6].

These automation tools are not yet routinely used by controllers, even though they are operational in all Centers and all major TRACON facilities. However, 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 RTA meeting feature in existing FMSs. Currently, controllers issue speed control instructions to aircraft to have them cross the constrained fixes at the STA issued by TBFM. The use of RTA meeting technologies has been demonstrated to improve the time-crossing accuracy and precision [26–29].

The 4D TASAR concept considers time of arrival constraints in its trajectory optimization to provide compatibility with time-based flow management concepts, and makes use of existing RTA meeting functionality in the FMS to execute the trajectory. There is no change in the location of separation responsibility in 4D TASAR, which enables the certification and operational approval requirements to remain similar to Basic TASAR. However, it should be noted that a tighter integration with certified avionics (e.g., the FMS) and the use of Digital TASAR functionality would facilitate less cumbersome and/or error-prone operational procedures, which would favorably affect the certification and operational approval requirements.

The 4D TASAR technology[5] will consider time constraints that specify limits on the time at which the aircraft can arrive at a waypoint. The 4D TASAR technology will have the capability to receive and apply

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[5] Throughout the remainder of the paper, the term "4D TASAR technology" will be used to describe the flight-deck automation system that implements the 4D TASAR concept. This technology will leverage, and build upon, capabilities demonstrated in the Traffic Aware Planner and the Digital TASAR technology, but will feature enhancements and design changes that distinguish it as a new capability.

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 cost index speed profile) component, as well as the lateral and/or vertical path changes. This enables continual optimization in speed as well as lateral and vertical flight path, even in the absence of any ATC constraints. 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, ATC can respond to the request with a Data Comm message.

3. Benefit Mechanisms of 4D TASAR

Nearly all airline costs are related to time. Salaries, fuel burned, aircraft use, maintenance schedules, and facilities leased all convert to dollars per hour. The basic unit of cost at an airline is cents per available seat mile (ASM). Given a fixed number of seats on an aircraft, ASMs relate directly to ground miles per hour between airports. Generally, the faster the flight, the lower the cost. This generalization is also true with respect to monetary value. Here the unit measured is the Revenue Passenger Mile (RPM). The faster the trip, the higher the rate of RPM accumulation (RPMs per hour) and the more valuable the flight is to the customer, making the flight more marketable. Thus, saving time on flights both reduces cost and increases potential revenue. Furthermore, for a given flight time between cities, optimizing the flight trajectory without changing the time will result in reduced fuel burn. This is why the TASAR automation is designed to seek an optimum for fuel, time, or a customized balance between the two—to minimize the total cost of a flight to the airline. The flight crew selects the optimization objective supplied by the company according to the variable cost values on each flight at any given moment in the airline’s total operation.

The addition of the time (and speed) element to the TASAR optimization capability may reduce flight time and/or fuel burn in several ways. The ATC flow constraints, issued to flights as a mechanism for balancing capacity with demand at airports and in congested sectors, are implemented by controllers today using procedures that add substantial delay and fuel cost over what is necessary to accomplish the objective. Optimizing the route, altitude profile and speed profile using 4D TASAR to achieve the capacity/demand objective provides greater efficiency. In the absence of ATC constraints, both the individual flights and the airline’s total operation still require speed modifications enroute to minimize individual flight cost and to make the connections and aircraft “turns” more efficient at the hub airports.

Benefits attributable to each of the scenarios set forth in Section 4 can be estimated based upon the number of opportunities calculated from real flight data recorded in the subject airspace. Time savings would initially be valued at the direct operating cost of the airplane. Time saved at the expense of additional fuel will be valued by the savings in connections not missed and other flights not delayed or cancelled. A reduction in the average block time for flights over time results in the airline taking time out of the flight schedule. This second process is a productivity benefit in which the schedule can be operated with fewer aircraft and flight crew hours.

The benefits described in this section would be attained in addition to those provided by Basic and Digital TASAR. Those concepts use simple flight crew procedures to make complex, dynamically-updated trajectory modification requests that save time and/or fuel using only lateral and vertical flight path changes, providing early accrual of benefits as each aircraft is equipped [20, 24]. This section analyzes the additional benefits from having speed change capability in the optimization algorithm.

3.1 Optimizing Conformance with Traffic Management Initiatives

In the future when TBFM is used routinely to enable Trajectory Based Operations (TBO), it is envisioned that RTA instructions will be assigned to aircraft crossing certain waypoints or metering arcs to manage inadequate capacity. This change in procedure will make it unnecessary to keep flights in the same physical line while metering them to the fix, a process called miles-in-trail that is used for this purpose. Miles-in trail requires modification of the speeds of most of the aircraft in the line in order to maintain a regular interval, placing them off optimum speed and changing their natural order of arrival by preventing passing by aircraft of dissimilar speeds. The natural arrival order is close to how they are scheduled to arrive at the airport. Airlines create their connecting flight schedules so that those aircraft that take longer to “turn around” (generally the larger aircraft) will arrive early in the bank of arrivals and the smaller aircraft later. The use of miles-in-trail procedures, eliminating passing, completely disrupts this order, undermining the efficiency of the connecting bank. The use of RTA instructions alone instead of miles-in-trail will provide savings. By optimizing the trajectory to the point of constraint, even greater time and fuel savings will be realized while not flying in a physical line to the arrival fix, and the integrity of the connecting bank can be maintained, reducing missed connection costs. There is already sufficient lateral and vertical flexibility in the airspace to permit independent trajectories to ATC control points, facilitating enroute passing.

When using miles-in-trail or other control functions such as merging flights converging from different paths to a common fix, controllers routinely issue speed control assignments to the aircraft in potential conflict. These speed changes are made conservatively, usually greater than required to achieve the target separation, resulting in successive “slow down”, “speed up” instructions. The 4D TASAR technology can optimize the speed to the control point, and more accurately achieve the desired crossing time while saving fuel in the process. When speed control is inadequate to achieve the necessary delay, vectoring off course is added to the process. Since speed control and vectoring are very labor-intensive processes for controllers, requiring extended periods of concentration on specific flights, controller workload will be significantly reduced when they are eliminated in favor of aircraft-controlled, fix arrival times.

It is expected that aircraft-controlled times at fixes will prove to be quite accurate, leading over time to a reduction in the number of constrained fixes, ultimately to one at the terminal merge point. This time precision will be made possible by the accuracy of the trajectory modeler in the 4D TASAR technology.

3.2 Speed and Time Optimization to Achieve Company Objectives

In the absence of an ATC time constraint, the 4D TASAR technology will optimize the speed of the flight to comply with the airline’s objective considering its Estimated Time of Arrival (ETA) versus scheduled arrival time and the costs of all variables impacted by this time. In addition to the direct operating costs of fuel, crew and maintenance, this calculation may also consider connections for passengers, freight, the cabin and cockpit crew, and the next scheduled flight of the airplane. This capability enables the company to use the 4D TASAR technology to respond dynamically to changes in the aircraft’s ETA, as well as the arrival times of other aircraft and conditions at the destination airport. Thus, the speed schedule as well as the lateral and vertical flight path of the aircraft may be modified multiple times during the course of the flight in response to changes in the operating environment. The company objectives are continually present on all flights, but the ATC constraints exist primarily on flights toward the largest, most congested airports. When imposed, these constraints are considered by the 4D TASAR technology in conjunction with the company objectives to produce the most optimized trajectory possible that is conflict free and achieves ATC constraints.

It is predicted that time will be routinely saved on multiple flights using 4D TASAR, so most flights will arrive early and the “on-time” performance of the schedule as a whole will improve. However, it is not cost effective for all flights to arrive early. Therefore, the scheduled time for each flight may be reduced by airline scheduling. This saves on costs that are based on the scheduled flight time, such as flight crew salaries and certain maintenance items. The resulting flight schedule produces the same number of ASMs, but does it using fewer airplane and flight crew hours, creating cost savings. The additional hours saved may be spread disproportionately among the fleet, so some airplanes may have enough time to permit an additional segment to be flown during the operating day. Thus, the time saved by 4D TASAR enables an increase in the number of ASMs produced using the savings from the total flight time to fly the original schedule. These additional flights represent a pure productivity increase without adding to the costs beyond those of flying the original schedule.

4. Use Cases for Incorporating 4D Constraints in Trajectory Optimization

This section provides use case scenarios that demonstrate the multi-faceted benefits of 4D TASAR operations. Four operational scenarios are presented that each highlight different use cases and benefits of the 4D TASAR concept in practice.

4.1 Scenario 1: Single Time Constraint

Flight 7316 from San Francisco to Denver pushes back at the scheduled time of 1753Z and lifts off 20 minutes later at 1813Z. The airline's flight plan calls for an "off to on" time of 2 hours 4 minutes, cruising at FL 370 and Mach 0.78. The weather forecast for Denver at the estimated time of arrival contains a wind from the north at 12 gusting to 16 knots with a 30% chance of snow showers lowering the visibility to one mile. This common upslope precipitation condition occurs in the early spring in Denver. The first part of the flight is routine, maintaining flight plan times and fuel burn values at waypoints enroute. When the aircraft passes the Wasatch (TCH) fix, Salt Lake City Center advises the flight that metering is now in effect for Denver and issues an RTA instruction for Flight 7316 to arrive at the Meeker fix (EKR) at 1945Z. Snow has started to fall at the airport and airplanes are taking longer to exit the runways resulting in a decreased arrival rate. This new rate causes the TBFM automation in the Denver TRACON to create a metering list containing an ATC STA for all aircraft predicted on the TOMSN8 arrival at the EKR arrival fix. The STA is made available through the FAA automation to the Salt Lake City Center controller without the need for a coordinating phone call from Denver to issue the instruction to Flight 7316.

The flight crew of Flight 7316 acknowledges the RTA at EKR and enters it into the FMS at the fix. The RTA instruction requires the flight to absorb a 5.2-minute delay, and the FMS quickly indicates "unable RTA", meaning that the speed would have to be reduced below the performance capability of the airplane at the current altitude to absorb the delay prior to the fix. In current day operations without 4D TASAR, the crew notifies ATC they are unable to achieve the time and then the controller issues vectors to absorb the delay. However, the 4D TASAR technology on Flight 7316 ingests the time of arrival constraint at EKR from the FMS and recommends a trajectory modification to step down to FL330 and reduce to 0.72 Mach to achieve the delay. By descending to FL330 and reducing to 0.72 Mach, the airplane could achieve the 90-knot groundspeed reduction to absorb the delay while flying much closer to its minimum drag speed and burning fuel at a lower rate than would have been the case at FL370 on path-stretch vectors at the previous speed. Since this trajectory is also conflict free from other traffic and constraints, the likelihood that ATC will approve the flight crew request is high. The crew calls Salt Lake City Center and makes the request to descend and slow down. It is quickly approved, as it still meets the RTA instruction, and by implementing the trajectory modification, controller and crew workload are reduced.

4.2 Scenario 2: Multiple Time Constraints from Single Source

FAA's plans for Traffic Flow Management automation include multi-center metering to coordinate the handling of constraints that affect multiple facilities and to enable distributing required delay over a longer flight path to multiple centers. This permits the delay to be absorbed using speed control alone. In this example, Flight 2522 from Atlanta to New York LaGuardia airport is issued an RTA instruction by Atlanta Center at the Washington/New York Center boundary that requires absorbing more delay than can be accommodated by slowing down in the Washington Center alone. The multi-center TBFM assigns 3 minutes of delay within Washington Center and 2 minutes within Atlanta Center for Flight 2522. These delays are issued as RTA instructions at Greensboro (GSO), a waypoint on the boundary of Atlanta and

Washington Centers, and Woodstown (OOD), a waypoint on the boundary of Washington and New York Centers.

In current operations, controllers do not typically issue RTA instructions. Rather, they issue speed instructions and vectors at the current altitude to meet a time constraint that is unknown by the flight crew. With 4D TASAR, Atlanta Center can issue the RTA instructions at both waypoints and the 4D TASAR technology will compute optimized trajectory modifications that are de-conflicted from all known hazards, meet all path constraints, and achieve both RTAs.

In this scenario, the 4D TASAR technology has both time constraints and up-to-date wind information. It determines that by modifying the trajectory to cross into Washington Center at LUMAY using the Q58 route rather than GSO on the J14 route due to an eastward shift in the jet stream, the flight can slow an additional 10 knots and still make the RTAs at both LUMAY and OOD. The crew of Flight 2522 makes the request to Atlanta Center, advising that both RTAs will still be met. The Center conflict probe confirms that the new trajectory is conflict free and the controller approves the change, permitting additional fuel to be saved on the flight.

4.3 Scenario 3: Multiple Time Constraints from Multiple Sources

An airline's schedule is created to produce the maximum revenue from its available resources, given the demand for air transportation services from the traveling and shipping public. This results in frequent use of "hub and spoke" distribution systems to connect passengers and freight through hubs rather than flying non-stops between all origin and destination city pairs. The advantage from this practice is enormous, but it also requires very efficient coordination of arrivals, departures and servicing the aircraft while at their terminal gates. Irregular events caused by weather, traffic congestion, mechanical failures and human inefficiencies make it necessary to adjust and adapt the times, the gates used, and sometimes swap crews and aircraft among flights during the evolving operation. It nearly always results in an adjustment of the desired arrival time of flights from their estimated times of arrival resulting from the winds of the day and any other anomalies that might have occurred earlier in the flight. In some cases, the revenue is enhanced by speeding up to arrive before the estimate, and in others, it is improved by arriving a little later.

In this scenario, the departure of Flight 6123 from Washington Dulles to Dallas Fort Worth (KDFW) airport is delayed by six minutes due to a delay in completing the boarding process. Strong headwinds make it hard to make up the time enroute by flying at a higher than planned speed, but there is enough margin in the published flight schedule to arrive at KDFW at the airline's planned arrival time. The crew follows the flight plan until they are in central Tennessee, when they are given an RTA instruction by Memphis Center to cross the Texarkana (TEX) fix "at or after" 1314Z. That constitutes a minimum two-minute delay for the flight, and the RTA is programmed into the FMS accordingly. Shortly thereafter, a message is received from dispatch that the gate for Flight 6123 will not be available until five minutes after arrival time because of a mechanical problem being repaired on the airplane currently at the gate planned for Flight 6123. There are now two time constraints applied to Flight 6123, one by ATC and the other by the company.

Existing practice would have the flight slow to make the TEX fix at the front of the ATC constraint window, then continue at normal speed to the airport, land, and wait on the ramp for the gate to become available. However, the 4D TASAR technology takes both constraints into account and recommends long range cruise speed and an altitude that minimizes total fuel burn. The trajectory optimization, when approved and executed, arrives three minutes late at TEX (still in the ATC window), and lands at KDFW to arrive at the gate just after the preceding aircraft has vacated. This takes advantage of the flexibility in the ATC constraint to optimize the airline's use of its own resources and save additional fuel as well.

4.4 Scenario 4: Speed Profile Optimization

Delays encountered in flight from all causes have one common factor: they usually contain uncertainty in severity and their delay-causing duration. This uncertainty suggests that a “time-to-go based” rationale for absorbing delay should be implemented in the 4D TASAR technology for accommodating constraints at forward waypoints.

In this scenario, Flight 5767 from Charlotte to Minneapolis (KMSP) departs on time on a day when thunderstorms are forecast across the upper Midwest, potentially affecting KMSP arrivals at the scheduled arrival time of Flight 5767. The FAA’s ATC System Command Center did not issue any ground delay program for KMSP before departure because the forecast probability for the convective activity had not reached 30%. However, as the flight enters southern Indiana, a squall line begins to develop over western Minnesota. This weather event prompts the ATC System Command Center to predict a capacity reduction and trigger a Traffic Management Initiative for flights still on the ground bound for KMSP containing 20 to 30 minute delays. Flight 5767 is advised of this situation by Indianapolis Center and by their own flight dispatch, but no constraint is yet issued. The company dispatch, anticipating that the flight will be delayed, requests that the flight crew change the 4D TASAR technology optimization objective to “fuel”. This results in a request to ATC for a modest speed reduction, and the request is approved by ATC. Shortly thereafter, TBFM issues a meter time at the KBULL arrival fix on the KKILR3 arrival that requires a substantial additional speed reduction, but not one that exceeds the performance limitations of the airplane. An RTA instruction corresponding to the TBFM meter time is issued by Minneapolis Center. The 4D TASAR technology ingests the constraint, and uses its capability to keep some time adjustment in reserve as the constraint point was approached. As the aircraft approaches KMSP, the direction of the thunderstorm changes, causing the ground delay program at KMSP to be terminated. Furthermore, the RTA instruction for Flight 5767 is cancelled. The 4D TASAR technology is once again given the “trip cost” objective from dispatchers at the AOC, and the flight is able to arrive only five minutes late since the expected delay was not already absorbed too far from the airport to make most of it up.

5. Recommendations for Technology Implementation

Based on the use cases discussed in Section 3 of this document, this section discusses technical implementation details of the 4D TASAR concept. Changes to the trajectory generator, trajectory optimizer, existing data sources, and the human-machine interface are discussed. A reference system architecture is provided and operational procedures are presented.

5.1 Modifications to the Existing Trajectory Generator

The 4D TASAR technology makes use of the BBTG described in [22] to perform the trajectory generation function. The BBTG is a precise, accurate, and efficient tool for predicting the trajectories of civil passenger aircraft, including the prediction of elapsed time and fuel consumed. Furthermore, the BBTG is designed to be adaptable to wide variety of aircraft models with various types of performance data presented in disparate encodings and formats.

The BBTG is an integral component of the Basic and Digital TASAR technologies, and provides predictions of lateral position, time, and altitude along the trajectory as well as total fuel consumption. Like many trajectory generators, the BBTG decouples the lateral trajectory computations from the vertical trajectory computations. The lateral portion provides lateral guidance by defining how the aircraft will follow a lateral path over the surface of the Earth and, and the vertical component provides vertical and longitudinal guidance by defining whether and how the aircraft will climb or descend along that path, as well as how the speed along the path is controlled. The BBTG provides solutions for hundreds of candidate trajectories in at most a few seconds of real time in order to populate the optimization algorithm [22].

This section discusses modifications to the BBTG that are required to realize the 4D TASAR concept, including using wind blending algorithms to provide more accurate predictions of fuel burn and waypoint time of arrival and adding logic to the vertical trajectory computations to modify the speed along the path.

5.1.1 Wind Blending in the Trajectory Generator

Most FMS avionics employ “wind blending” in the trajectory prediction function. Wind blending allows the trajectory generator to use wind data derived from a mix of currently sensed wind values and forecast values at downstream points [30]. Different FMS manufacturers have different approaches to process wind data and to blend forecast with sensed wind. An example wind blending methodology adapted from [31] is shown in Figure 1. Note that at the present position of the aircraft, only sensed wind is used. At 200 nautical miles along the route in cruise, or 5000 feet above or below the aircraft’s current altitude, the sensed wind is blended 50% with the forecast wind. At 700 nautical miles along the route, or 18,000 feet above or below the aircraft’s current altitude, only forecast wind data are used[6].

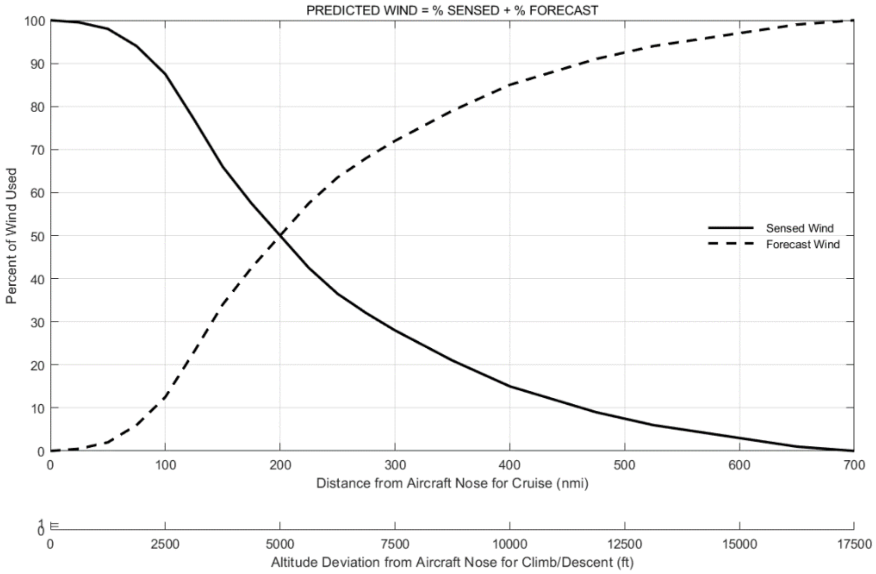

Figure 1: Notional Wind Blending Algorithm

The BBTG seeks to predict a trajectory that very closely matches the trajectory predicted by the aircraft’s FMS and thus, should apply a similar wind blending methodology to its trajectory predictions. Blended sensed/forecast wind data are used to increase the accuracy of several facets of a trajectory generator’s prediction, including estimated times of arrival, fuel burn, rate of climb/descent, and the transition between lateral (i.e., turns), and vertical (i.e., top-of-descent) legs [32]. It is postulated that the 4D TASAR technology will benefit from using wind blending in its trajectory generator due to more accurate predictions of time of arrival and fuel burn.

5.1.2 Incorporation of Time Constraint Data

A time of arrival constraint must be provided to the 4D TASAR technology. These constraints, as described in Section 4 of this document may come from air traffic control, the airline, the flight crew, or any combination of those entities. There may be situations, as discussed in Section 4, where an aircraft is provided with multiple time of arrival constraints at unique points on the trajectory. Time constraints are entered into the aircraft’s FMS, from which the 4D TASAR technology reads them.

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[6] Note: Wind blending at other points on the trajectory between these distances is provided by interpolating along the function shown in Figure 1.

Currently, time constraints for an RTA operation are only “AT” constraints. However, future time of arrival constraints may take one of several forms, including “AT”, “AT or AFTER”, “AT or BEFORE”, or “BETWEEN”. For each of these constraint types, there is a universal tolerance associated with the constraint where the aircraft maintains conformance with the constraint (if the source is ATC) or objective (if the source is the airline or flight crew). Table 1 below depicts the tolerances for each constraint type. In the table, “t” is the trajectory prediction time, “t_0” is the constraint time for “AT”, “AT or AFTER”, or “AT or BEFORE” constraints, “t_0” and “t_1” are the lower and upper constraint times for a “BETWEEN” constraint, “t_m” is the midpoint between “t_0” and “t_1”, and “δ” is the universal tolerance.

RTCA Special Committee 227 has published standards for time of arrival control as 95% compliance with accuracy levels of ±10 seconds for time of arrival control operations that involve the descent phase of flight, and ±30 seconds for time of arrival control operations that involve the cruise phase of flight given a defined meteorological uncertainty model [33]. It is suggested that, depending on the location of the time control point, that these accuracy levels are used to define the tolerance, “δ,” for the 4D TASAR technology.

Table 1: Tolerance Definitions for Each Constraint Type

Constraint Type	Time of Arrival Constraint	Lower Tolerance	Upper Tolerance
AT	$t = t_0$	$t_0 - \delta$	$t_0 + \delta$
AT or BEFORE	$t < t_0$	$t_0 - 2\delta$	t_0
AT of AFTER	$t > t_0$	t_0	$t_0 + 2\delta$
BETWEEN ($t_1 - t_0 > 2\delta$)	$t_0 < t < t_1$	$t_0 - 2\delta$	$t_0 + 2\delta$
BETWEEN ($t_1 - t_0 < 2\delta$)	$t_0 < t < t_1$	$t_m - \delta$	$t_m + \delta$

The reason for these tolerances is to preclude a requirement that the BBTG produce a prediction that arrives at a point exactly at a particular required time. The ETA of the prediction at that point must merely be within some range of times defined by the properties of that constraint and by a predetermined universal tolerance value applied to all constraints. Algorithmically, fewer iterations are required to reach a solution that contains the best integer value for cost index used to determine the speed profile along the trajectory.

5.1.3 Modifications to the Vertical Trajectory Generation Function

Currently, the Basic TASAR and Digital TASAR technologies do not modify the speed of the aircraft. Optimizations are performed in three dimensions—horizontal (longitude/latitude) and vertical (altitude). To meet a time of arrival constraint, the 4D TASAR technology must be able to modify the longitudinal (speed) dimension, which occurs during the generation of the vertical component of the trajectory.

The first step in this process occurs in the PBGA, which performs the trajectory optimization function. The PBGA creates trajectory intent that specifies a lateral path change, a cruise altitude change, or changes to both the lateral path and cruise altitude. That trajectory intent information is then passed to the BBTG. In the 4D TASAR technology, if trajectory intent obtained from the PBGA would not meet the time constraints, the BBTG will iterate on possible trajectories until the ETA at the RTA waypoint is within the pre-specified tolerance of the RTA, as discussed in Section 5.1.2. There are a number of methods for accomplishing this iteration, depending how speed is specified in the trajectory intent from the PBGA. For example, if the trajectory intent specifies a cost index and adjusting cruise speed might meet the constraint, the BBTG will first adjust the cost index[7]. If the trajectory intent specifies a cruise Mach or Calibrated Airspeed (CAS), the BBTG will adjust the cruise Mach or CAS (whichever applies). If the time constraint is missed solely due to speed in climb or descent, the BBTG will place minimum or maximum speed limits along the part of the trajectory that can help meet the constraint.

For a given trajectory, it is assumed that there is a predictable “unconstrained” time at which the aircraft would reach any point on the trajectory if there were no time constraints. If all “unconstrained” times satisfy

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[7] Note: previous research has demonstrated that using cost index as the independent variable for this iteration results in a trajectory that is fuel optimal for the prescribed flight time [45, 46].

the relevant time constraints, the aircraft's guidance systems will cause the aircraft to reach each point at the predicted "unconstrained" time, and thus, the aircraft will not modify its speed in response to the time constraint. Furthermore, it is assumed that if some "unconstrained" time violates a time constraint, the 4D TASAR technology will provide guidance that adjusts the aircraft's speed, but will not speed up or slow down the aircraft more than is necessary to satisfy all time constraints. Finally, it is assumed that the algorithm for satisfying time constraints will not alter the lateral or vertical trajectory intent received from the PBGA or any published procedural altitude or speed constraints to achieve the time of arrival constraint.

Figure 2 shows two simple examples of the application of a time constraint. In these figures, the horizontal axis measures elapsed time and the vertical axis measures distance traveled along the path. The horizontal dashed lines, annotated with "WYPT1" indicate the position of a time constraint along the path, and the gap between the arrowheads on that line represents the permitted window of time during which the aircraft must pass the constraint point. In these examples, the constraints are shown as "BETWEEN" constraints. In order to see how these examples apply to other constraints, consider an "AT" constraint as a "BETWEEN" constraint bracketing the time tolerance around the "AT" constraint's required time of arrival (i.e., the arrowheads touch each other at a single point), and consider "AT or AFTER" and "AT or BEFORE" constraints as "BETWEEN" constraints with one missing arrowhead.

In each part of Figure 2, the "unconstrained prediction" (shown as a solid gray line) is what is predicted forward from some point on the path (e.g., the trajectory prediction initial conditions) if the predicted speeds are computed from information in the intent and performance model without regard for time constraints. In Figure 2a, the unconstrained prediction arrives at the constraint point too late. Therefore, the leg (or legs) of the trajectory prior to WYPT1 must be recalculated using increased predicted speeds. The recalculation of the relevant portion of the trajectory is performed iteratively one or more times to find a trajectory that satisfies the time constraint. In each iteration, the BBTG adjusts one or more parameters (such as cost index) that control the speed at which the aircraft is predicted to fly at any point on the trajectory (e.g., cost index). When the aircraft reaches the constraint point at the maximum time bound (allowing for the tolerance) according to a BBTG prediction, it becomes the constrained prediction, shown in Figure 2 as a dashed black line. Once the BBTG has adjusted the speed to meet the time constraint at WYPT1, the speed on subsequent legs of the trajectory reverts to the unconstrained speed prediction, shown in Figure 2 as a solid black line. In Figure 2b, the unconstrained prediction arrives at the constraint point too early, so the constrained prediction uses decreased predicted speeds such that the aircraft arrives at the constraint point at the minimum time bound.

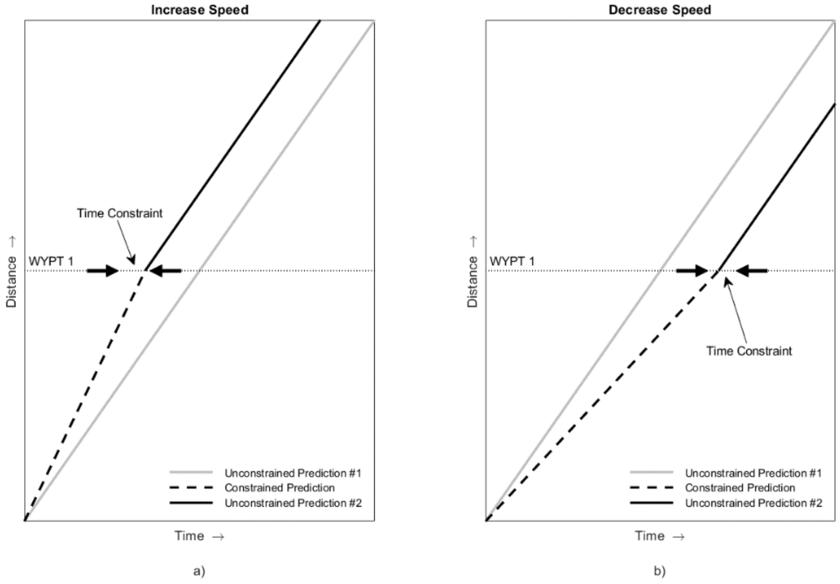
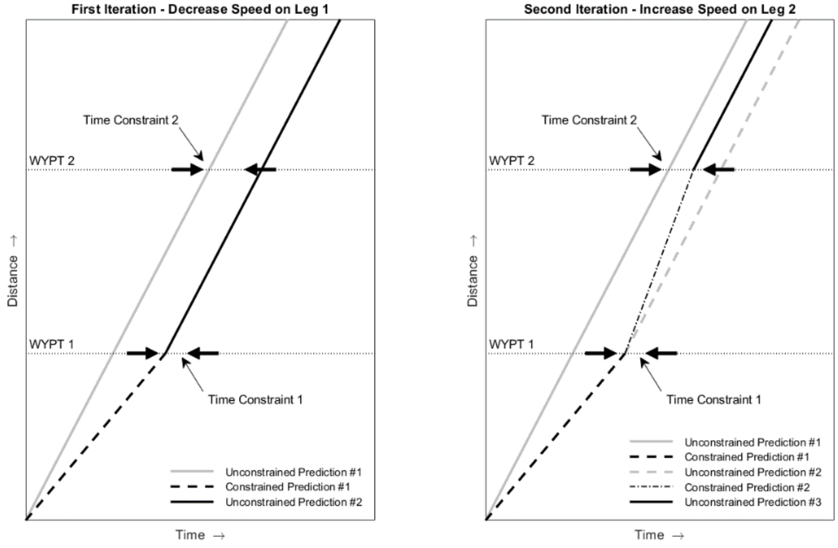


Figure 2: Examples of Single Time Constraint

The BBTG for a 4D TASAR technology will also accommodate multiple time constraints on a single trajectory. Figure 3 demonstrates the process for computing a trajectory that is subjected to multiple time constraints. In Figure 3, there are two constraints, one at WYPT1 and another at a downstream fix called WYPT2. In this example the unconstrained prediction, shown in Figure 3 as a solid gray line, satisfies the constraint at WYPT2, but does not satisfy the constraint at WYPT1. Therefore, a constrained prediction is made to satisfy the constraint at WYPT1. Like the example presented in Figure 2b, the leg (or legs) of the trajectory prior to WYPT1 must be recalculated using decreased predicted speeds to find the constrained prediction, depicted in Figure 3a by a dashed black line. Once the BBTG has adjusted the speed to meet the time constraint at WYPT1, the speed on subsequent legs of the trajectory reverts to the unconstrained speed prediction, shown in Figure 3a as a solid black line.



a) b)

Figure 3: Example of Iterative Process to Solve Multiple Time Constraints

However, unconstrained prediction #2 violates the time constraint at WYPT2. Therefore, another iteration of the BBTG must occur to satisfy the time constraint at WYPT2. A constrained prediction is made between WYPT1 and WYPT2 using increased predicted speeds, shown in Figure 3b as a dash-dot line, which satisfies the time constraint at WYPT2. After WYPT2, the trajectory reverts to the unconstrained speed shown in Figure 3b as a solid black line.

If no time constraint is present on the active route, this same iterative approach may be used to determine a more optimal speed profile for the aircraft to fly. The BBTG will iteratively search for the cost index value that provides a speed profile that satisfies the optimization objective. For example, if the PBGA generates trajectory intent that minimizes fuel burn at the current airspeed, the BBTG may additionally choose a speed profile that slows the aircraft down along that path, resulting in additional fuel savings. Conversely, a speed profile that increases the speed along that same trajectory will save additional time.

5.2 Modifications to the Existing Trajectory Optimizer

The 4D TASAR technology makes use of the PBGA described in [21] to perform the trajectory optimization function. The PBGA is able to search a large quantity of candidate route changes, accounting for a multitude of diverse “fitness” factors. Through successive generations of mating and mutation, the PBGA determines the optimal solution, where “optimal” is defined by a fitness function that relates to the optimization objective (e.g., minimum fuel, minimum time, minimum cost). For instance, as the PBGA evaluates candidate route changes (starting with random sampling), it applies fitness penalties to those in conflict with traffic, weather, and Special Use Airspace (SUA) while rewarding those that are more “on time” and have greater cost savings (measured in time or fuel). Characteristics of route-change “winners” are perpetuated as-is or through mating to future generations, while “losers” are dropped. The outcome of AOP PBGA is a strategic route change that is both conflict free (within defined parameters) and optimized according to the objective set by the flight crew and/or airline.

This section discusses proposed beneficial changes to the PBGA to realize the 4D TASAR concept. These changes include new solution types, as well as new lateral patterns that may be implemented to meet a time of arrival constraint along an arc instead of at a point.

5.2.1 New Trajectory Modification Solution Types

The Basic TASAR technology provides three types of trajectory modification solutions: Lateral, Vertical, and Combination Lateral + Vertical (known as Combo) solutions. The Lateral solution form is a modified route (MOD RTE) in the FMS[8]. The Vertical solution form is a single step climb or descent (STEP) occurring at a point along the trajectory. Finally, Combo solutions take the form of a MOD RTE in conjunction with a step climb.

When the 4D TASAR technology is used to optimize the route in the presence of a time of arrival constraint, an initial cost index and time component are added to each of these types of solutions. The initial cost index is obtained from the BBTG prediction of the speed profile required to achieve the time of arrival constraint, and the time component is obtained from the BBTG prediction of the ETA at each constrained waypoint.

For example, if ATC provides a time constraint (e.g., AT or AFTER 1230Z) at waypoint *ABC*, the PBGA responds with a solution that has:

- An initial integer cost index to set the speed profile (e.g., 67).
- A time constraint at *ABC* based on the ETA prediction from the BBTG (e.g., AT 1232Z) for the RTA-meeting capability in the FMS to execute against.

Additionally, a new trajectory modification solution is permitted in the 4D TASAR concept: a speed-only solution. The Speed solution is in the form of the active route (ACT RTE) with an updated cost index that determines the speed profile of the aircraft and the indicated airspeed that the aircraft would fly after implementing the request if approved. Appendix A provides more details regarding the form of each type of solution, and a comparison of Basic TASAR and 4D TASAR solutions.

5.2.2 New Lateral Pattern for Metering Arcs

The TBFM automation works by building arrival time schedules to Constraint Satisfaction Points (CSPs). The TBFM scheduler establishes a sequence of aircraft based on each flight’s ETA at the CSP, and then assigns a STA to each flight that satisfies the CSP’s inter-arrival spacing requirements. A CSP is defined as a meter arc, a meter fix, meter point, or other meter reference elements [34].

As discussed in Section 4.2, TBFM includes multi-center metering to coordinate the handling of constraints that affect multiple facilities and to enable distributing required delay over a longer flight path to multiple centers. For example, if metering causes a situation that requires an aircraft to absorb more delay than can be accommodated by slowing down in the one Center alone, TBFM will work backward along the intended trajectory of the aircraft and assign the remaining delay to the preceding Center. This permits the delay to be absorbed using only speed control. In this example, a metering arc may be used to control the flow of aircraft over the Center boundary, instead of at a single point. ATC frequently uses a metering arc rather than a fix to accommodate controller vectoring and to account for aircraft not established on an arrival route or assigned a meter fix.

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[8] Note: Building upon the capabilities of the proposed Digital TASAR technology, a 4D TASAR “Lateral” solution may include a number of latitude/longitude coordinate waypoints, and/or updated arrival procedures.

The use case scenario described in Section 4.2 features a metering arc at the boundary of adjacent Center airspace. In the scenario, the 4D TASAR technology recommends a trajectory modification that crosses the metering arc at a point not originally on the active route, but on the metering arc. This scenario simultaneously provides a user-preferred optimized trajectory and satisfies the time of arrival constraint.

To accommodate meter arcs, the 4D TASAR technology must be made aware of the geographical definition of the meter arc (e.g., the latitude/longitude coordinate points of the arc). These data (and other ATC operational data) may come from SWIM. Additionally, a new PBGA pattern must be implemented that makes use of the metering arc. This pattern would allow trajectory modification solutions to satisfy a constraint at a CSP that may not exist on the active route. Further research is required to define the pattern and understand the impacts of trajectory modification recommendations that use this pattern for traffic flow management.

5.3 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, Automatic Dependent Surveillance – Broadcast (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 proposed changes to input data sources that would enable and/or provide additional benefits for a 4D TASAR technology.

5.3.1 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 of 40 km 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 do not consider time constraints, 4D TASAR requires higher fidelity winds to ensure accurate predictions of the estimated time of arrival at each waypoint. 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 [30]. 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 recommended that the 4D TASAR technology use the 3-km HRRR model for its wind data source.

Edwards, et al. posit that higher resolution wind data delivered to the aircraft frequently will allow the FMS trajectory generator to provide guidance that is more accurate when performing time of arrival control operations [30]. However, the impacts of this additional information may vary across the NAS, since airlines are inconsistent with different practices and procedures for processing forecast wind data provided to aircraft and different FMS manufacturers permit different amounts and types of forecast wind data to be entered [36]. Since the 4D TASAR technology will use 4-D gridded forecast wind data, the benefits hypothesized by Edwards, et al. may be realized, and be greater for a 4D TASAR technology that incorporates high-fidelity and high-frequency forecast wind data into its trajectory predictions, than they are for an FMS.

Furthermore, modern aircraft provide the flight crew and avionics with data regarding sensed wind information. The aircraft measures the difference between true airspeed and groundspeed and between track and heading to determine both wind magnitude and wind direction. These data are typically available from the FMS for consumption by third-party applications. By fusing sensed winds and forecast wind data, accurate time of arrival predictions may be achieved along the trajectory, as discussed in Section 5.1.1.

5.3.2 Fuel Data

The Basic TASAR technology receives fuel loading information from the aircraft's FMS in order to predict fuel savings for each optimized trajectory recommendation. The fuel loading is derived by subtracting the aircraft's zero fuel weight (a parameter in the performance model) from the aircraft's gross weight[9]. Aircraft carry reserve fuel onboard in addition to fuel required to fly from the departure airport to the destination airport. Flight crews, and their airlines, often load the aircraft with additional fuel above the legal reserve fuel requirements. The amount added, called extra fuel, is a combination of airline standard operating procedure and pilot discretion.

In Basic TASAR operations, it was very unlikely that a given trajectory recommendation would present a situation in which, in order to save time, the predicted fuel burn would cause the aircraft to arrive at the destination airport with less fuel than the legal reserves. However, in a 4D TASAR implementation, the 4D TASAR solution may include an increased fuel burn to accommodate a large ATC delay while masking the delay to the crew's awareness. Therefore, it is proposed that the 4D TASAR technology protect against trajectory optimization recommendations that include a fuel at destination value that is less than the legal reserves, and alert the flight crew when the predicted fuel at destination has used some of the extra fuel.

From a technical implementation perspective, this protection may be provided by including both the legal reserve fuel data from the FMS as a static manual entry input to the 4D TASAR technology on startup, and the extra fuel as a configuration setting. The configuration setting for extra fuel should range from zero (i.e., only protect against reserve fuel) to 10,000 lbs. on most jet transports.

5.4 Data Comm Messages Appropriate for 4D TASAR

Since the 4D TASAR concept builds upon the Digital TASAR concept, flight crews using a 4D TASAR technology will be able to make trajectory modification requests to ATC via Data Comm. The functionality of 4D TASAR described in this paper will be sufficiently supported by existing message sets [37, 38]. Table 2 contains messages from the Digital TASAR concept that may be used for 4D TASAR procedures. From left to right in the table are the Data Comm message identification number, the intent of the message, message elements (variables are italicized), and the Digital TASAR use case identifying when each message could be used.

Table 2: Digital TASAR Data Comm Messages Used for 4D TASAR Operations

Message ID	Message Intent/Use	Message Element	4D TASAR Use Case
DM24	Request for the specified route	REQUEST [*Route Clearance*]	• Request a lateral, vertical, or combination solution that contains time constraints[10] along the active route. • Request a speed solution that has multiple speed changes at waypoints in the route.

The 4D TASAR concept can make use of an additional message in the existing Data Comm message set not used in Digital TASAR for Speed solutions. DM18, shown in Table 3, permits the flight crew to request an airspeed to fly. While DM24 in Table 2 also allows a Speed solution to be requested, DM18 provides a

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[9] Note: This weight value also includes the weight of passengers and cargo. However, in nominal operations it is assumed that this value is static.

[10] The time constraint requested as part of DM24 refers to an ATC-issued RTA instruction if one exists.

more unambiguous mechanism to request the speed solution. The limitation of DM18 is that only one speed can be requested, and the request is for immediate implementation (i.e., DM18 does not support multiple speed requests or a speed request at a future waypoint).

Table 3: Additional Existing Data Comm Messages Used for 4D TASAR Operations

Message ID	Message Intent/Use	Message Element	4D TASAR Use Case
DM18	Request for the specified speed	REQUEST [*Speed*]	• If ATC has assigned a cruise speed, the flight crew may request a speed solution that contains a single speed change (e.g. modify cruise speed).

While the existing message set is sufficient for 4D TASAR procedures, the messages proposed in Table 4 would permit unambiguous requests of 4D TASAR solutions.

Table 4: Proposed New Data Comm Messages Used for 4D TASAR Operations

Message Intent/Use	Message Element	4D TASAR Use Case
Advise ATC of specified speed	ADVISE [*Speed*]	• If ATC has not assigned a cruise speed, the flight crew may advise ATC[11] of a speed solution that contains a single speed change (e.g. modify cruise speed).
Advise ATC of specified speed at one or more positions	AT [*Position*] ADVISE [*Speeds*]	• Advise a speed solution that has multiple speed changes at waypoints in the route • Advise a speed solution that contains a single speed change (e.g. modify cruise speed) at a future waypoint.

5.5 Human-Machine Interface Design Goals

The flight crew fulfills an essential role in the 4D TASAR concept. They ultimately make the decision whether to optimize the flight and what trajectory modification request they make to ATC. Therefore, the 4D 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 to human factors that reflect the pilot's interaction with, and experience using, the 4D TASAR technology.

The flight crew interacts with the 4D TASAR technology through a human-machine interface (HMI). To maximize the pilot's use of 4D 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 4D TASAR HMI. Air transport pilot subject matter experts (SMEs) consulted on the design of a human-machine interface for a 4D TASAR application offered several useful perspectives. The design goals were to (1) provide unambiguous presentation of 4D TASAR solutions to the flight crew, and (2) allow the flight crew to cross-reference the optimized route across multiple data sources (e.g., FMS, on-board weather radar, EFB-based weather applications) when assessing its acceptability.

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[11] It is the flight crew's responsibility to advise ATC when the cruising airspeed varies plus or minus 5 percent or 10 knots, whichever is greater, from the current airspeed given in the flight plan. [47]

5.5.1 Unambiguous Display of 4D TASAR Solutions

Based on SME feedback, one of the most important considerations for 4D TASAR HMI design is the need to ensure that the flight crew is aware of all pertinent information to the operation, while avoiding situations where the flight crew is overloaded with information. The flight crew must be aware of all time of arrival constraints considered by the 4D TASAR technology. The pilot SMEs identified that both graphical and textual display of altitude, speed, and time constraints was highly desired to allow the pilots to quickly assess proposed changes to the route or a change in arrival time. To prevent information overload that may distract the flight crew from their normal duties, textual and numerical information should take up minimal space on the display, and may be included as a selectable layer on the display to prevent clutter.

Since the 4D TASAR concept builds upon the Digital TASAR concept, trajectory recommendations may be complex. Therefore, the combination of additional constraint information and increasingly complex trajectory recommendations necessitates the need for a user to identify key information at a glance. Being able to view this routing graphically overlaid with information such as constraints, convective weather, wind fields, turbulence areas, and Significant Meteorological information (SIGMETs) will give the flight crew a complete picture of the impact of the new route in an efficient and easily understood format.

5.5.2 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 4D TASAR technology, this could be achieved through a “copy/paste” functionality between applications.

To build trust in the system, flight crews should have an awareness of which data sources are contributing to an optimized route. By displaying these sources and their availability, the flight crew can better understand why the automation recommended the displayed trajectory modifications. The critical data required for all optimizations are aircraft state data, the optimization objective, and winds aloft. Without these data, the 4D TASAR technology would be inoperable. Therefore, an “inoperable due to …” status message should be displayed to the flight crew to indicate that the 4D TASAR tool is currently in an inoperable state and the rationale for the message.

Other sources, such as ADS-B traffic data and convective weather data, provide information to filter out unusable solutions, thereby increasing the likelihood of ATC accepting the requested trajectory modification. Since these data are supplemental to the optimization task, the 4D TASAR technology can still provide recommendations in the absence of these data. However, the solution may be contain an unknown conflict. For example, if convective weather data becomes temporarily unavailable, the 4D TASAR technology will generate solutions that will not account for weather. Therefore, the recommended trajectory modifications may penetrate an unknown area of weather, which is not acceptable. The 4D TASAR technology should provide the flight crew with the status of all data parameters so, in the event that a data source becomes unavailable, this flight crew could cross-reference the solution against other available data sources in the flight deck.

5.6 System Architecture

The 4D TASAR technology implementation uses and builds upon the existing software components of the Basic and Digital TASAR technologies. Similar to Basic TASAR, a system architecture that uses an EFB hosting the 4D TASAR technology is highly desired. The form of 4D TASAR solutions, the requirement to maintain cognizance of all constraints that the aircraft is subjected to, and the ability to utilize the Digital TASAR functionality for making requests necessitates continuous synchronization between the FMS and 4D TASAR technology. Recent industry advancements allow EFB applications to interface directly with the aircraft's FMS [40]. These interfaces will allow the 4D 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 4D TASAR technology; specifically, to transmit Data Comm requests through certified avionics or update the cost index based on the 4D TASAR solution.

A high-level definition of the components of a 4D TASAR technology follows. Figure 4 provides a schematic that illustrates component connectivity.

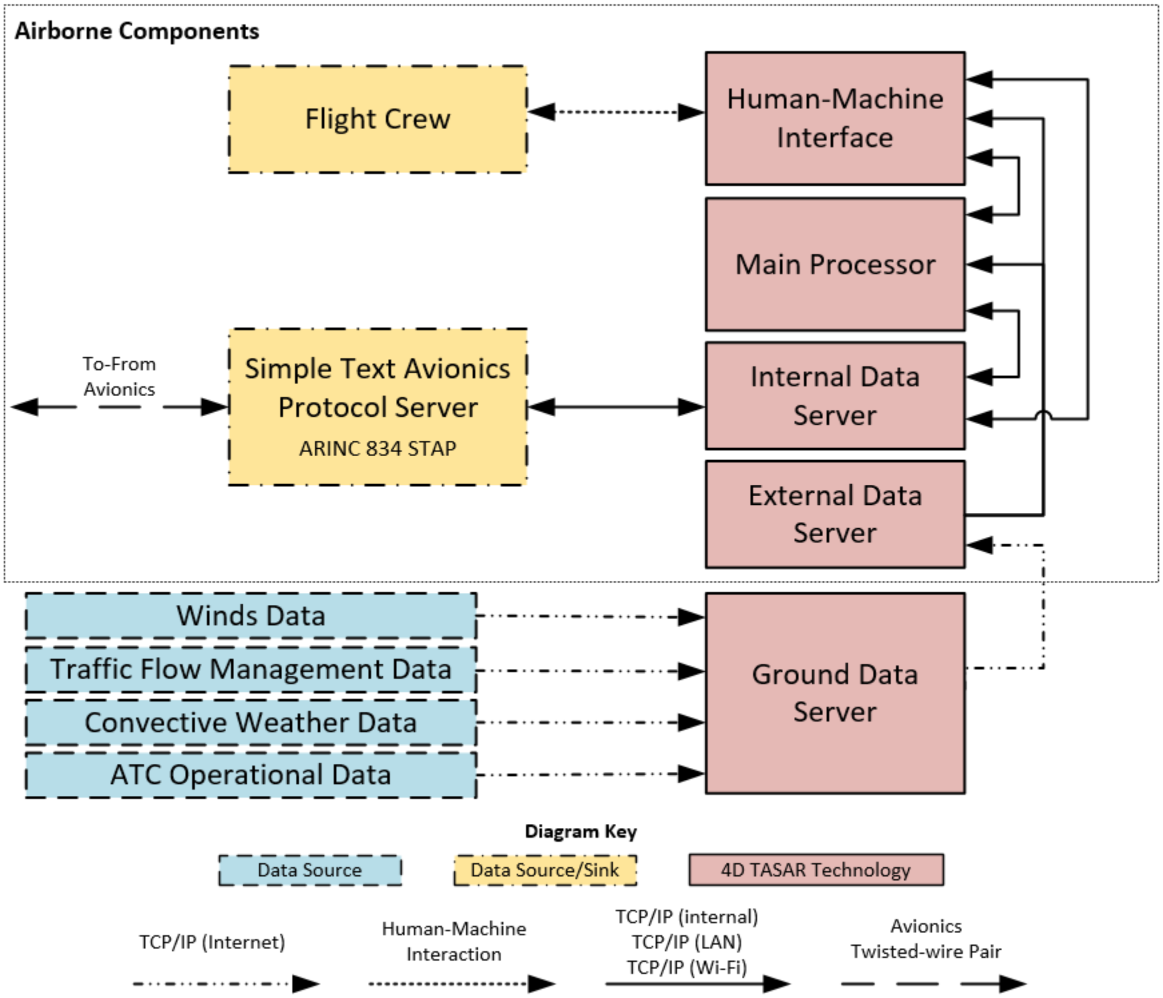

Figure 4: 4D TASAR Technology Reference System Architecture

5.6.1 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 Human-Machine Interface. It consists of a trajectory optimizer (the PBGA discussed in Section 5.2) that generates candidate solutions, a conflict probe that searches for conflicts along those candidate solutions, and a trajectory generator (the BBTG discussed in Section 5.1) that computes a trajectory that meets any speed, time, or altitude constraints present on the active route for the candidate solutions. The 4D TASAR Main Processor will incorporate the changes described in Sections 5.1 and 5.2.

5.6.2 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 pilot-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), time and fuel outcomes for each trajectory solution, conflict information, and additional information regarding the internal state of the system. The 4D TASAR implementation of the HMI will incorporate the modifications described in Section 5.5.

5.6.3 Internal Data Server

The Internal Data Server is a component that was introduced in the Digital TASAR technology. It serves as an interface between the onboard components of the 4D TASAR technology and the 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 4D 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 4D TASAR 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 (e.g., connections providing data to the External Data Server described in Section 5.6.4). The Internal Data Server ingests an ARINC 834 data feed from an AID (Aircraft Interface Device) 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), formats the selected trajectory data into the appropriate format (i.e., the proper Data Comm message outlined in Section 5.4) and routes it to the aircraft's FMS and ultimately to ATC.

5.6.4 External Data Server

The External Data Server serves as an interface between the airborne components of the 4D TASAR technology and data that originate external to the aircraft. It handles the downloading, decrypting, decompressing, and formatting of winds aloft, convective weather, SUA, and ATC 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. The 4D TASAR External Data Server will incorporate the changes described in Section 5.3, including high-fidelity forecast wind data and ownship-sensed winds.

5.6.5 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 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 4D TASAR technology with winds aloft data, convective weather data, SIGMET data (convective and turbulence), and SUA data appropriate to the location of the aircraft and 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. NASA designed, built, and hosted a prototype Ground Data Server for the Alaska Airlines TASAR operational trial [41]. However, a commercialized Ground Data Server may be owned and operated by an AOC or a third-party service provider.

5.7 Operational Procedures

5.7.1 Trajectory Modification that Meets Time of Arrival Constraint

A required time of arrival can be created by either ATC or dispatchers in the AOC. ATC would issue a time of arrival constraint to the aircraft via voice communication or Data Comm, whereas dispatchers provide a recommended arrival time through ACARS. In some cases, the required time of arrival generated by a ground system will likely not take an aircraft's performance or fuel load into consideration, necessitating a review by the flight crew to determine if they are capable of adhering to the RTA. Once the flight crew determines they are capable of meeting the RTA constraint, they accept it via Data Comm for ATC-generated RTAs, or notify dispatch via ACARS that they will follow the recommended guidance. The RTA data would then be entered into the FMS (manually for ATC Voice Comm or dispatch ACARS, or automatically for ATC Data Comm). Once the RTA information is loaded into the FMS and executed, the time of arrival constraint is automatically transmitted from the FMS into the 4D TASAR technology.

Once the 4D TASAR technology provides the flight crew a route optimization solution that considers the time of arrival constraint and provides an operating benefit, the flight crew would select it for further consideration and review 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 4D 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[12]. 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 request 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 change, the flight crew would load the clearance into the FMS, accept it through Data Comm, 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 4D TASAR trajectory modification request that considers a time of arrival constraint is shown in Figure 6 in Appendix B.

5.7.2 Request Trajectory Modification that Optimizes the Profile

There are cases in which the flight crew would determine that the current flight profile could be optimized to achieve fuel or time savings. In this case, the flight crew would reference the 4D TASAR technology to

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[12] Note: 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

review the suggested lateral, altitude, speed, or combination route optimizations. Once the flight crew selects an acceptable route modification, they would review it and note how the route differs from the active route. The flight crew would then cross-reference the optimized route against weather and airspace data that is not available to the 4D TASAR technology such as turbulence data. A route that requires a significant deviation from the active route may require communication with the AOC via ACARS for concurrence. Once concurrence on a route modification is reached, the flight crew would create a digital TASAR request and transmit the request to ATC via data comm. ATC could then approve the route modification without changes, approve the route modification with changes, or reject the changes outright.

A request that is approved without changes would prompt the flight crew to load and execute the route modification into the FMS. An approved request with route changes would prompt the flight crew to review the changes to the route modification to determine whether the changes would exceed the vehicle performance and fuel load capabilities of the aircraft as well as the route's proximity to weather and other hazards. If the changes to the route modification are acceptable, the crew will accept the changes, load, and execute the route in the FMS. 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 4D TASAR trajectory modification request that optimizes the speed profile is shown in Figure 6 in Appendix B.

6. Future Research

The 4D 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 this future research. Topics include how delay is absorbed by the speed modification algorithms, understanding the operational benefits of making multiple trajectory modification requests to meet time of arrival constraints, the expansion of the "Trip Cost" optimization objective to include more airline-specific data in optimizations, usability of the 4D TASAR HMI, and other human factors considerations.

6.1 Algorithm Behavior Approaching the Waypoint

As the ATC requirements for times at waypoints is just as dynamic as the airline's desired time at the gate, the method chosen by the algorithm to meet the time constraints should maintain the flexibility to change the arrival time both earlier and later, within the performance tolerance of the airplane, as presented in Section 5.1.2. This flexibility is at its maximum when the aircraft is farthest from the time of arrival control point. For this reason, the algorithms should not attempt to absorb all of the delay early in the flight; rather, the delay should be proportionally absorbed as a function of the time or distance remaining before crossing the constrained waypoint. Figure 5 below illustrates three methods for absorbing the required delay in this more flexible manner.

Flexibility in the time to meet the constraint can be further improved if a continuously varying speed is used to meet the time constraint instead of using discrete speeds (as shown in Section 5.1.3, Figure 3). NASA's previous work on time of arrival concepts should be evaluated for their possible implementation in the 4D TASAR technology [42, 43].

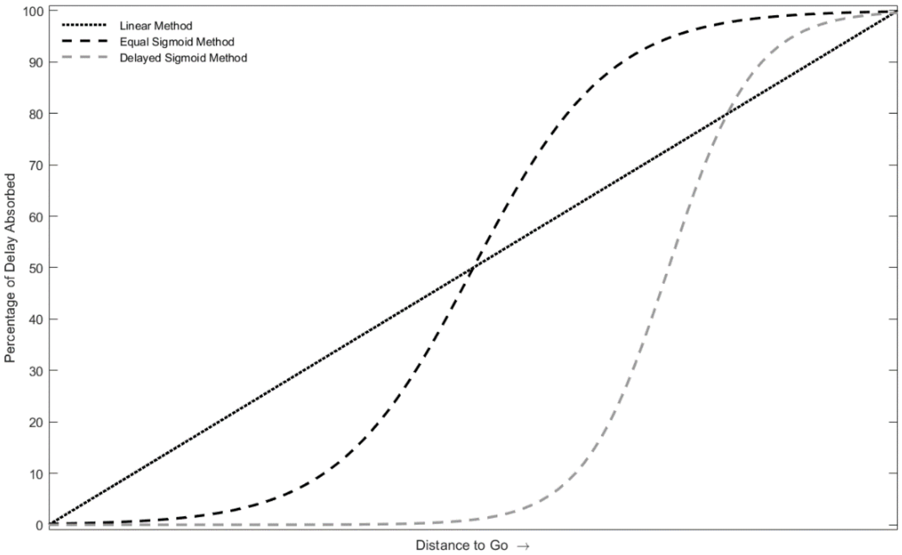

Figure 5: Delay Absorption as a Function of Distance to Control Point

6.2 Multiple Trajectory Change Requests to Meet Time Constraint

Many modern aircraft can meet single time of arrival constraints by using capabilities that exist in the FMS that modify the speed profile of the aircraft. Once the time of arrival constraint is issued to the aircraft and loaded into the FMS, the RTA meeting capability will iterate through the cost index parameter to find a speed profile that achieves the time of arrival constraint. Once the cost index is set, the speed profile is provided as guidance to the autoflight and autothrottle systems that execute the guidance. Periodically as the flight progresses, the FMS will re-compute the trajectory to ensure that the time of arrival constraint is still met, and if it is not, the cost index is iterated again to determine a new speed profile that meets the time of arrival constraint. If the iterations are not able to converge on a solution that achieves the time of arrival constraint, the flight crew are alerted, at which point they will notify ATC that they are unable to meet the constraint.

A 4D TASAR technology uses multiple dimensions to achieve the time of arrival constraint (lateral, vertical, and speed). There may be instances where one dimension is used initially to meet the time constraint (e.g., a lateral path stretch trajectory modification), but as the flight progresses and the situation changes, the original trajectory modification may not meet the time of arrival constraint. Unlike the FMS RTA capability, which in this scenario would require the flight crew to notify ATC that they are unable to meet the constraint, the 4D TASAR may have additional trajectory modification recommendations that meet the time of arrival constraint. In this situation, the flight crew would make a request to ATC to modify their trajectory in order to comply with the time constraint. Future research should investigate whether the crew should request a route change to meet the RTA, request a change to the RTA, or, similar to the FMS procedures, notify ATC that they are unable to meet the time of arrival constraint. Furthermore, the process for making this request and a comparison of instances where the 4D TASAR technology provides solutions where the FMS cannot meet the RTA are also future research topics.

6.3 Expansion of Trip Cost Objective Related to Speed Optimization

The optimization objectives available to a pilot using TASAR today are least fuel, least time, and lowest cost for the remainder of the flight, and they are labeled Fuel, Time and Trip Cost respectively. These objectives are sought with the current optimization algorithm using only lateral and vertical trajectory changes while looking for a path that will save fuel, time, or a weighted combination of the two that will minimize the overall direct operating cost for that flight at the pre-planned cruise speed. The ability to propose a different speed to fly as well as the path in space has consequences for each of the existing three objectives. Thus, adding speed flexibility to the optimization algorithm improves the results for both fuel and time optimization. Similarly, the improved values of fuel or time saving will alter the calculation of least cost, improving that as well.

Most importantly, the Trip Cost objective can be broadened to become just “Cost”, meaning the least cost contribution from that flight to the total airline operation. Rather than focusing on the fixed cost values of fuel, crew and maintenance burden alone, the very real but variable costs of connecting passengers, flight crew and airframes to their next flights can be factored into this objective on a real time basis as the airline operational scenario (weather, ATC, ground and aircraft resources) evolves during the operating day. By building this automated process into the 4D TASAR technology, it could determine the complete flight trajectory in both its speed and flight path components using the cost optimization objective, both at the start of the flight and with modifications that occur during flight. This optimization is complex with many variables and non-linearities. The values of the variables differ among airlines (e.g., the terminals, routes, and resources available to each) and within an airline (e.g., the values of all connections), but those aspects could be customized in each airline’s implementation of the 4D TASAR technology.

The stakes are very high for correctly characterizing this complex cost-optimization process. Without getting into any single airline’s business model, the methodology for combining the many variables can be developed, and the means for relating them to the new “Cost” objective to be used on each individual flight can be determined through additional research, analysis and development. This research and development would represent a great service to the aviation industry as a logical follow-on to the TASAR development itself and it is not something likely to be pursued commercially without initial government research.

6.4 Human-Machine Interface Usability

In addition to presenting unambiguous information, it is also imperative that the HMI devices themselves should be simple to use and in accordance with the current HMI design practices. Relevant procedures and guidelines should be clear and concise and must be readily available to the flight crew. Some of the areas of interest in the future refinements of HMI for 4D TASAR are:

- The use of colors to depict tiered information to the flight crew.
- The use of labels, prompts, and feedback displays to increase efficiency.
- The use of interactive graphic displays to help navigate and comprehend large information sets.
- Time required for the flight crew to become familiar with the HMI for normal operations.

To ensure the 4D TASAR HMI design meets the needs of the users, a series of usability tasks should be conducted during the development process. The output of these tasks would ideally yield detailed requirements that would be fed to a software development team for incorporation in successive software versions. Validation of the concept and initial requirements elicitation could be achieved through a series of focus groups with 3 to 5 active airline pilot participants in each. These focus groups would be moderated by a human factors or user experience expert who would explain the 4D TASAR concept, use scenarios to describe the operation, and highlight potential benefits. Wireframe prototypes or illustrations could be utilized to provide a storyboard of the key scenarios. The primary output from this activity would be a list of desired features, design goals, and potential usability pitfalls. These outputs would drive usability metrics for user performance and subjective acceptability.

Usability testing with simulation would begin once a detailed HMI design is implemented. This usability testing would consist of airline pilot participants completing scenarios targeted towards different functionality of the 4D TASAR application in either a part task or whole task simulator. Subjective ratings of utility and ease of use for different elements of the application would be collected in addition to collecting pilot behavior and route solution performance data. A final validation of the detailed HMI could be performed in flight test using a mixed crew of test pilots and subject pilots.

6.5 Human Factors Future Research

The 4D TASAR concept presents questions regarding how wide implementation would affect ATC workload and efficiency. The increase in the number of DataComm messages to which ATC would be expected to respond could potentially increase the task load of individual controllers and reduce system wide efficiency. Before 4D TASAR can be widely implemented in the NAS, an investigation into the impact and acceptability of the concept should be conducted. One of the first research topics of interest is the determination of the number and frequency of route requests that may increase controller workload to an unacceptable degree. Furthermore, determining NAS conditions such as weather or congestion events that may produce an unacceptable level of workload and simulating them with a controller in the loop requires further research. The results of these studies could inform guidelines for how often and under what conditions flight crews should make route requests. Research into increasing the number of requests a controller could respond to and accept would need to focus on improvements to controller displays and interfaces and potentially task load allocation between sectors.

The level of complexity and automation needed or desired within a 4D TASAR application should be studied as well. Principally, the question of how much interaction with the decision process for new routes should the pilot be involved in. Follow-on questions include:

- Will an increasingly automated flight planning system make the pilot complacent and lose situational awareness?
- What inputs should be designed for the pilot to maintain awareness and interaction with the system and the solution?
- Will reduced automation levels or period of operation make the system unusable or non-practical for short flights, such as commuter or air taxi operations?
- How complex can the system and procedures be to fit in the stringent training time of airlines?

After the initial deployment of 4D TASAR technology to a cockpit environment, it might be beneficial to explore user interfaces for non-flight crew such as dispatchers and Unmanned Aircraft System (UAS) operators. These interfaces would support the expansion of 4D TASAR use outside flight deck in environments such as AOC, or a ground control station for an UAS. Due to limited flight system knowledge of non-flight crew compared to that of flight crew, it is essential to re-examine the HMI features and the information flow in order to tailor the interface while ensuring maximum efficiency. In the case of AOC, the use of 4D TASAR could mean reduced workload for flight crew, as well as reduced likelihood of error by validation of request for flight plan change. In the context of UAS operations, the use of a 4D TASAR technology may result in increasingly efficient flights with benefits comparable to commercial air transport operations that use 4D TASAR.

7. Conclusions

The 4D TASAR concept is expected to provide significant enhancements over the Basic TASAR concept by allowing airspace users to increase their level of flight efficiency and operational autonomy while conforming to system-level time of arrival constraints. The benefits described in this document are attainable in the near-to-mid-term NAS, and those benefits are provided immediately to users who choose to equip their aircraft with this technology. The 4D TASAR concept provides an exemplary use case concept that integrates directly with FAA TBFM and TFMS systems, providing airlines with an opportunity to use equipment installed on the majority of their fleet and providing the FAA with a technology that demonstrates the value of their investment in the ground automation to support TBO.

The 4D TASAR concept 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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Appendix A. Solution Forms for 4D TASAR

The 4D TASAR concept permits four types of trajectory modification solutions:

- Lateral: modify the route
- Vertical: modify the cruise altitude
- Speed: modify the along-path speed profile, and
- Combination: combination of the Lateral, Vertical, and Speed solutions.

Table 5 provides a comparison of conceptual solutions between Basic TASAR and 4D TASAR Example solutions are provided below each solution form; cyan values appended with “NEWP” are either new waypoints, new altitudes, or an updated cost index added by the PBGA, and magenta waypoints appended with “REJN” are the points retained on the active route. Waypoints (e.g., “WYPTA”) may be defined as named fixes or latitude/longitude coordinates.

Table 5: Solution Types for Basic TASAR and 4D TASAR

Solution Type	**Basic/Digital TASAR**		**4D TASAR**	
Lateral	Solution Form	{MOD RTE}	Solution Form	{MOD RTE} + {Time @ Pt1, Time @ Pt 2, …}
	Example	***NEWPA NEWPB REJNC***	Single RTA Example	***NEWPA NEWPB REJNC @ 1220Z***
			Multiple RTA Example	***NEWPA NEWPB REJNC @ 1220Z / WYPTD @ 1233Z***
Vertical	Solution Form	{STEP}	Solution Form	{STEP}, {Time @ Pt1, Time @ Pt 2, …}
	Example	***FL360***	Single RTA Example	***FL360 / REJNC @ 1220Z***
			Multiple RTA Example	***FL360 / REJNC @ 1220Z WYPTD @ 1233Z***
Combo	Solution Form	{MOD RTE} + {STEP}	Solution Form	{MOD RTE} + {STEP}, {Time @ Pt1, Time @ Pt 2, …}
	Example	***FL360 / NEWPA NEWPB REJNC***	Single RTA Example	***FL360 / NEWPA NEWPB REJNC @ 1220Z***
			Multiple RTA Example	***FL360 / NEWPA NEWPB REJNC @ 1220Z REJND @ 1233Z***
Speed	N/A		Solution Form	{ACT RTE} + {Speed @ Pt1, Speed @ Pt 2, …}
			Single Speed Immediately Example	***CI: 76, SPD: 310 KIAS*** ***CI: 76, SPD: 0.8M***
			Single Speed at Future Position Example	***NEWPA CI: 76, SPD: 310 KIAS*** ***NEWPA CI: 76, SPD: 0.8M***
			Multiple Speed Example	***NEWPA CI: 76, 0.75M, NEWPB CI: 63, SPD: 290 KIAS***

Appendix B. Operational Procedure Flowchart

Section 5.7 outlines two example operational procedures that can be conducted as part of the 4D TASAR concept—trajectory optimization in the presence of time of arrival constraints and along-path speed profile optimization. Figure 6 presents a flowchart describing the procedures. Dashed boxes represent starting points of the procedure. For trajectory optimization in the presence of time of arrival constraints, the process starts with either the AOC or ATC creating an RTA and sending an instruction to the flight crew. For along-path speed profile optimization, the process starts when the 4D TASAR technology generates an optimized route.

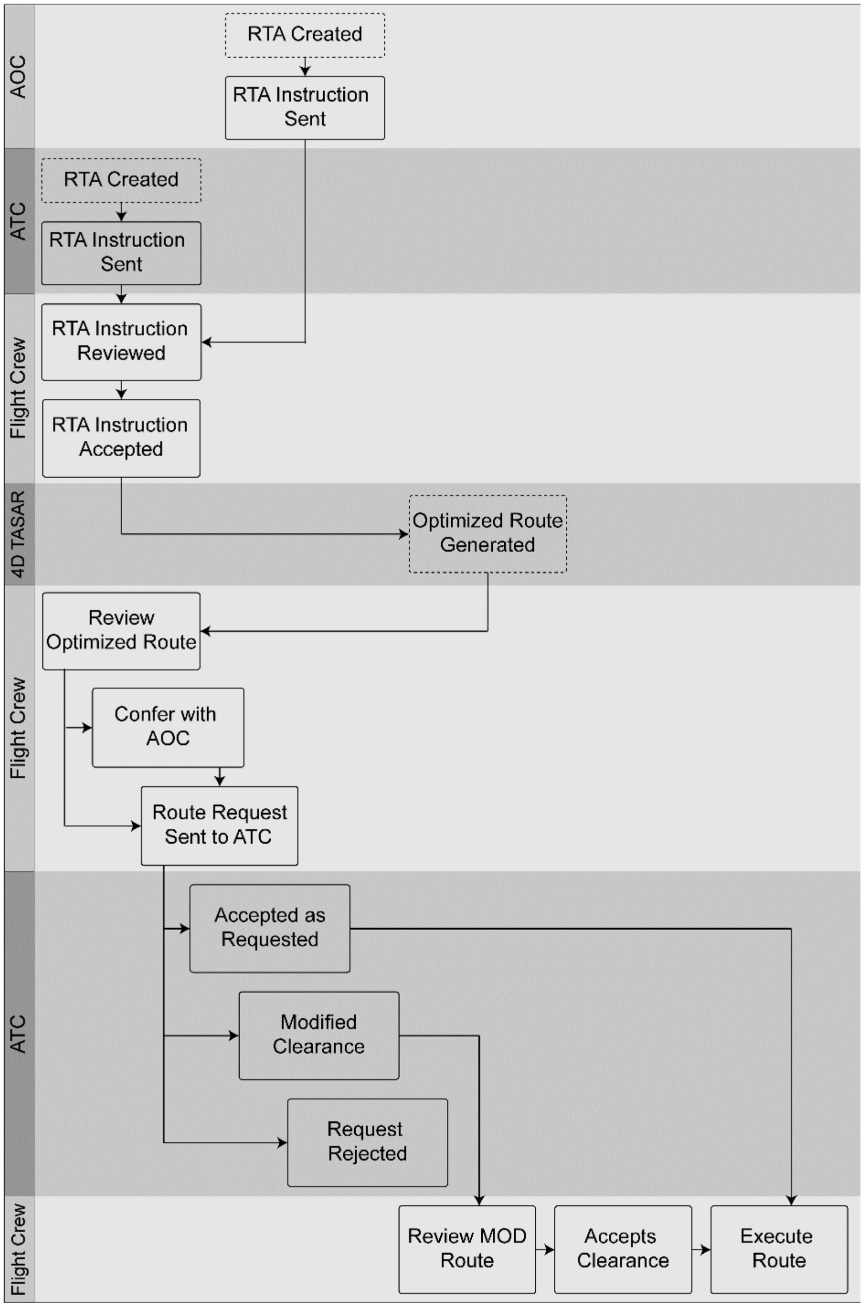

Figure 6: Trajectory Modification Requests Workflow considering Time of Arrival Constraints

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Underwood, Matthew C.; Cotton, William B.; Hubbs, Clay E.; Vincent, Michael J.; KC, Sagar; Karr, David A.

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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. To achieve system-level traffic flow management objectives while accommodating user business preferences, the 4D TASAR concept discussed in this report adds the speed dimension its trajectory optimization recommendations, permitting 4D trajectory optimization.

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