D3.3: REPORT ON AIR-GROUND COOPERATIVE OPERATION OF LONG-HAUL FLIGHT BASED ON FF-ICE

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EXECUTIVE SUMMARY

Addressing environmental challenges, especially global warming, is more than ever a must for the community. This matter is becoming an increasing priority at regional and global level. Europe has been one of the pioneers in climate change policy making since the last 20-30 years. To this end, several mechanisms have been developed, adopted and are in operation, and they include aviation as well. Aviation is crucial in the everyday life of citizens; it facilitates mobility of people, goods and services across the continent and enables connectivity to global networks. Examined from another angle, aviation also has a significant impact on citizens' welfare, as noise and air pollution are key factors in the health and quality of life of citizens. It was recognized very early, that there is no 'silver bullet', i.e. no meaningful change can be expected from one single step, but a whole set of new measures have to be implemented in a coordinated way. This is even true when due to Covid-19, the air traffic is drastically reduced and it is expected that in best case scenario, can pick up the 2019 numbers by 2024, as this expansion is expected to continue afterwards due to dynamics of global economic and social trends. However, the fallback experienced in the performance of aviation offers the chance to rebuild it greener than before. One important option is offered by certain specific thematic ones under Horizon 2020. The development of new ATM procedures, ATCO decision support tools and aircraft technologies are all intended to provide greener answers to the above-mentioned needs.

The international project "Greener Air Traffic Operations" (GreAT) has been launched in line with this perspective in a very special cooperation of Chinese and European partners, including airline operator, air navigation service provider, authority, consultants, research institutes, system developers and universities.

In MWP3, the first objective is to develop a Heterogeneous En-Route Airspace Management (HERAM) concept by identifying the boundary to divide China's en-route network into the eastern (fixed route) and western (flexible route) region, putting focus on the planning of Flexible En-Route Airspace in the West of China (FERA-WoC). The second approach is to optimize long haul flight trajectory based on integrated air-ground information (e.g., traffic situation, dynamic upper wind field), which aims at achieving a wind-optimal path and flight profile to decrease total fuel consumption and emissions during long haul flight in both structured and flexible en-route airspace.

With this document, the foundation is created for developing and advancing greener ATM procedures and techniques for long-haul flight. This is done by performing a detailed description of trajectory management process and method, conflict-free trajectory planning and separation management.

Air-ground cooperative operation of long-haul flight based on FF-ICE is described to increase the availability of user-preferred 4DT profiles and flexibility of air traffic operation. The 4DT management process based on FF-ICE and the related application scenarios are presented for implementing the greener long-haul flight, which supports the cross-border sharing and cooperation of 4DT. To support the traffic flow management in density airspace, the approach of trajectory management models and algorithms related to demand and capacity balance, traffic synchronization and conflict management are described. In addition, air-ground cooperation based on data-link is part of this document.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

GLOSSARY

Acronym	Signification
4D	4 Dimensional
4DT	4-Dimensional Trajectory
4DTRAD	4D Trajectory Data Link
ACC	Area Control Center
ACL	ATC Clearance
ACM	ATC Communication Management
ADS-B	Automatic Dependent Surveillance-Broadcast
ADS-C	Automatic Dependent Surveillance-Contract
AMC	ATC Microphone Check
APP	Approach
ATC	Air Traffic Control
ATM	Air Traffic Management
ATN	Aeronautical Telecommunication Networks
ATMRPP	Air Traffic Management Requirements and Performance Panel
ATO	Actual Time of Over
AOC	Airline Operation Center
AOP	Airport Operation Provider
ASBU	Aviation System Block Upgrade
ASP	ATM Service Provider
ATD	Airspace Technology Demonstration
AU	Airspace User
CFL	Cleared Flight Level
CPDLC	Controller Pilot Data Link Communications
CTA	Controlled Time of Arrival
CTO	Controlled Time of Over
DCL	Departure Clearance
DLIC	Data Link Capability

Acronym	Signification
EOBT	Estimated Off Block Time
EPP	Extended Projected Profile
ERAM	En-Route Automation Modernization
ETA	Estimated Time of Arrival
FERA	Flexible En-Route Airspace
FIXM	Flight Information Exchange Model
FF-ICE	Flight and Flow Information for A Collaborative Environment
FPL	Flight Plan
GUFI	Globally Unified Flight Identification
HERAM	Heterogeneous En-Route Airspace Management
ICAO	International Civil Aviation Organization
IOP	Interoperability
iTEC	interoperability Through European Collaboration
MLAT	Multilateration
NASA	National Aeronautics and Space Administration
NFL	Entry Flight Level
OLDI	On-Line Data Interchange
PBO	Performance-Based Operations
RTCA	Radio Technical Commission for Aeronautics
SESAR	Single European Sky ATM Research
SID	Standard Instrument Departure
STAR	Standard Instrument Arrival Routes
TBO	Trajectory Based Operation
TMA	Terminal Area
TOA	Time of Arrival
XFL	Exit Flight Level

1. INTRODUCTION

1.1. PURPOSE OF THE DOCUMENT

This document provides a technical report on air-ground cooperative operation of long-haul flight based on FF-ICE. It outlines the 4DT management process based on FF-ICE and the related application scenarios are presented for implementing the greener long-haul flight. To support the traffic flow management in density airspace, the approach of trajectory management models and algorithms related to demand and capacity balance, traffic synchronization and conflict management are described. In addition, air-ground cooperation based on data-link is part of this document.

1.2. INTENDED READERSHIP

The intended audience for this document encompasses project personnel and all partners involved in the green air traffic operation technology project based on the four-dimensional trajectory.

1.3. STRUCTURE OF THE DOCUMENT

This document addresses the techniques and methods applied within GreAT project MWP3-Greener Long-Haul Operations.

The structure of the document is as follows:

- **Chapter 1 "Introduction"** describes the purpose of the document, intended readership, and explains the abbreviations and acronyms used throughout the document
- **Chapter 2 "Basic Concept of FF-ICE**" describes the significance of FF-ICE concept, and its implementation route from the International Civil Aviation Organization (ICAO). This part is mainly ICAO literature research.
- **Chapter 3 "Greener Long-Haul Operations based on FF-ICE"** describes the 4DT management process of a full flight stage based on FF-ICE. Section 3.1 is the literature research of ICAO FF-ICE documents and section 3.2 is the outcome of greener long-haul trajectory management in this project.
- **Chapter 4 "ATM System Requirements"** describes the requirements of ATM system to support the 4DT management for greener long-haul flight. Some progresses in Europe and USA are also summarized. This part is mainly literature research for future development of ATM systems.
- **Chapter 5 "Trajectory Optimization and Separation Management Method"** describes the methods which are used to optimize the traffic flow and trajectories for greener long-haul operations. This part is the mainly outcomes of this project aiming at the detailed trajectory management models and algorithms.
- **Chapter 6 "Air Ground Cooperation Method"** describes the method which is used to perform trajectory synchronization and trajectory negotiation between aircraft and ATC, which supports the execution of optimized trajectory in both structured and flexible en-route airspace. This part is the outcome of this project aiming at the air-ground cooperation.
- **Chapter 7 "References"** lists all the applicable and reference documents.

2. BASIC CONCEPT OF FF-ICE

Currently, the means for sharing flight plan information between ATM service providers and airspace users relies on multiple two-party message exchanges in the form of: a filed flight plan (FPL), current flight plan, estimate messages, voice coordination, air traffic services inter-facility data communication messages, air-ground data communication and online data interchange messages. This information sharing mechanism has some disadvantages, such as insufficient information exchange, inconsistent information content, lack of flexibility and expansibility.

Specifically, airspace users have mature and sophisticated flight planning tools and specific aircraft performance parameter data, which can form an accurate 4D trajectory to represent flight intention. Restricted by current flight plan submission mechanism, airspace users submit relevant flight data in form of ICAO 2012 FPL, including 2D horizontal route and requested fight level and speed. The submitted FPL is used by Air Traffic Management (ATM) related parties. At the same time, 4D profile data is generated based on FPL, general aircraft parameters, basic assumptions, and internal constraints. This leads to the inconsistency of trajectory data between airspace users and ATM, which restricts the improvement of air traffic predictability and traffic flow management efficiency.

In order to further refine the future operation and data requirements of Flight and Flow (FF) information for the global ATM system, the ATMRPP, an air traffic management demand and performance expert group under the ICAO Navigation Commission, has proposed a mechanism that can replace the existing ICAO flight plan-flight and flow information for a collaborative environment FF-ICE [1]. This concept takes a comprehensive consideration of the needs of ATM units, focusing on data exchange, data sharing, data integrity, and data confidentiality of flight and flow information. The following content is mainly a literature research of ICAO documents [1-3].

The FF-ICE concept specifically refers to the flight and flow information required for the management, notification, and coordination of flight operations by stakeholders in the collaborative environment envisaged in the "Global Air Traffic Management Operational Concept"[2]. Its advantages and characteristics include:

a) Information is more accurate and comprehensive in FF-ICE.

In the current stage of operation, airspace users have relatively mature and complete flight planning tools, specific aircraft operating parameters, and the ability to accurately plan and characterize flight trajectories. However, some valuable data will be lost when the ICAO 2012 flight plan is generated. It only sends data such as the take-off and landing airport, 2D route, requested flight altitude and speed to the related ATM departments. Meanwhile, the ATM department generates flight profiles for traffic flow management based on ICAO flight plans, general aircraft parameters and basic assumptions, while applying unpublished or internal restrictions.

In FF-ICE operations, airspace users can provide richer flight data, including 4D flight profiles, specific aircraft performance data, etc. The ATM department uses and distributes 4D profile data, and at the same time uses specific aircraft performance data for the trajectory calculation of decision-making tools, and provides airspace users with altitude constraints, time of entry and other airspace restriction data. Both airspace users and ATM departments can obtain more accurate and comprehensive operational data. FF-ICE will become an important foundation for Performance-Based Operations (PBO) and Trajectory-Based Operations (TBO) promoted by the ICAO in the future.

b) Information consistency has been improved in FF-ICE.

The future transition from traditional flight plan to FF-ICE will be important. The flight information format will undergo an important transition from message-based to data-based. The flight information contained in FF-ICE is very rich, and data-based flight information also makes it easier to interact between different units and systems. Each system of ATM units, airlines, and airports can receive and process FF-ICE-based flight information, and revise and supplement it accordingly.

The ICAO recommends the use of the globally unified flight identification GUFI to ensure that all stakeholders can use unique flight information for the same flight. GUFI is like the identity code of a flight, including a series of information such as flight number, execution date, creation unit, departure airport, destination airport and so on. When the FF-ICE information of a flight is created for the first time, it is assigned to the flight and runs through the entire life cycle of the flight from pre-flight to execution and then to post-flight. The FF-ICE information based on GUFI will greatly improve the consistency of flight information at different stages.

c) Information usage is more flexible in FF-ICE.

The flexibility of FF-ICE information is mainly reflected in two aspects: one is that data-based FF-ICE information can be used more flexibly in the different information processing systems of each operating unit to complete applications such as interaction, supplement, and improvement. Second, compared with the traditional flight plan, FF-ICE information will be more easily processed by the flight information processing system, and the data-based FF-ICE will enable it to have downward compatibility in format and version.

In the Aviation System Block Upgrade (ASBU) issued by the ICAO, FF-ICE is used as the main lead of the global interoperable system and data module, and it is proposed to be implemented gradually in three stages [3].

- **Module B1-FICE**: Improve interoperability, efficiency, and capacity through the FF-ICE Phase 1 application before departure. In pre-departure, use the common flight information exchange model (FIXM) and the eXtensible Markup Language (XML) standard format to provide ground-to-ground flight information exchange.

- **Module B2-FICE**: Improve collaboration through multi-center ground-to-ground integration. FF-ICE supports trajectory-based operations by using flight object implementation and interoperability (IOP) standards to exchange and release information for multi-center operations, and continues to use FF-ICE after the flight has departed.

- **Module B3-FICE**: Implement a complete FF-ICE to improve operating performance. The airborne system and the ground system share all flight-related operational data with the help of system-wide information management SWIM, supporting collaborative ATM and trajectory-based operations.

3. GREENER LONG-HAUL OPERATIONS BASED ON FF-ICE

3.1. TRAJECTORY MANAGEMENT BASED ON FF-ICE

This section is a literature research of ICAO document “Manual on Flight and Flow Information for a Collaborative Environment (FF-ICE)” [1]. The trajectory management process based on FF-ICE runs through the entire stage of the flight. In the FF-ICE concept, the processing of flight information can be divided into 3 stages according to the time dimension: strategic planning stage (from 1 year to several months before the off-block of flight), pre-tactical planning stage (from months to several hours before the off-block time), and tactical stage (from a few hours before off-block time to the flight operations). The strategic planning stage is mainly to carry out aviation business planning. The participants in the pre-tactical planning stage are mainly airline AOC/dispatchers and all organizations supporting flight operations, and they are responsible for the preparation, submission, and modification of flight plans. The main participants in the tactical phase are the aircraft and all organizations that support flight operations, mainly the management of real-time flight trajectories. This project focuses on the FF-ICE-based trajectory management process in the pre-tactical and tactical stages.

The flight information that the pre-tactical planning stage focuses on is the 4D flight plan data. At this stage, FF-ICE services mainly include six categories: planning service, filing service, flight data request service, publication service, notification service and trial service.

- **Planning Service**: The FF-ICE Planning Service permits an ASP to provide restrictions and constraints applicable to a flight back to the operator, and obtain early flight intent information that will aid in demand assessment and resource planning. This assists the operator in their planning, and should permit overall lower workload to achieve collaborative planning. Information related to planning services includes: preliminary flight plan message, flight plan update message, flight plan cancellation message, submission response message, and planning status message.

- **Filing Service:** FF-ICE will permit submission of a filed flight plan using a standardized XML format in lieu of the teletype-format FPL used today. FF-ICE also provides feedback to the operator regarding whether the flight plan was successfully processed, and whether it is acceptable to the ASP. Information related to filing services includes: filed flight plan message, flight plan update message, flight plan cancellation message, submission response message, and filing status message.

- **Flight Data Request Service:** FF-ICE will require an ASP to make available a query and reply service. This service can potentially be extended by the ASP to allow an operator to verify, for example, the status of a flight previously submitted. While the normal FF-ICE exchanges would not make this necessary it could be useful in certain non-nominal situations where there is uncertainty regarding the current status of a flight. Information related to flight data request service includes: flight data request message, submission response message, and flight data response message.

- **Notification Service:** The notification service is an optional service currently foreseen for the notification of departure and arrival. However, it is anticipated that as FF-ICE develops beyond pre-departure other events in the life cycle of a flight will be added. Information related to notification service includes: flight departure message, flight arrival message, and submission response message.

- **Trial Service:** The trial service allows an operator to submit a "what-if" flight plan to ascertain the effects of a change being considered, without changing the intended flight plan currently on file. Information related to trial service includes: trial request message, submission response message, and trial status message.

- **Publication Service:** The publication service provided by an ASP allows an operator to obtain information, as related to the ASP concerned, concerning its flights. An operator will be able to subscribe to events or other criteria, as facilitated by the service provider, concerning its flights. The service does not provide an operator with the ability to obtain current information from an ASP concerning only a specific flight.

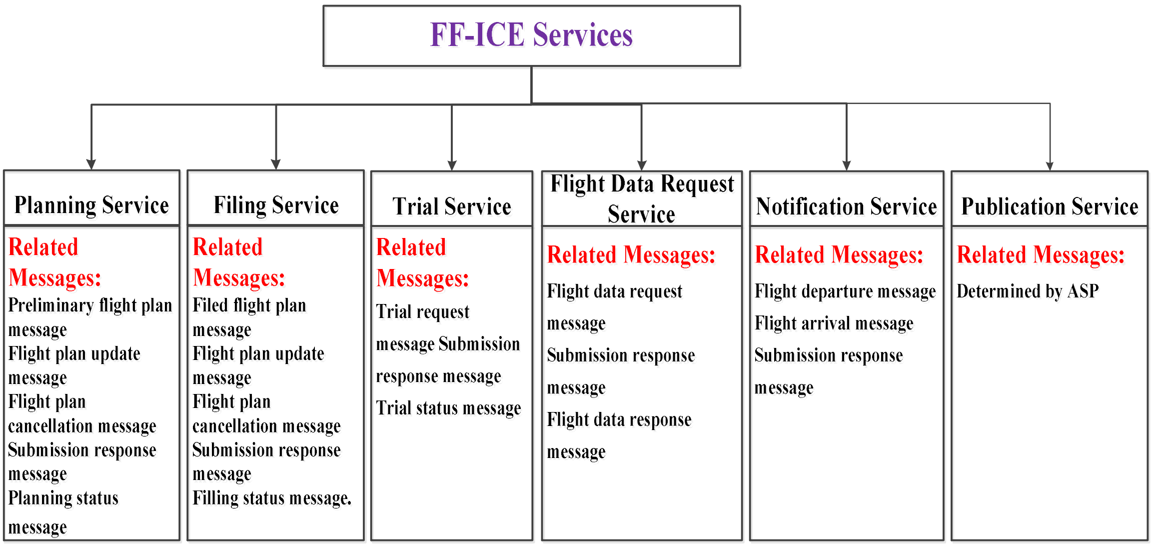

Figure 3-1: FF-ICE related information services

The specific operation process of FF-ICE includes initial information provision and verification, pre-tactical operation planning, tactical operation planning, flight operation, multi-ASP negotiation, etc.

- **Initial Information Provision and Verification.** The process of this step is shown in the following figure and the initial information provided by the airspace user AU includes:
  - estimated block time and date;
  - departure aerodrome;
  - destination aerodrome;
  - aircraft type;
  - aircraft operator;
  - FF-ICE originator;

- type of flight; and
- preferred 4D trajectory airborne segment including data items as required to provide the level of accuracy required.

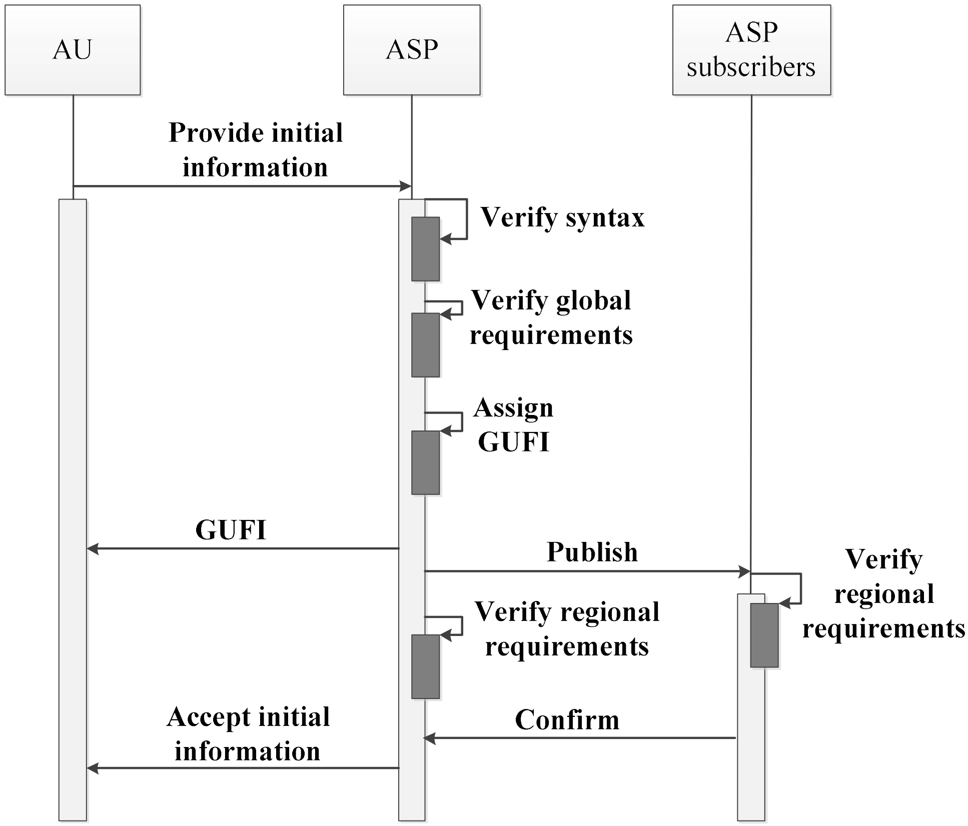

Figure 3-2 Initial information provision and verification

Pre-tactical Operation Planning. In the pre-tactical operation planning stage, after the initial timetable is provided and permission is obtained, the following activities need to be carried out based on clearer information.

- Based on the latest data submitted by the AU, the ATM department evaluates the matching of traffic demand with the airport/airspace capacity, and carries out flow management to improve the overall operation efficiency of the airspace. In this process, in order to support greener air traffic operations, the formulation of flow management measures needs to consider factors such as reducing air delays and optimizing the use of altitudes.
- The AU considers operation restrictions and performances such as fuel consumption, and updates the flight plan.
- AU provides preference information for the flight.

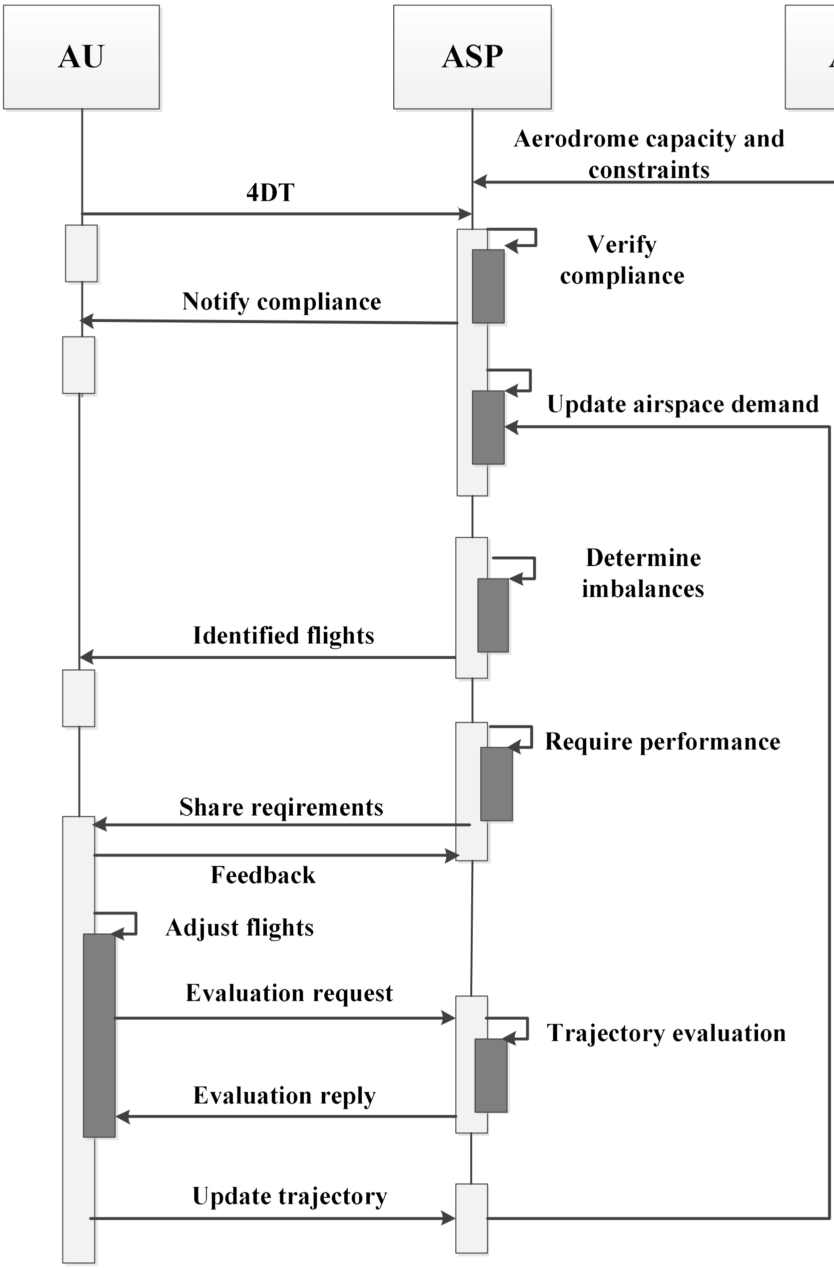

Figure 3-3 Pre-tactical operation planning

- **Tactical Operation Planning.** The tactical operation planning stage includes providing desired 4D trajectory, obtaining agreed 4D trajectory, constraints on trajectory, and surface operations.

    - **Providing desired 4D trajectory**. Close to the actual departure time of the flight, more accurate information (weather, wind, equipment status, etc.) can be obtained for planning. AU use restricted information such as airspace, capacity, and environment to generate desired 4D trajectories. The AU can allocate resources to each flight to determine a desired 4D trajectory based on known requirements and internal goals (for example, minimizing fuel consumption).

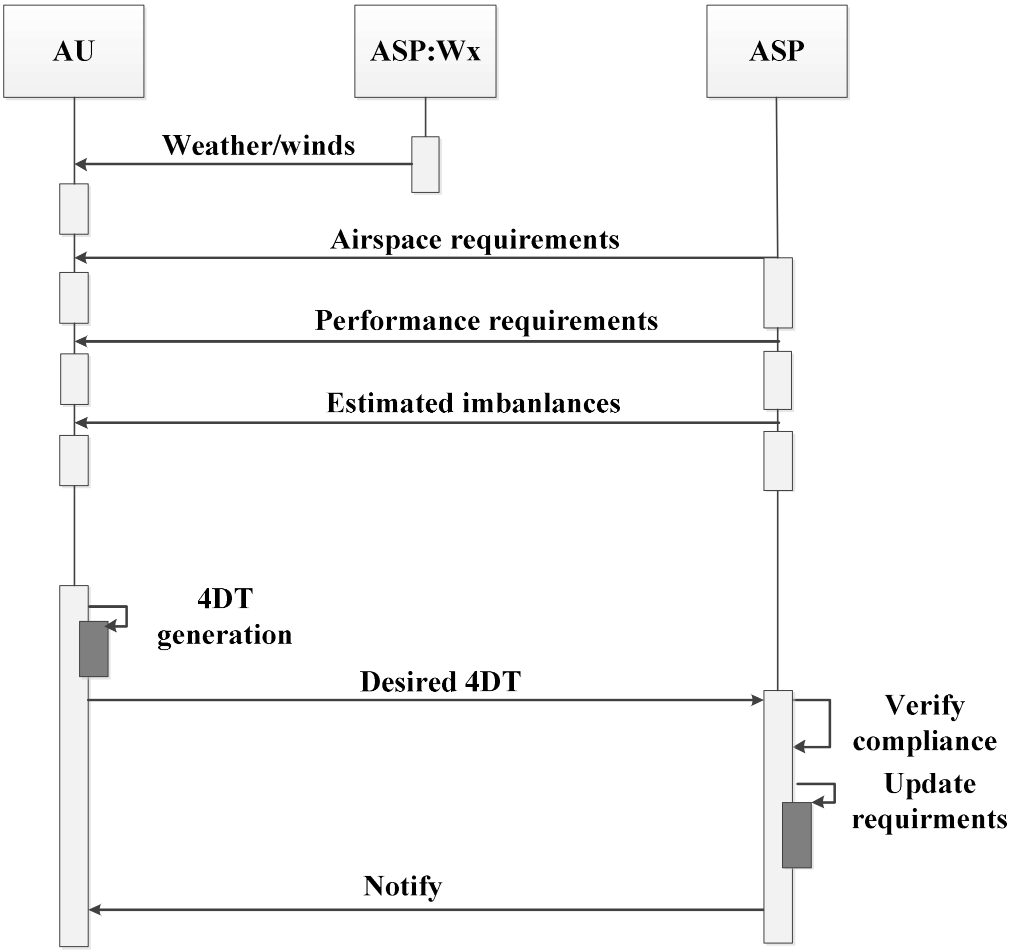

Figure 3-4 Providing desired 4D trajectory

- **Obtaining agreed 4D trajectory**. Negotiations between ATM participants and AU are conducted to obtain the agreed 4D trajectory. In a collaborative environment, AUs are aware of various constraints and adjust the flight trajectory according to the known constraints to obtain the best solution. If through this process, an agreed 4D trajectory cannot be obtained at a required time point, the predetermined rules will be enforced, and the preference information previously provided by the AU may be considered to meet the performance. To obtain the agreed 4D trajectory, the following three situations need to be considered:

  1) Restrictions specified by ASPs. Each ASP specifies the restrictions that must be met by the 4D trajectory. Different ASP may use different systems and tools to generate trajectory restrictions in their controlled airspace, and the basic principles they follow should be consistent.

  2) Ranked 4D trajectory. The AU provides a series of 4D trajectories arranged in sequence, and the ASP selects the most suitable 4D trajectory that can meet the performance of the system (including consideration of environmental protection and other performance). The collaborative decision-making process is used to determine the selection of trajectory.

3) Operational preference. AUs provide the proposed preferred 4D trajectory. ASPs may change certain parts of the 4D trajectory (such as route, time, and altitude) based on flight preferences and performance limitations.

The AUs can provide ASPs with a series of 4D trajectories arranged in sequence. These trajectories have deviation tolerance (delay tolerance) and indicate the order of preference. If the optimal 4D trajectory cannot be kept within the deviation tolerance, the next 4D trajectory in order will be selected first. AUs may provide additional preference information, including:

1) Operator's flight priority: Allows providing the highest priority to the designated flight designated by the AUs according to the operational goal.

2) Operational practice: Indicate the unacceptable choices of the AU, such as the choice of runway, flight level, etc.

3) Preferences for flight activities: Show options for flying 4D trajectories. These preferences can be expressed by the tolerance of desired trajectory.

In the process of forming the agreed 4D trajectory, the ASP considers the above-mentioned inclination selection and conducts trajectory negotiation.

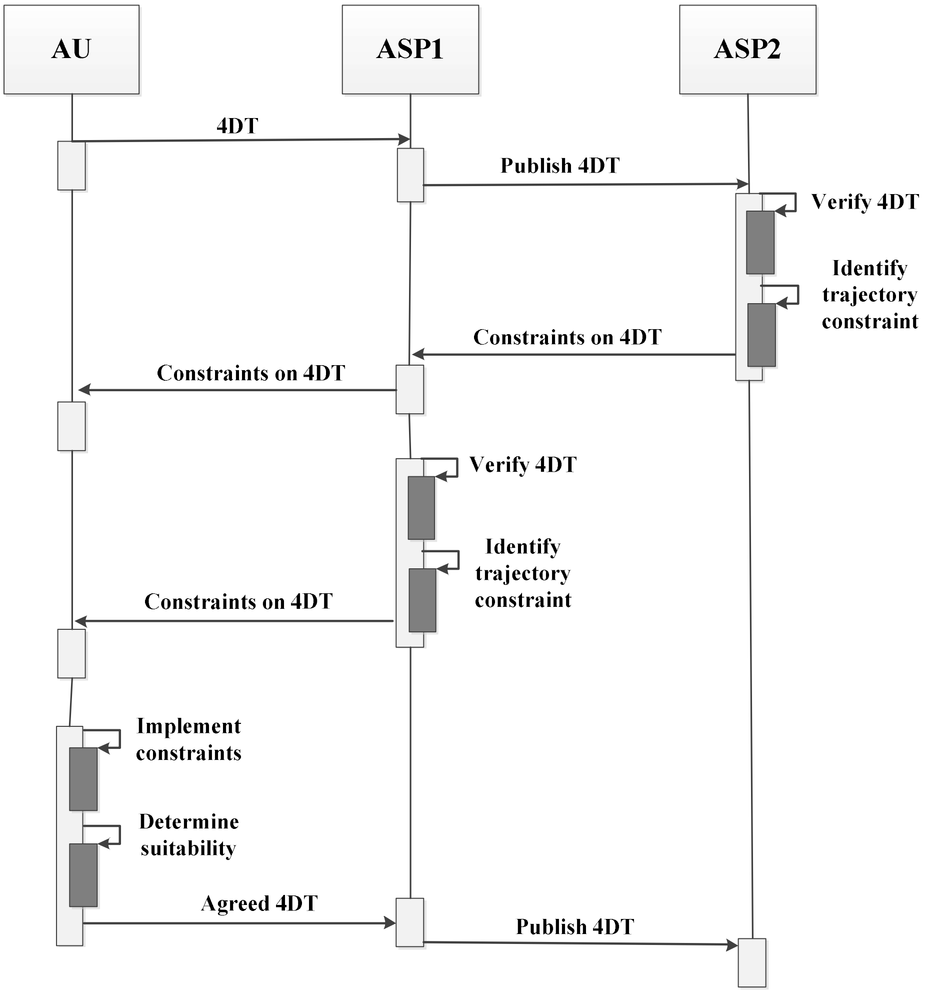

Figure 3-5 4D trajectory negotiation at tactical operation planning stage

- **Constraints on trajectory**. Traffic synchronization or conflict management may need to impose constraints on the trajectory (including the controlled arrival time of the prescribed trajectory, imposing restrictions on altitude, speed, or lateral restrictions, etc.). The constraints determined by the ASP and the tolerance to meet these constraints are provided to AU through a 4D trajectory that needs to be negotiated. AUs consider these constraints in the following situations:

  1) The flight can meet these constraints, and update the 4D trajectory to obtain a new trajectory that meets the constraints. The AU submits it as an agreed 4D trajectory to be executed during the flight;

  2) When dissatisfied with the constraints, the AU proposes a new alternative trajectory in the form of a 4D trajectory that needs to be negotiated;

  3) Due to aircraft performance considerations, flight cannot meet these constraints.

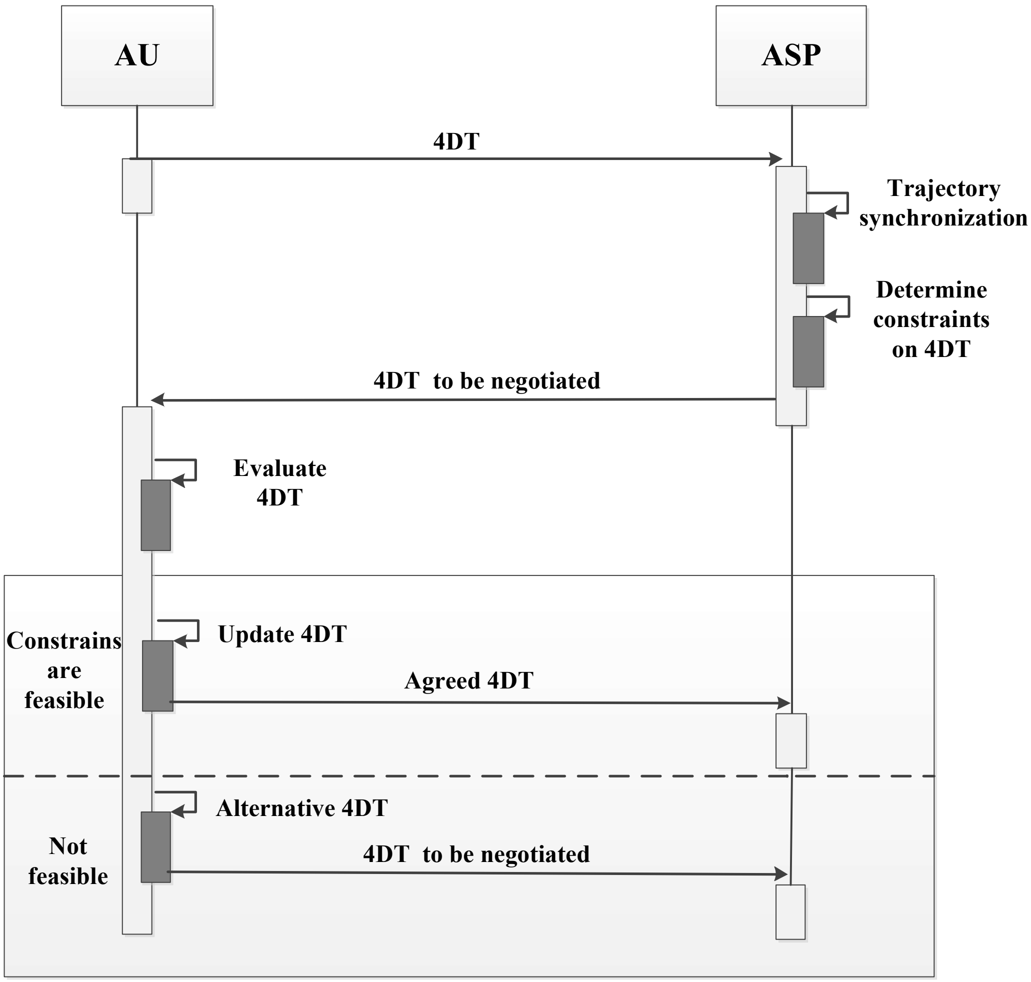

Figure 3-6 Constraints on trajectory for trajectory synchronization

- **Surface operations.** For airports equipped with a surface automation system, the surface plan can be very detailed and accurate. The surface plan must be shared with AU so that the time and route on the surface are consistent with other operational plans. If shared between participants, time coordination with approach department can be carried out, minimizing surface operation time and fuel consumption.

When the flight is ready to receive the departure clearance, the above functions have been completed and the performance requirements have been reached.it means:

1) Collaboration requirements and capacity balance constraints have been met;

2) Strategic conflict management and traffic synchronization have reached the accuracy required before departure;

3) The surface trajectory has been defined according to the requirements;

4) An agreed 4D trajectory has been obtained, which includes information items that meet the requirements.

- **Flight operation.** Throughout the flight process, the 4D trajectory that has been implemented in FF-ICE will be updated to provide higher accuracy for other goals such as traffic synchronization and separation management. Traffic synchronization and separation management can also cause trajectory updates. The current ATM unit of the flight is responsible for updating the latest trajectory information. When the current ATM unit does not have FF-ICE capabilities, airlines may also update flight status through information services.

  In order to support a greener long-haul flight, the AU evaluates the estimated fuel consumption of the trajectory based on real-time wind and airspace conditions. When finding a more optimized flight level and route, it actively negotiates the trajectory with the ASP.

- **Multi-ASP negotiation.** A long-haul flight usually involves the coordination between multiple ASPs. Different ASP will dynamically assess the feasibility and operational efficiency of the trajectory based on their own operating status. Different ASP may carry out trajectory assessment and management based on different decision-making systems or tools, but the basic principles should be the same. That is, under the condition of ensuring safety, make the flight fly as short as possible and the best flight level is used to keep the minimum deviation from the user's desired trajectory.

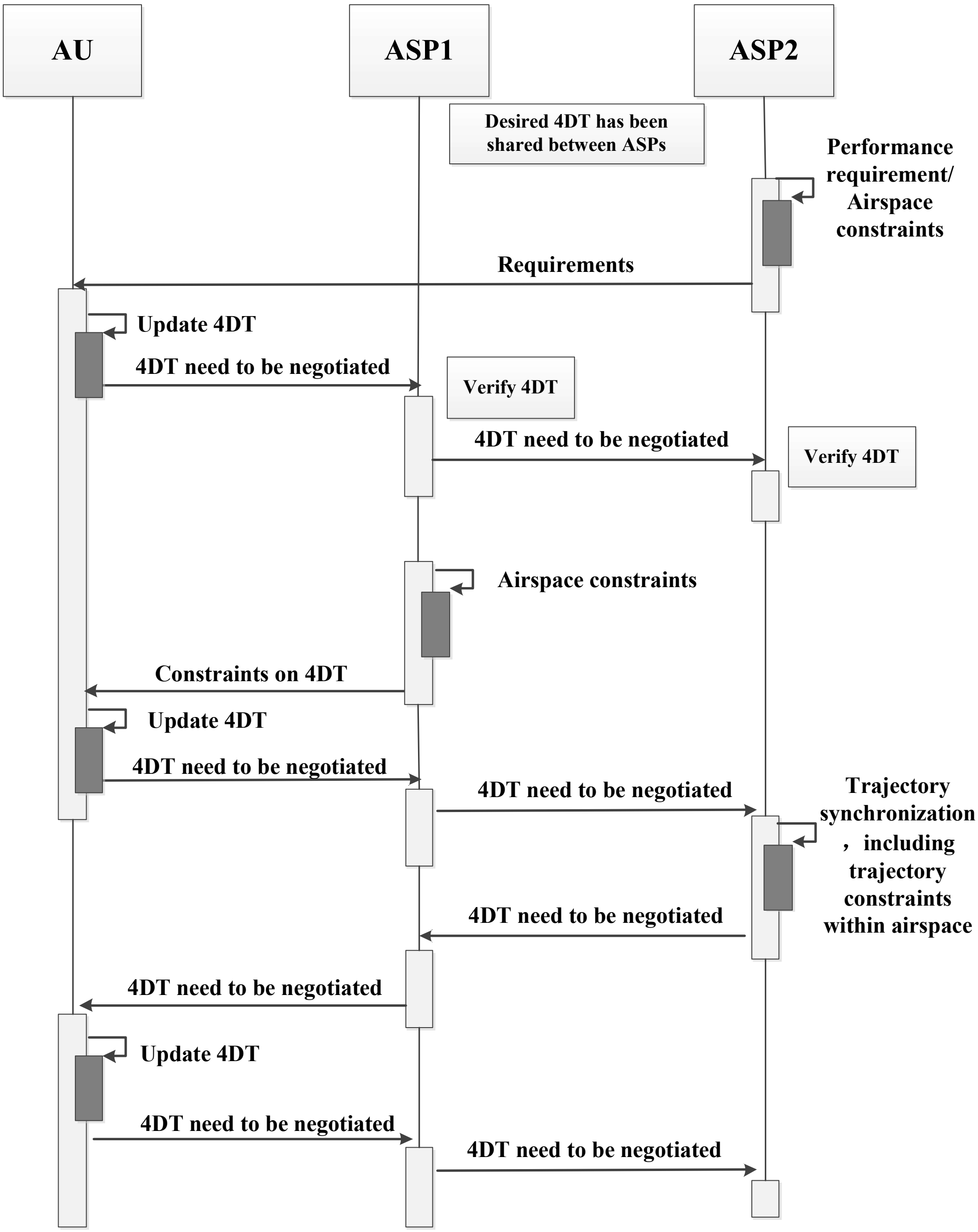

Figure 3-7 trajectory negotiation in multi-ASP environment

3.2. TYPICAL APPLICATION SCENARIOS

This section is the outcome of greener long-haul trajectory management based on the literature research of ICAO documents in this project.

In the management of greener long-haul flights, the application of FF-ICE related concept and technologies can improve the efficiency of trajectory sharing and coordination, as well as improve the predictability of traffic flow for the ASP by obtaining more comprehensive AU intentions. This provides the supports for efficient and greener airspace management.

Several performance indicators may be considered during the negotiation process, such as route availability, traffic flow and airspace capacity, flight cost (delay and fuel consumption).

The following scenarios are shown to illustrate the process of trajectory management based on FF-ICE:

- 12 hours before the flight takes off, the airline submits the preliminary flight plan to the relevant ASPs. After each ASP receives the preliminary flight plan, it responds with "ACK" to confirm that the preliminary flight plan has been received. After evaluation, it will reply to "CONCUR" again to confirm the feasibility of the preliminary flight plan. There are three states of the planned trajectory: CONCUR, NON-CONCUR and Negotiate.

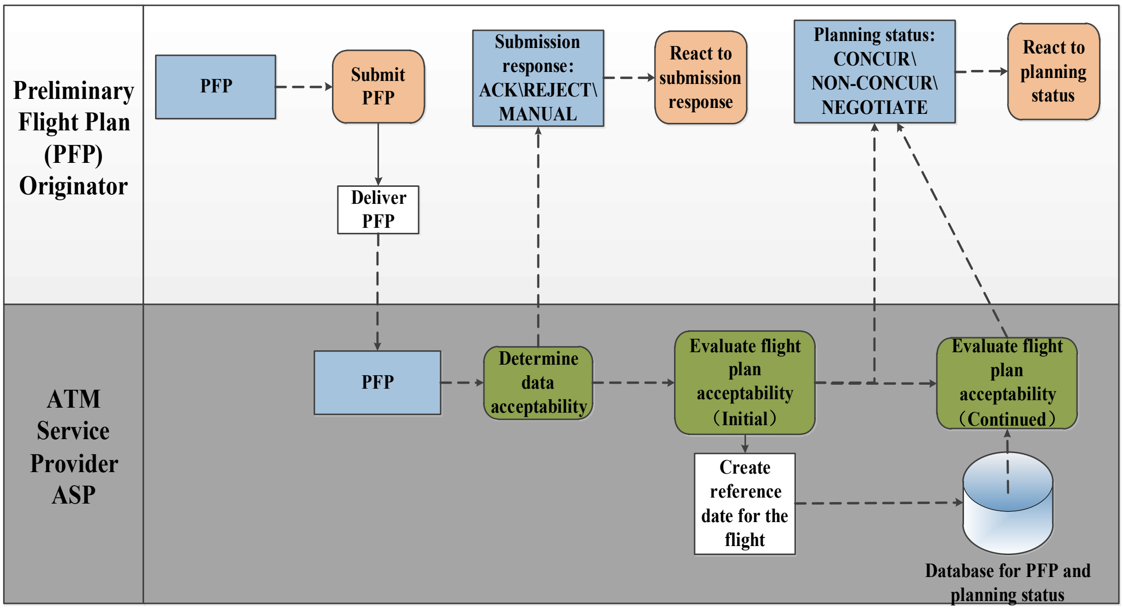

Figure 3-8 Process of PFP submission and evaluation

- 10 hours before flight takes off, ASP B publishes significant weather in its airspace, which will affect the execution of the planned trajectory. At the same time, the status of the flight plan is changed to "Negotiate". Then airline submits a trial request based on the new trajectory 2 (as shown in figure 3-9) to ASP B and C, and the ASPs feedback "ACK" and "CONCUR" in turn, indicating that the planned trajectory 2 is feasible.

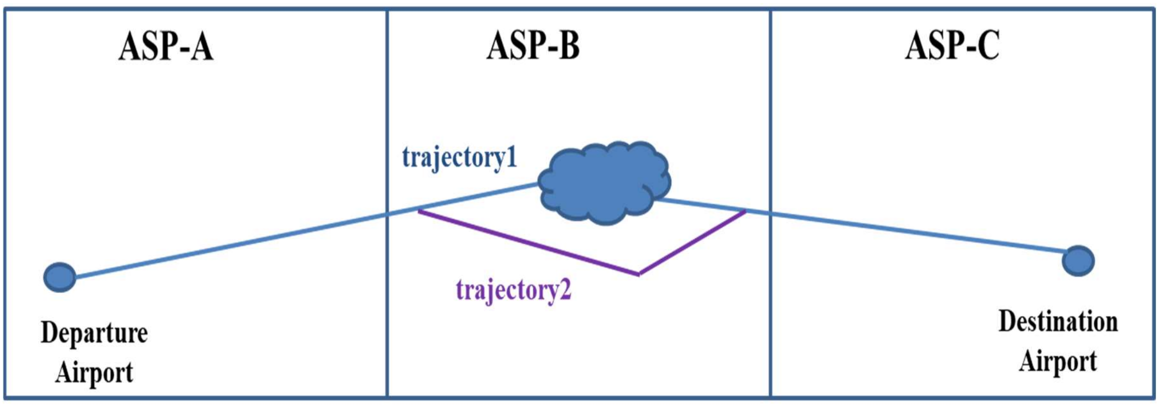

Figure 3-9 Schematic diagram of operational scene

- 8 hours before the flight takes off, the airline submits the flight plan based on trajectory 2, and the ASP A, B and C responding with "ACK" in turn. At the same time, the ASP A and B respond to the planned trajectory status as "ACCEPTABLE". Due to the reason of airspace, the planned trajectory status returned by the ASP C is "NOT_AACEPTABLE". The feedback of ASPs does not need in a sequential approach. The negotiation process works in a concurrence approach. But a deadline is needed to facilitate the completion of the negotiation process.

- 3 hours before flight takes off, after assessment the airline decides to wait on ground and submits the second trial request based on the new EOBT time. The ASP A, B and C responding with "ACK" and "CONCUR" in turn. Then the updated planned trajectory was submitted by airline. The departure time was delayed by 1 hour based on the original planned trajectory 2. The ASP A, B and C respond with "ACK" and "ACCEPTABLE" respectively.

Based on the above process, the agreed 4D trajectory of flight is determined before take-off. Through this coordinated process, the related ASPs of the long-haul flight have reached a consensus on the trajectory. Compared with the current operation, it can significantly improve the predictability of the traffic situation. It also promotes more efficient traffic flow management by reducing air holdings and maneuverings in the tactical operation phase, as well as reduces fuel consumption and emissions.

After the flight taking off, it flies following the agreed 4D trajectory. Subsequent ASPs will dynamically obtain the latest 4D trajectory data of the flight. Due to traffic sequencing/conflict management and other reasons, the controller may adjust the 4D trajectory by the Controlled Time of Arrival (CTA), and the aircraft will optimize the speed profile based on the CTA.

- 1 hour after takeoff, the flight cruises in ASP A airspace according to agreed 4D trajectory. ASP A shares last trajectory updates and Actual Time of Over (ATO) as aircraft crossing the main waypoints. The ETA of entering ASP B will be dynamically updated according to the actual operation due to the influence of uncertainties such as wind.

- 30 minutes before flight entering ASP B, a CTA is generated based on the lasted predicted traffic situation. This CTA will first be shared by ASP B to ASP A. and then it will be uploading to aircraft through the data link by ASP A.

- After the aircraft confirms to execute the CTA, it will transmit the latest airborne predicted trajectory data. Then ASP A will update and share the 4D trajectory of flight. The subsequent ASP will also update the 4D trajectory.

4. REQUIREMENTS OF ATM SYSTEM

During the operation of greener long-haul flight, airlines, aircraft, ATC centers and other related parties establish a unified 4D trajectory-based air traffic situation. They manage the 4D trajectory at all stages of flight through coordinated decision-making, and this will improve the ATM system capability and air traffic operation efficiency. In this section, literature research for future development of ATM systems is presented.

4.1. CAPACITY REQUIREMENTS

Through the analysis of the operational concept and the trajectory management process, combined with the development and technical maps of ATM systems, it can be summarized that the capability requirements of the greener long haul trajectory operation for ATM system include the following aspects [4, 5]:

- The system generates safe and conflict-free trajectories for all aircraft, and do not allow the space between aircraft to be less than the safe separation minima;
- The system has a faster calculation speed and meets the requirements of the operating time limit;
- The system could support multi-aircraft and multi-equipment operations. In high-density airspace, it can reduce the controller's workload and improve situational awareness;
- The system can optimize air traffic according to specific goals (such as environmental protection, efficiency, safety, etc.);
- The system can exchange and share digital information for both air-ground and ground-ground aspects.

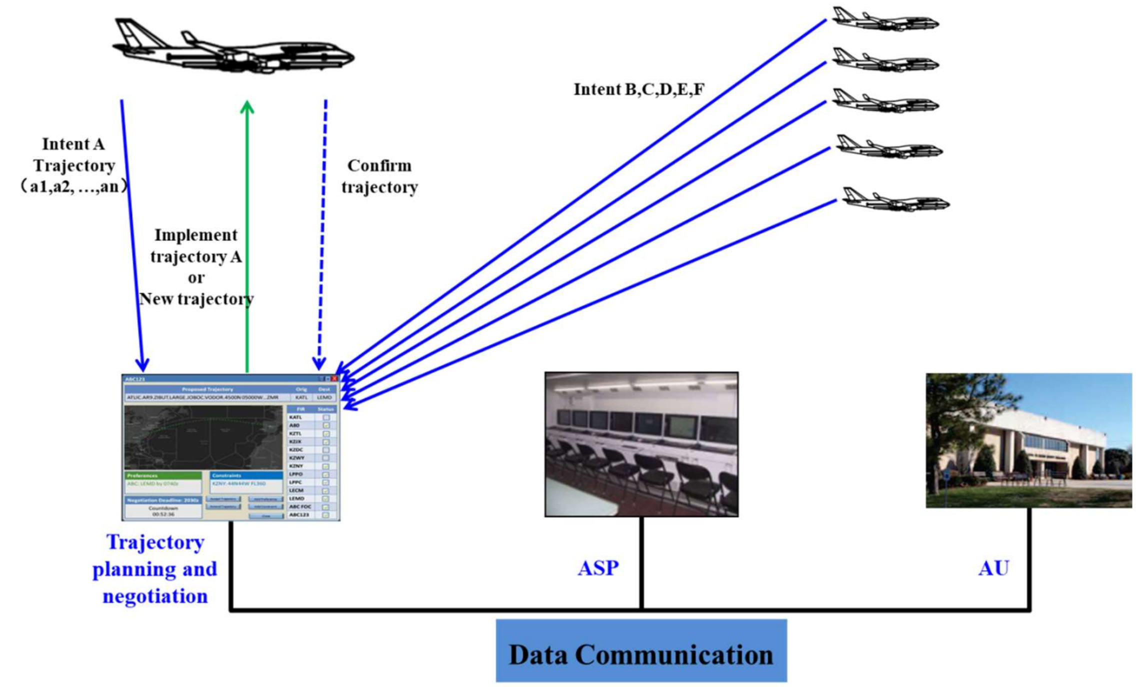

Figure 4-1 ATM system based on trajectory planning and negotiation

Specifically, the trajectory-based ATM system should support the following functions and applications [6].

1) Trajectory negotiation before departure

The ATM department needs to participate in the process of trajectory negotiation before the flight departures. The ATM system integrates the 4D trajectory submitted by the airline into the traffic flow, dynamically evaluates performance indicators such as safety, efficiency and environmental, forms the overall traffic situation of the airspace, and provides an intuitive display to the controllers. The system can generate and provide ATM constraints based on comprehensive consideration of operational optimization objectives and restrictions, to plan and negotiate the trajectory.

2) Trajectory negotiation after departure

The ATM department needs to participate in the negotiation process for the revision of the agreed trajectory after takeoff. Specially, the one ATM department or ASP needs to be able to participate in the process of trajectory negotiation before the flight enters its controlled airspace. The ATM system dynamically obtains the latest 4D trajectory information of the flight, evaluates the latest airspace operation situation and user’s flight intentions, as well as proposes necessary operation constraints to support the trajectory negotiation process.

3) Use of trajectory parameters

By using the 4D trajectory parameters provided by the AU/aircraft, the ATM department can integrate the trajectory parameters in the ground system to improve the accuracy of the trajectory prediction. And in the planning/revision of the trajectory, the flight intention and performance requirements of the AU are taken into consideration.

4) Creation and issuance of trajectory clearance

The ATM systems can create and issue ATC closed-loop clearances based on complete agreed trajectory information, and require execution accuracy (time and space). It is also responsible for the subsequent revision of the clearances. Trajectory clearances and control instructions would be sent to the aircraft through CPDLC.

5) Trajectory operation monitoring

The ATM system can dynamically update the trajectory and support the display of the aircraft's 4D trajectory based on the received monitoring data. According to the current status of the aircraft/flight, calculate the horizontal and vertical separation information between the pair of trajectories. When the horizontal and vertical distances are less than the specified horizontal and vertical separation parameters, the system issues a conflict warning. The Controlled Time of Arrival CTA may be used to resolve these conflicts.

6) Trajectory information management

The ATM system would receive the 4D trajectories shared by AUs and other ATM systems in real time, and integrate them into the system’s trajectory database after verification and flight association. These trajectories are used by the applications such as traffic situation assessment and analysis. At the same time, one ATM system can provide other systems with the latest 4D trajectory data and related trajectory constraints of flights in its responsibility area.

4.2. R&D ABOUT TRAJECTORY-BASED ATM SYSTEM

In terms of ATM automation system research and development, the ERAM system developed by Lockheed Martin is a key component of the NextGen plan in the United States [6-7]. It has been deployed in 20 FAA area control centers since 2015 and has been continuously improved to support the implementation of trajectory-based operations. And its characteristics are as follows:

- More accurate trajectory model, creating 4D trajectory from take-off to landing for each flight, improving situational awareness;
- Seamlessly share and coordinate flight paths between area control centers to improve operation efficiency under severe weather and traffic congestion;
- Enhance the processing capabilities of military aircraft to ensure that there is no conflict between training and military missions and civilian flights;
- Supports variable separation standards and trajectory planning applications, allowing controllers to flexibly manage airspace to increase capacity.

Focusing on the trajectory management capabilities required by TBO, NASA has been leading the airspace technology demonstration project (ATD) since 2014, developing and verifying efficient trajectory management technologies and tools from three aspects: arrival and departure, terminal areas, and en-route.

- ATD-1: Integrating controller separation management tools, traffic sequencing tools and airborne separation management, and it enhance the operation capability of high-density terminal areas through air-ground coordination [10];
- ATD-2: Realizing the integrated trajectory management of air and surface through air-ground and ground-ground coordination;
- ATD-3: Integrating airspace traffic situation and real-time weather to optimize flight routes, improve trajectory flexibility and dynamics [11, 12].

In order to support the realization of the Single European Sky ATM Research SESAR, while maintaining consistency with ICAO's Aviation System Block Upgrade ASBU plan, Indra has led the development of the iTEC (interoperability Through European Collaboration) series of products with the 4D trajectory operation concept as the core [11]. Its main features for:

- More advanced and friendly human-machine interface provides real-time information for the execution and planning controllers, flight data operators, operation and technical supervisors of ACC, TMA, and APP operations;
- Enhanced multi-sensor integrated surveillance, including Mode S-based aircraft download data, ADS-B, MLAT, secondary radar, etc.;
- Fully realize OLDI-based ground-ground interoperability between internal and external;
- Interoperability between aircraft and controllers based on air-to-ground data link;
- More advanced flight plan processing, accurate 4D trajectory calculation and electronic flight strip operation;

- Enhanced safety net and ATM tools supporting tactical control and planning operation, including consistency monitoring and conflict management.

5. TRAJECTORY OPTIMIZATION AND SEPARATION MANAGEMENT METHOD

Trajectory optimization and separation management method is a key element to improve the ATM system capacities and support the management of greener 4D trajectory. This section is mainly outcomes of this project aiming at the detailed trajectory management models and algorithms.

5.1. CALCULATION OF 4D TRAJECTORY FOR LONG HAUL FLIGHT

4D trajectory is a data collection of related elements describing a series of trajectory points of the aircraft, including the position, altitude, speed, time and heading of the trajectory points. The 4D trajectory prediction and calculation is one of the supporting technologies for the optimization of greener long-haul flight and is also the technical basis for trajectory optimization and spacing management. And it is also a solution to adapt to future airspace operations under high-density traffic conditions. Accurate and effective 4D trajectory prediction can improve the predictability of air traffic operations, and enhance the safety and efficiency of the airspace.

In the pre-tactical trajectory planning stage, the Estimated Time of Arrival ETA of the main waypoints is calculated based on the flight plan, airspace structure and aircraft performance model data, and integrated to form a complete 4D flight trajectory. In the tactical execution stage, the method of dynamic trajectory correction based on airborne download data is studied, and the real-time online dynamic prediction of the 4D trajectory is carried out using the predicted profile information downloaded by the aircraft, as well as the observed and predicted meteorological data.

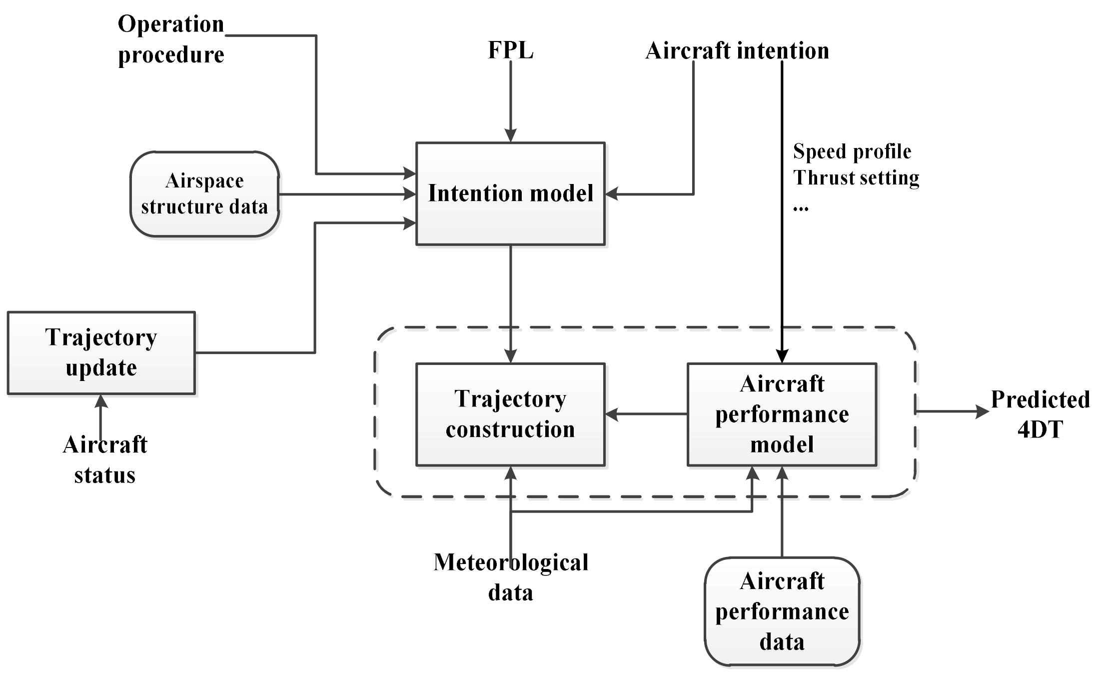

Figure 5-1 Model-based trajectory prediction architecture

The 4D trajectory can be divided into three sections: horizontal flight path, altitude profile and speed profile. The horizontal flight path is determined by the aircraft's initial heading and ending heading, as well as the coordinate of each waypoint in FPL and SID/STAR. The altitude profile is determined by the waypoint height on the horizontal flight path and the minimum and maximum flight path angles specified during climb/descent. The speed profile is determined by the speed of the waypoint on the horizontal flight path. Each profile is processed independently and then coupled. The horizontal distance in the horizontal flight path is an independent variable in the altitude profile and the speed profile.

During the greener long-haul operation, the environmental factor that has the greatest impact on the efficiency of the flight is the wind, which largely determines the speed and fuel consumption of the flight. In the calculation of the speed profile, the currently available stable wind forecast data source is the GRIB weather report, which provides three weather forecasts that are for the next 6 hours, 12 hours, and 24 hours. The scope of the forecast covers the whole world, and it describes the basic atmospheric parameters (including wind speed) at 3447 designated latitude and longitude grid points.

This project assumes a dynamic grid model to describe meteorological information, as shown in the figure.

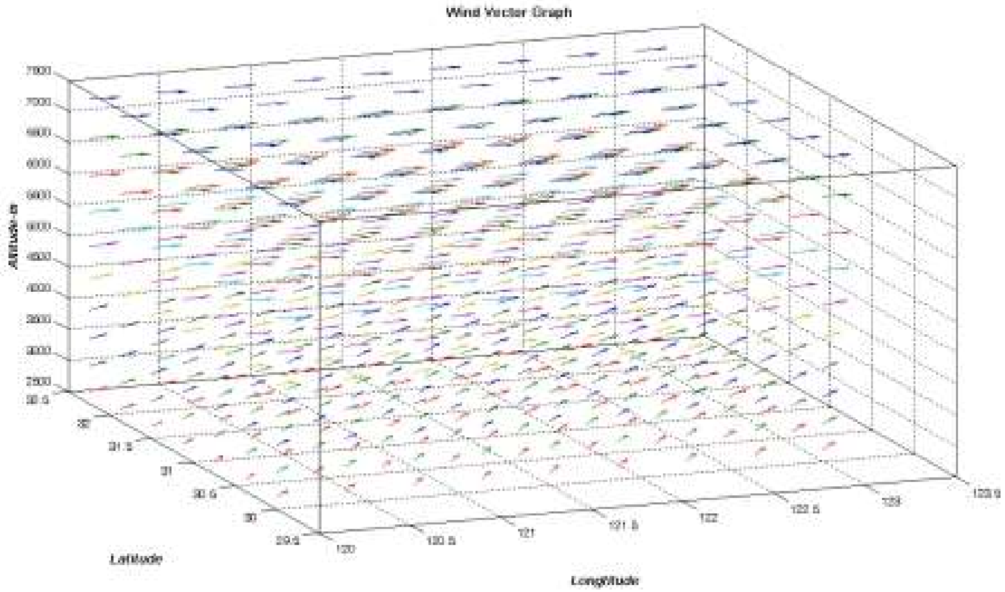

Figure 5-2 Diagram of wind grid

In the initial situation, airspace is divided into grids consistent with the grid defined by GRIB, and a mapping relationship with the airspace and route is also established. Then at each grid point, the corresponding meteorological element data is given, including wind speed, wind direction, temperature and so on. According to calculation needs, we analyze and interpolate the wind/temperature data in GRIB format to obtain the wind/temperature data in a single latitude and longitude grid that is evenly divided. According to the predicted position and altitude information, we use the corresponding wind data to obtain the wind speed $\vec{V}_{\text{wind}}$ at the position of the 4D trajectory point, and perform vector calculation with the true airspeed $\vec{V}_{TAS}$ calculated by the performance model to obtain the aircraft ground speed $\vec{V}_{GS}$. It realizes the correction of the wind to the trajectory prediction result.

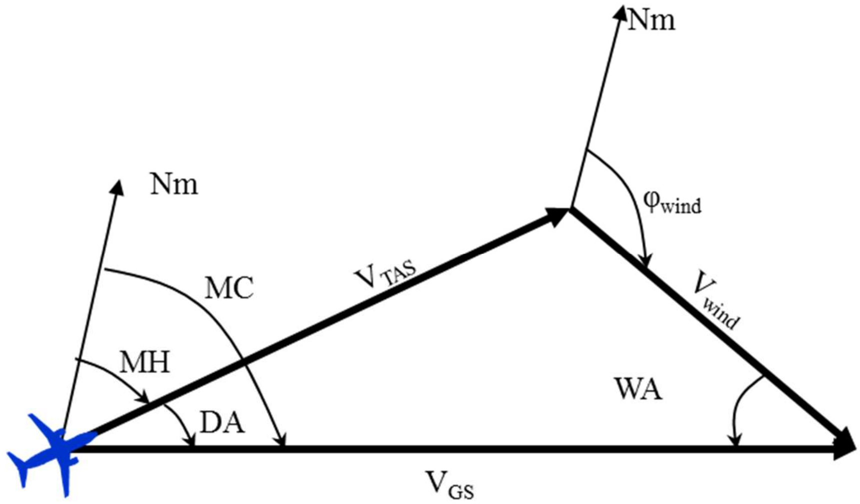

Figure 5-3 Speed calculation diagram

The mathematical model of speed calculation is as follows:

$$WA = \varphi_{\text{wind}} - MC$$

$$DA = \arcsin\left[V_{\text{wind}} / V_{TAS} \times \sin(WA)\right]$$

$$V_{GS} = V_{TAS} \times \cos(DA) + V_{\text{wind}} \times \cos(WA)$$

$$\Delta S = V_{GS} \times \Delta t$$

$$MH = MC - DA$$

Where φ_{wind} is the wind direction; V_{wind} is the wind speed; V_{TAS} is the true air speed, V_{GS} is the ground speed; WA, DA, MH and MC are the corresponding angles in the above figure; Nm is the reference direction; ΔS is the distance, and Δt is the time.

5.2. DETECTION OF FLIGHT CONFLICTS IN THE PRE-TACTICAL STAGE

Conflict detection refers to identify whether there will be conflicts or dangerous approaches between aircraft based on the predicted 4D trajectories. In other words, it is judged whether the distance between aircraft is less than the minimum safety spacing standard (separation minima). Detecting potential conflicts can predict the locations of the conflicts in advance, and reserve sufficient time for controllers to resolve the conflicts. This will reduce the incidence of flight safety accidents, and ensure the safe and smooth operation of flight.

In order to better detect the conflict locations in the large-scale airspace and trajectories, a 4D grid-based conflict preliminary filter algorithm is proposed. The method first uses a 4D space-time grid to discretize the related airspace, and the size of each grid cell is set according to the flight safety spacing standard. At this time, the discrete trajectory points of the aircraft are assigned to the corresponding 4D grids, and potential flight conflicts can be detected by checking each non-empty adjacent grid. Generally, if the trajectory points of different aircraft coexist in the 4D grid or the trajectory points of different aircraft exist in the adjacent grids, it may be detected that there is a potential conflict.

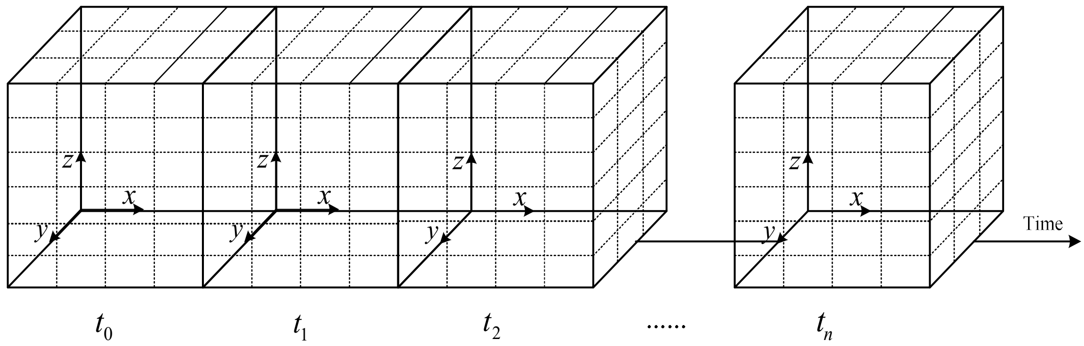

Figure 5-4 Diagram of 4D space-time grid

Set (x_0, y_0, z_0, t_0) as the coordinate origin of the 4D grid space-time position. Although the time axis changes continuously, it is impossible to detect the conflicts at any moment in actual operation. Only a certain time periods can be used to realize the conflict detection in a discrete time period.

In order to realize the preliminary screening of flight conflicts based on the 4D grid, set the 4D coordinates of any reference aircraft as, where is the track point number, and define it to fall in the airspace grid unit on the time period.

In order to realize the preliminary detection of flight conflicts based on the 4D grid, set the 4D coordinates of any reference aircraft i as $(x_{ij}, y_{ij}, z_{ij}, t_{ij})$, where j is the trajectory point number, and define it to fall in the airspace grid A_{ij}^0 on the time $t_n = t_{ij}$. To detect whether the aircraft's trajectory has a potential conflict risk, it is necessary to determine whether its corresponding 4D grid or neighborhood grid at each time has trajectory points of other aircraft coexisting. The "three-dimensional" matrix $A_{ij} = \begin{bmatrix} A_{ij}^1 & A_{ij}^2 & A_{ij}^3 \end{bmatrix}$ is composed of the defined the grid A_{ij}^0 and its 26 neighborhoods, where:

$$A_{ij}^1 = \begin{bmatrix} A_{ij}^{111} & A_{ij}^{112} & A_{ij}^{113} \\ A_{ij}^{121} & A_{ij}^{122} & A_{ij}^{123} \\ A_{ij}^{131} & A_{ij}^{132} & A_{ij}^{133} \end{bmatrix}_{3\times3}, A_{ij}^2 = \begin{bmatrix} A_{ij}^{211} & A_{ij}^{212} & A_{ij}^{213} \\ A_{ij}^{221} & A_{ij}^{222} & A_{ij}^{223} \\ A_{ij}^{231} & A_{ij}^{232} & A_{ij}^{233} \end{bmatrix}_{3\times3}, A_{ij}^3 = \begin{bmatrix} A_{ij}^{311} & A_{ij}^{312} & A_{ij}^{313} \\ A_{ij}^{321} & A_{ij}^{322} & A_{ij}^{323} \\ A_{ij}^{331} & A_{ij}^{332} & A_{ij}^{333} \end{bmatrix}_{3\times3}.$$

The matrix A_{ij}^1, A_{ij}^3 represents the 9 grid neighborhoods of A_{ij}^0 on the upper and lower levels respectively. A_{ij}^2 represents the 9 grid neighborhoods of A_{ij}^0 in the same level. Grid A_{ij}^0 and A_{ij}^{222} are the same grid. As shown in the following figure, A_{ij}^0 and A_{ij}^{222} are the purple grid in the middle.

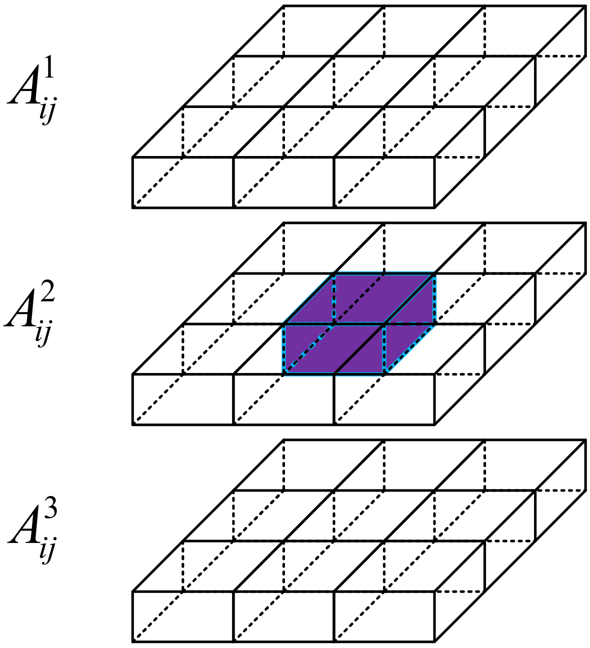

Figure 5-5 Diagram of the "three-dimensional" matrix

It is defined that when there are other aircraft trajectory points in grid A_{ij}^0 or its neighborhood grids, that is, there are any elements in the matrix $A_{ij}^{mnk} = 1, \quad m, n, k \in \{1, 2, 3\}$, indicates that there is a potential flight conflict. Otherwise, when all elements are zero, it means that there is no conflict.

$$\sum_{m=1}^{3} \sum_{n=1}^{3} \sum_{k=1}^{3} A_{ij}^{mnk} = 0.$$

The potential conflict detection method is implemented using a hash table data structure. For a given discrete 4D trajectory, each trajectory point is mapped to each 4D grid, and a series of flight identification information is stored in the corresponding grid. There is no need to store 4D coordinates in the data structure, which greatly reduces the required memory space. After the cleared departure time is modified, the total number of potential conflicts can also be easily updated.

Since it is judged whether there is a flight conflict only based on the divided 27 grids, the safety spacing standard is invisibly expanded by 3 times, and it is easy to cause too many false alarms. Therefore, the potential flight conflict situation judged by the 4D grid detection method is only a preliminary filter process. To obtain accurate conflict detection results, further calculation is required. It mainly focuses on the detection of flight conflicts on the predicted 4D trajectory. The geometrically deterministic algorithm is used to infer whether the vector difference between the aircraft's trajectory points is less than the minimum safety spacing standard through the predicted 4D trajectory, to realize the flight conflict detection.

Assuming that the flight conflict preliminary filter algorithm based on 4D grid has determined that there is a potential flight conflict between the trajectory points on the two aircraft's predicted trajectories (numbered i, j respectively) at the time t, and the corresponding three-dimensional space coordinates are respectively denoted as $p_i^k(x_i^k, y_i^k, z_i^k)$ and $p_j^k(x_j^k, y_j^k, z_j^k)$, the relative position vector between the aircraft is expressed as $\overrightarrow{p}_{i,j}^{k,l} = (\Delta x_{i,j}^{k,l}, \Delta y_{i,j}^{k,l}, \Delta z_{i,j}^{k,l}) = p_A - p_B$. Set aircraft A as a reference aircraft, and a schematic diagram of a safe protection zone delineated with aircraft A is shown in the following figure.

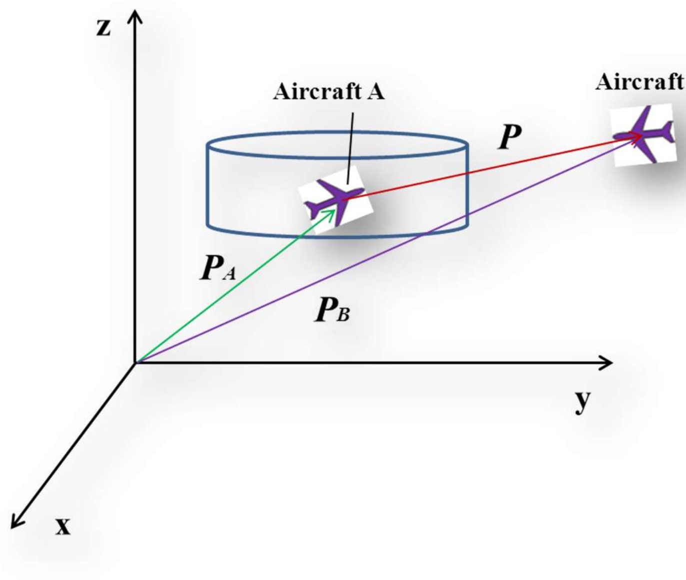

Figure 5-6 Diagram of the geometric position of the aircraft

When there is a flight conflict between the reference aircraft A and the test aircraft B, the following equations are satisfied:

$$\begin{cases} \sqrt{(\Delta x_{i,j}^{k,l})^2 + (\Delta y_{i,j}^{k,l})^2} < s \\ |\Delta z_{i,j}^{k,l}| < H \end{cases}$$

where, H is the minimum vertical safety distance, that is the height of the cylindrical protection area; s is the minimum horizontal safety distance, that is the radius of the designated cylindrical protection area.

5.3. MULTI-AIRCRAFT CONFLICT-FREE 4D TRAJECTORY PLANNING

Assuming there are n aircraft $(F_1, F_2, ..., F_n)$, and each aircraft is composed of several trajectory points, which are recorded as $F_i = \{p_i^k, k \in N^+\}$. According to the safety spacing standard, the 4D grid-based conflict preliminary filter algorithm is used firstly. Then, the accurate detection of flight conflict based on geometric method is implemented the preliminary filter, and finally a conflict matrix is obtained C:

$$C = \begin{bmatrix} C_{11} & C_{12} & \dots & C_{1n} \\ C_{21} & C_{22} & \dots & C_{2n} \\ \dots & \dots & \dots & \dots \\ C_{n1} & C_{n2} & \dots & C_{nn} \end{bmatrix}_{n \times n}$$

where $C_{ij} = \begin{cases} 1, & F_i \ and \ F_j \ have \ a \ conflict, \text{and } i \neq j, \\ 0, & \text{else}, \end{cases} \quad i, j = 1, 2, ..., n.$

Definition: aircraft delay time set $D = \{\delta_i \in T, \forall 1 \le i \le n, i \in N\}$, where T represents the discrete delay time, that is $T = (0, ts, 2ts, ..., \delta_{\max})$, where $\delta_{\max}$ represents the maximum allowable delay time; ts represents the interval period of the delay time.

In order to reduce the number of conflicts and the average delay time, the objective function for comprehensively controlling the total remaining conflicts and the delay time is set as $F_{\max}$. The maximum value of this function is the minimum total remaining conflicts and total delay time. The function expression is as follows:

$$F_{\max} = \frac{n - \sum_{i=1}^{n} \frac{\delta_i}{\delta_{\max}}}{1 + nrc},$$

where n represents the number of aircraft; nrc represents the total remaining number of conflicts among the aircraft, and the calculation expression is:

$$nrc = \sum_{i=1}^{n} \sum_{i<j}^{n} C_{ij}.$$

Through analysis, it can be known that if the algorithm is used in a big data, large-scale time combination optimization problem, it will be difficult to reduce the complexity of the algorithm. Assuming that there are 800 flights, the maximum delay time is set $\delta_{\max} = 90\min$, and the interval period of the delay time is $ts = 20s$, then delay time has 270 possible variables. According to the calculation of the complexity formula, it is found that the combined search space is very large, and the objective function is nonlinear. It also increases the complexity of the optimization algorithm.

$$f(o_{old}) = \frac{n\delta_{\max}}{2 \cdot ts} \left(\sum_{i=1}^{n} P_i \right)^2,$$

where $f(o_{old})$ represents the complexity of traditional optimization algorithms; P_i represents the total number of aircraft trajectory points.

In order to deal with the efficiency of large-scale 4D trajectory planning and simplify the complexity of the algorithm, a collaborative conflict-free trajectory planning method based on dynamic grouping strategy can be adopted. The method first dynamically grouped aircraft according to the conflict or interaction relationship between aircraft, and then for the conflicting aircraft in each group, by adjusting the initial departure time of or controlled time of arrival to avoid conflicts or interaction. Finally, the best trajectory planning is obtained by cooperating with each group of aircraft.

This algorithm not only minimizes the number of conflicts and reduces the average delay time, but also effectively reduces the complexity. The specific planning process is shown in the following figure.

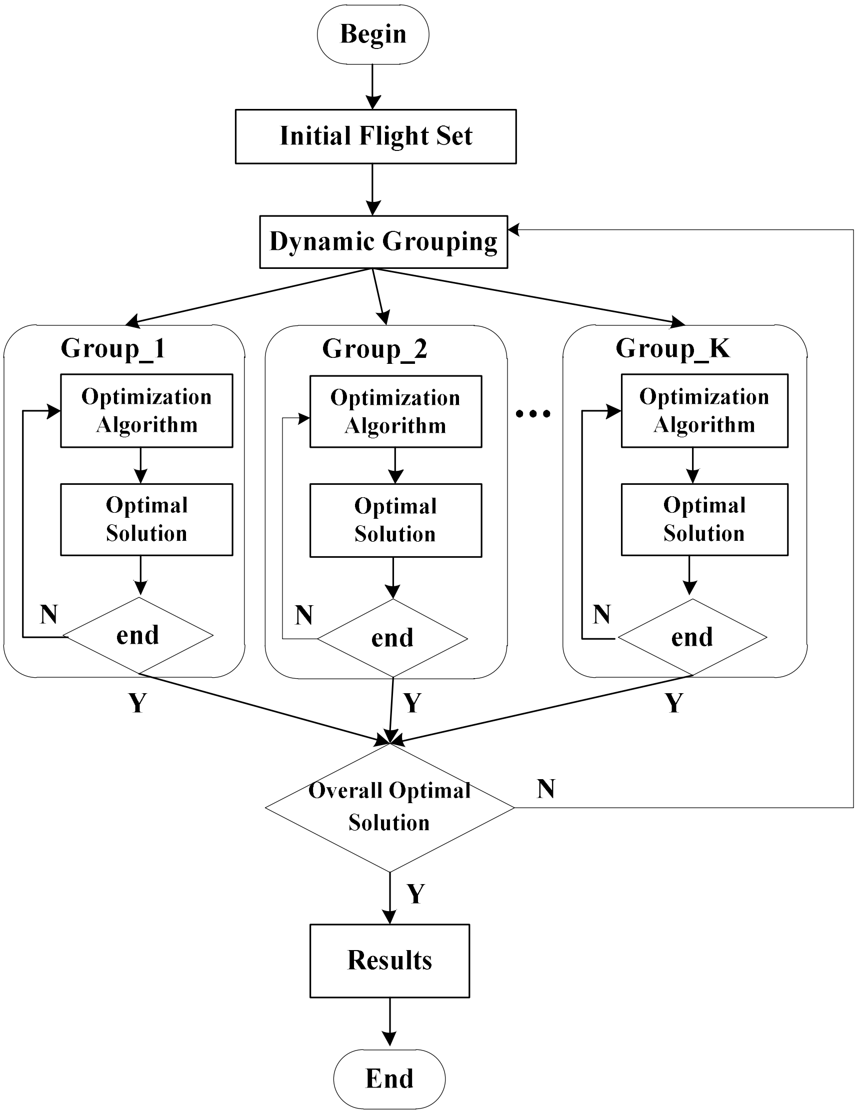

Figure 5-7 Flow chart of collaborative trajectory planning based on dynamic grouping strategy

The basic idea of the dynamic grouping strategy is mainly to group the conflict or interaction aircraft into the same group, to facilitate the unified adjustment of these aircraft. Compared with the overall aircraft planning, the complexity of the algorithm is reduced to a certain extent.

According to the dynamic grouping strategy, the aircraft is divided into different groups according to flight conflicts. The specific grouping steps are: First, a certain aircraft in the set F is selected and divided into the first group $group_1$. At this time, if the remaining aircraft in the set F have conflict with the aircraft in the $group_1$, move the conflicting aircraft in the set F to the $group_1$. When none of the aircraft in the set F is conflict with the aircraft in the $group_1$, the grouping is executed repeatedly to get $group_i$ until the set F is empty. The specific implementation algorithm flow is shown in the figure.

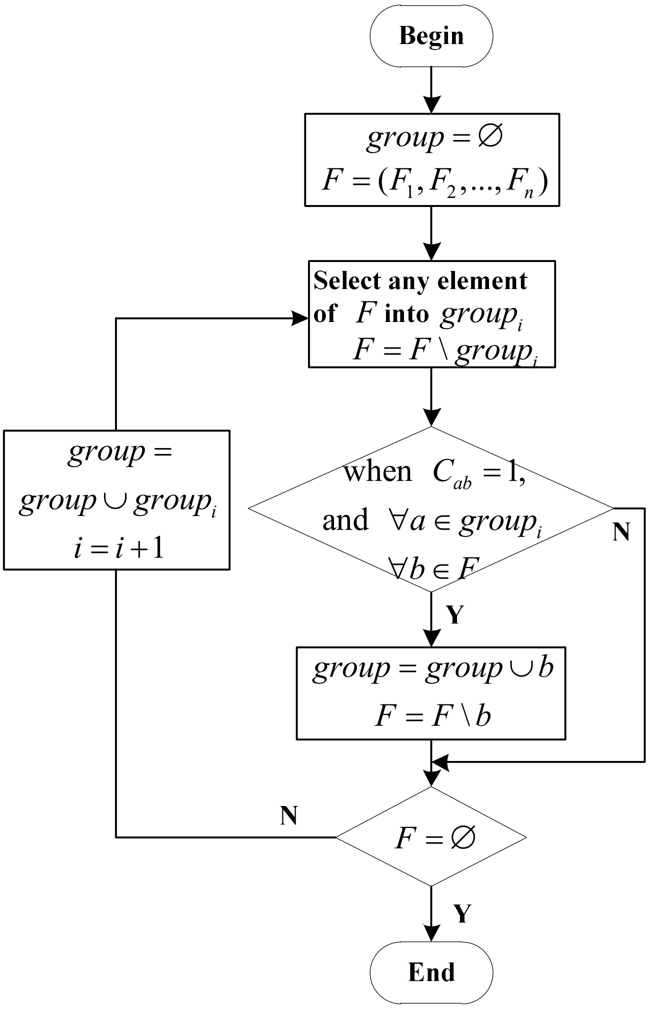

Figure 5-8 Dynamic grouping strategy flowchart

Definition: The set of all aircraft F is composed of K groups, denoted as:

$$F = \{group_1, group_2, \cdots, group_K\}$$

where

$$group_k = \left(F_k^1, F_k^2, \cdots F_k^{m_k}\right), 1 \le k \le K, 1 \le m_k < n, \sum_{k=1}^{K} m_k = n$$

In the formula, m_k represents the total number of aircraft in the $group_k$; F_k^i represents the number i aircraft in the $group_k$.

The dynamic grouping strategy can divide the conflict or interaction aircraft into the same group, and the aircraft that have no conflicts or interaction to each other into different groups. It satisfies the following correlations:

$$\begin{cases} \forall F_k^i \in group_k, \exists F_k^j \in group_k \Rightarrow C_{ij} = 1, \\ \forall F_k^i \in group_k, \forall F_k^j \in group_l \Rightarrow C_{ij} = 0. \end{cases}$$

In particular, when there is no conflict or interaction between various aircraft, it is satisfied that:

$$\forall i \neq j, i, j \in F \Rightarrow C_{ij} = 0.$$

In this case, a random grouping strategy is used to divide the aircraft into groups with the same number of aircraft. After each dynamic grouping, due to the adjustment of the initial departure time between different groups, new conflicts may occur. Therefore, after each grouping, it is necessary to analyze whether the dynamic grouping needs to be adjusted again according to the result.

When determining the conflict or interaction between aircraft, the following applicable constraints specific situations are usually considered:

- **Exceeding the airspace capacity limit**: the number of aircraft passing through key waypoints or entering the designated airspace in a unit time exceeds the set capacity value, it is considered that there is an interaction between these aircraft;
- **Violation of the minimum separation requirements specified by ATC**: When there is a meteorological influence, the ATC usually increases the spacing requirements during handover to ensure the orderly operation of air traffic. When the longitudinal separation between aircraft is lower than the specified threshold, it is considered that there is interaction between these aircraft;
- **Flight conflict**: When the horizontal and vertical separation is less than the minimum safe separation, it is considered that there is conflict between the two aircraft. Usually, the minimum vertical safe height is 300 meters or 1000 feet. The minimum horizontal safe separation needs to be determined according to the specific airspace conditions.

Compared with traditional ATS airspace, airlines can choose more flexible flight routes in the free route airspace. Therefore, when constructing the trajectory planning model in the free route airspace, the main optimized variables include:

- The position to enter the free route airspace (entry point);
- The position to exit the free route airspace (exit point);
- Airspace entry time;
- Cruise speed and altitude.

In the process of aircraft trajectory planning, 15 minutes may be used as the time unit. And the 4D trajectory is changed by adjusting the time and altitude at the airspace entry and exit points to solve the conflict or interaction between flights. The main principles followed are as follows:

- Adjusting the time of departure or entering/exiting the airspace has the highest priority. When only adjusting the time cannot eliminate the conflict or interaction, adjusting the flight altitude is considered;
- When the estimated traffic flow per unit time exceeds the airspace capacity, the excess aircraft will be moved to the next time period;
- Flights moving from the previous periods to this period have higher priority;
- The controlled time of arrival CTA is usually after the estimated time of arrival ETA. When there is no available time slot between the ETA and the end of this time period, the CTA of the aircraft may be set a certain time (according to the distance

from the aircraft position to the waypoint) before ETA to meet the requirements of maximum capacity utilization.

5.4. AIRCRAFT SAFETY SEPARATION MANAGEMENT

The aircraft safety separation is the minimum distance between aircraft which is set to prevent two or more aircraft from colliding in the air and ensure the order and safety of air traffic. At the same time, it can improve the full use of time and space resources. Under normal operational conditions, the separation of aircraft should not be less than the required minimum distance. The aircraft separation is generally divided into horizontal and vertical separation in terms of spatial configuration. The horizontal separation includes lateral and longitudinal separation. The schematic diagram of the aircraft separation is shown in the figure below.

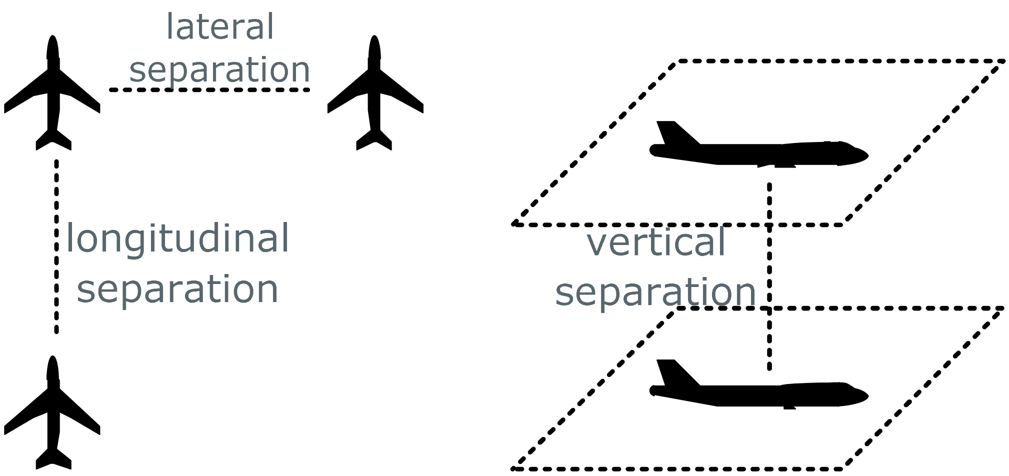

Figure 5-9 Diagram of the aircraft separation

Two different types of trajectories are defined in the process of conflict management in the real-time flight phase:

- **Tactical trajectory**: Tactical trajectory is predicted based on the projected route information in the FPL, radar data and current ATC clearance information, regardless of airspace restrictions, handover agreements, etc. The prediction range of tactical trajectory is 6 minutes after the current position, mainly used for aircraft conflict identification in the current sector.

- **Planning trajectory**: Planning trajectory is predicted based on the projected route information in the FPL and radar data, it is assumed that the aircraft will meet the entry flight level NFL or exit flight level XFL of the sectors. The prediction range of planning trajectory is usually 12-15 minutes after the current position. It is mainly used to identify the conflicts caused by cross-border operations and the handover.

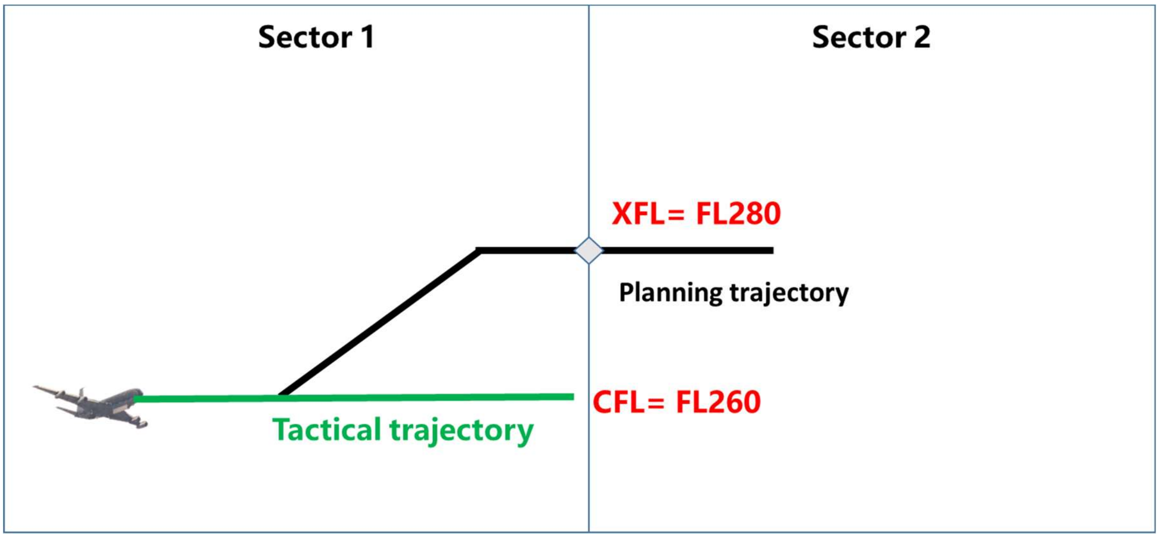

Figure 5-10 Tactical trajectory and planning trajectory

In the process of trajectory prediction, the actual ground speed of the aircraft is obtained through the combination of airspeed and wind speed. The data downloaded from MODE S radar includes indicated airspeed, track angle and heading, which is very useful for the speed estimation in trajectory prediction. In the horizontal direction, when there is no flight path deviation, the tactical trajectory is calculated using the current position along the reference path. If the flight path deviation occurs, the current heading and current ground speed*4 minutes are used to calculate, and the criterion of horizontal deviation is 3 kilometers.

For the calculation of the climb phase, if the true rate of climb is not available, the nominal rate of climb of 1500ft/min is used for calculation. The buffer range in the calculation of the rate of climb is as follows:

- When a CFL deviation occurs, the buffer of the climb rate is ±200ft/min of the current climb rate;
- If the climb rate is not specified by ATC, the buffer range is 50-3000ft/min when the climb rate is lower than the critical value to reach the CFL; when it exceeds the critical value to reach the CFL, the buffer range is ±500ft/min of the current climb rate;
- In the case of a deviation of the climb rate, the buffer range is 50-6000ft/min when the climb rate is lower than the critical value for reaching the CFL; when it exceeds the critical value to reach the CFL, the buffer range is ±1500ft/min of the current climb rate;
- For a given specific rate of climb, the buffer range is ±100ft/min of the specified rate of climb. When an ATC clearance is not lower than a certain rate of climb, the lower limit is the rate of climb minus 100ft/min, and the upper limit is the rate of climb plus 1500ft/min, but the minimum is 3000ft/min. When an ATC clearance is not higher than a certain rate of climb, the lower limit is 50ft/min, and the upper limit is the rate of climb plus 100ft/min.

The ATM automation system performs conflict detection based on the calculated tactical trajectory and the planning trajectory. In the process of conflict detection, in order to increase the safety margin, it is necessary to increase the longitudinal distance of the current speed for 1 minute on the basis of the minimum safety separation as an additional buffer protection zone. When one flight enters the protection zone of another flight, the system would identify that there is a flight conflict, as shown in the figure below.

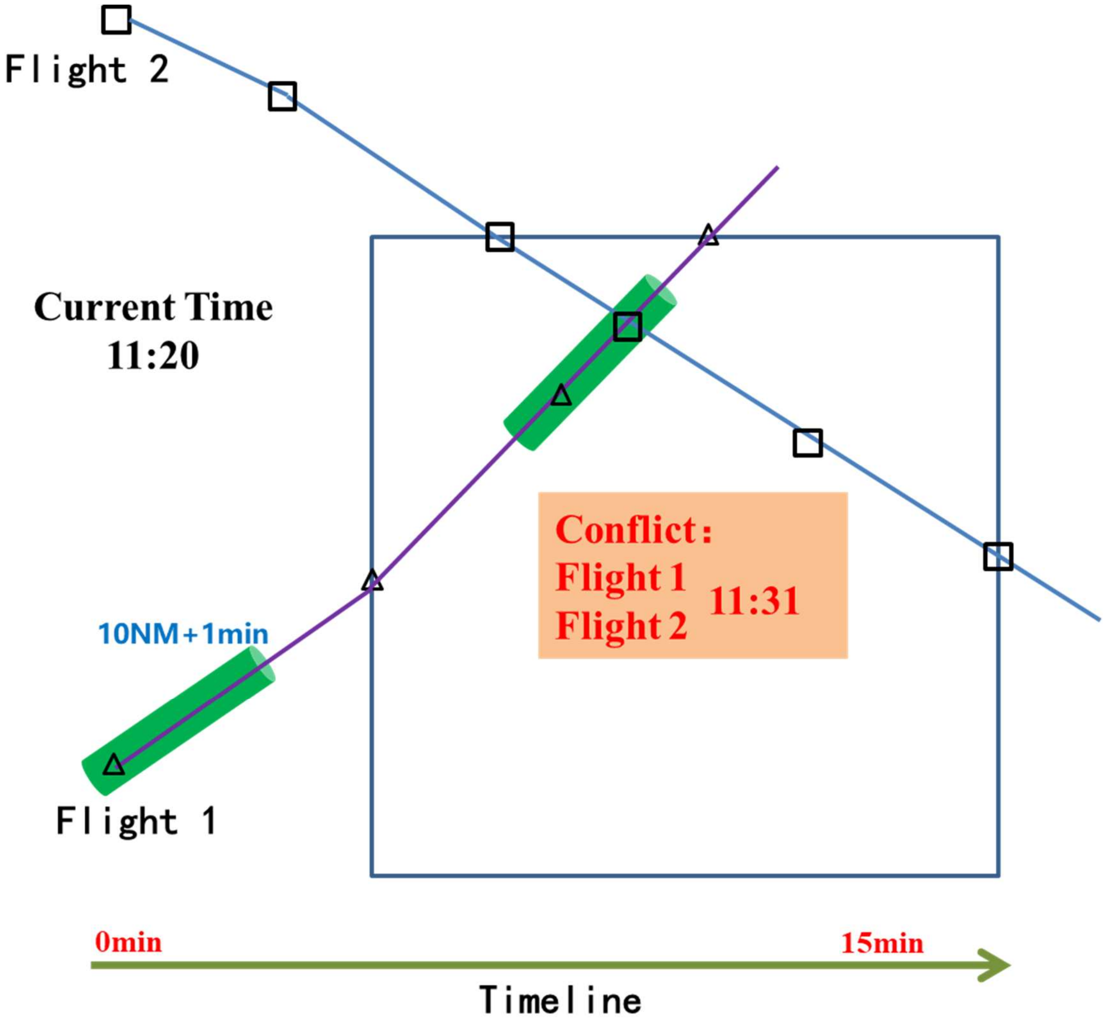

Figure 5-11 Diagram of conflict detection

When a conflict alarm occurs, the controller needs to resolve the conflict based on experience and/or system suggestions. The system uses the what-if method to resolve conflicts and calculates the assumed trajectory according to the range that the flight can be adjusted in altitude and horizontal direction. And it also evaluates whether the assumed trajectory conflicts with other flights. In the upper airspace, flight level adjustment for conflict resolution is preferred method. The basic principles of conflict resolution are as follows:

- Provide the lateral or flight level clearance for conflicting aircraft, while not affecting other aircraft to maintain their current trajectory;
- Avoid using speed adjustment methods as much as possible;
- Mixed resolution methods cannot be used (for example, climb to FL230 and turn right 10 degrees);
- The flight level is FL0 to FL500, the climb rate range is 0,500, 1000 up to 5000ft/min. The heading is a maximum of 40 degrees left and right, with 5 degrees as a step.

- The time range of the resolution suggestion should be longer than that of conflict detection to avoid new conflicts immediately after resolution.

6. AIR GROUND COOPERATION METHOD

Air ground cooperation is the foundation to implement more efficiency 4D trajectory is tactical operation phase. Section 6.1 is an overview of air-ground data link application and section 6.2 is the outcome of this project aiming at the air-ground cooperation to support greener long-haul flight operation.

6.1. OVERVIEW OF AIR-GROUND DATA LINK APPLICATION

At present, the definition and research work of aeronautical communication services is mainly concerned with the communication part of flight safety and normal flight operations, and is carried out around the communication services of air traffic services and flight operation. In terms of air traffic service communication, it mainly focuses on the communication between pilots and controllers at each stage of the flight, supplemented by notice to airmen and meteorological information, and provides a series of services. The definition of flight operation communication service focuses on the execution of flights and the status of aircraft maintenance.

The more representative communication service definition work is a series of standard development projects jointly carried out by the RTCA and EUROCAE. Through these projects, the security, performance, and interoperability requirements of air-ground data communication services in the air traffic service communication field have been developed.

In the standard ATN Baseline 1, the main services defined include: Data Link Capability (DLIC), ATC Communication Management (ACM), ATC Clearance (ACL), Departure Clearance (DCL), and ATC Microphone Check (AMC). At present, the basic services in ATN Baseline 1 have been put into operation in main areas of Europe. The ATN Baseline 2 standard enhances existing services and adds new data communication services, including 4DTRAD, which supports trajectory-based operations, and D-TAXI, which supports surface operations.

In the ATN Baseline 2 interoperability standard RTCA DO-351A, the Time of Arrival TOA range (earliest and latest arrival time) and speed profile data items are added to the ADS-C request and periodic report. At the same time, the data format of the Extended Projected Profile EPP is improved, and the estimated speed, waypoint type, constraint information, etc. are added. It can improve the ability of air-to-ground trajectory synchronization in the next-generation ATM system.

The specific data format of the TOA window is as follows:

```
TOARange::=Sequence
  {
    computation-time      [0]
    eta                   [1]
    latitudeLongitude     [2]
    name                  [3]
    windErrorModelUsed    [4]
    earliest              [5]
```

```
        latest                  [6]
      }
```

The specific data format of the EPP is as follows:

```
ExtenedProjectedProfile::=Sequence
{
    computation-time            [0]
    way-point-sequence          [1]
     {
         latitude           [0]
         longitude          [1]
         level              [2]
         name               [3]
         estimated-time     [4]
         estimated-speed    [5]
         vertical-type      [6]
         lateral-type       [7]
         level-constraint   [8]
         speed-constraint   [9]
         time-constraint    [10]
      }
current-gross-mass                  [2]
}
```

The current air traffic services communication and flight operation communication services are still mainly voice, which supports most of the services. It is expected that after 2022, the application of data communication in the ground and the air will continue to grow, and will become the main means of air-ground communication in the future years. And the information exchanged between the ground and the air will be more abundant. Then, the voice communication will be used as auxiliary and emergency communication, and completes the transformation of digital communication and ATC operation.

6.2. TYPICAL SCENARIOS

- Synchronization of air-ground trajectory information

Air-ground trajectory information synchronization realizes the coordination of ground trajectory and aircraft trajectory. The ground system receives the profile data from the aircraft through the data link and participates in the 4D trajectory negotiation on the ground. After obtaining the unanimously approved 4D trajectory, it is uploaded to the aircraft through the data link to ensure the synchronization of the aircraft and ground trajectory. It should be noted that the flight should negotiate and determine the approved

4D trajectory 20-30 minutes before departure at the latest. Usually, for one flight up to 3 trials can be done before reaching an agreement. Therefore, ATM needs to formulate a mechanism to ensure that each flight is assigned an executable 4D trajectory.

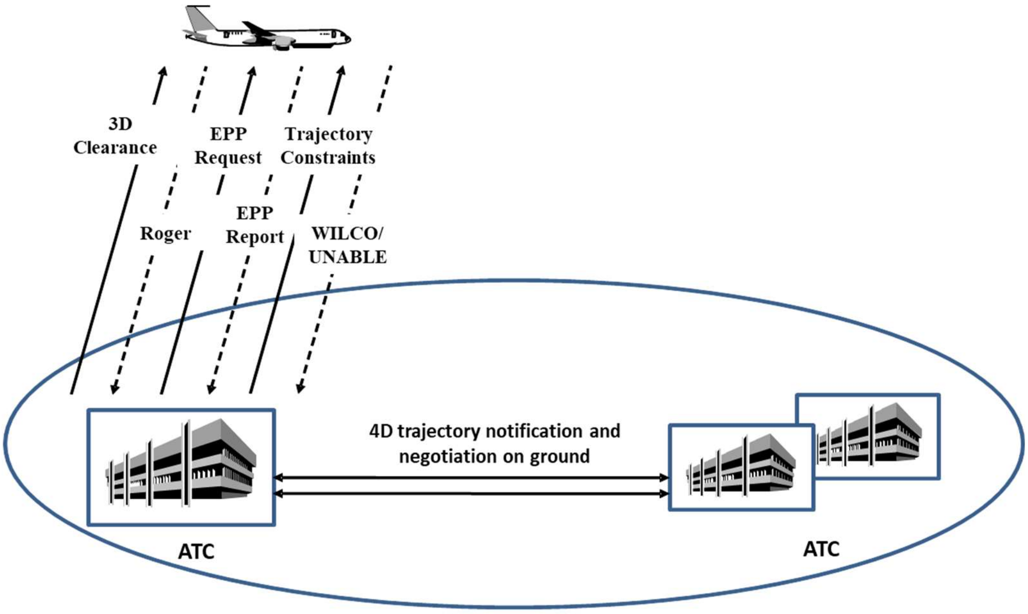

Figure 6-1 Diagram of air-ground trajectory synchronization

Table 6-1 Operation process of air-ground trajectory synchronization

Step	Description
1	The ground ATC center uploads the aircraft clearance information (Runway, SID, planned route)
2	The airborne communication system receives the clearance information and informs the crew members
3	The crew members evaluate the clearance information and it is loaded into the FMS of the aircraft
4	When the crew member confirms that the received clearance information can be executed, the crew returns a WILCO message to activate the received clearance information
5	The ground ATC center receives the WILCO message from the crew and notifis the controllers
6	The ground ATC center requests airborne 4D trajectory data
7	The aircraft downloads EPP data
8	The latest 4D trajectory information will be notified to relevant ATC units (for example the downstream ACCs and APP)
9	Relevant trajectory constraints are uploaded to the aircraft using the data link

10	The flight crew evaluates the feasibility of the trajectory constraints. If it cannot be implemented, the ground ATC center needs to coordinate the relevant units to get a new clearance information or trajectory constraints.

- Trajectory negotiation, notification and update

During the flight, the aircraft continuously downloads the onboard 4D trajectory through the EPP data of ADS-C. And the current ground ATC units will notify the relevant l units of the latest 4D information integrated into the EPP data, to facilitate them to monitor the flight process and flight intentions.

- **4D trajectory update and notification**. The current ATC unit of the flight is responsible for the update and notification of the latest 4D trajectory.

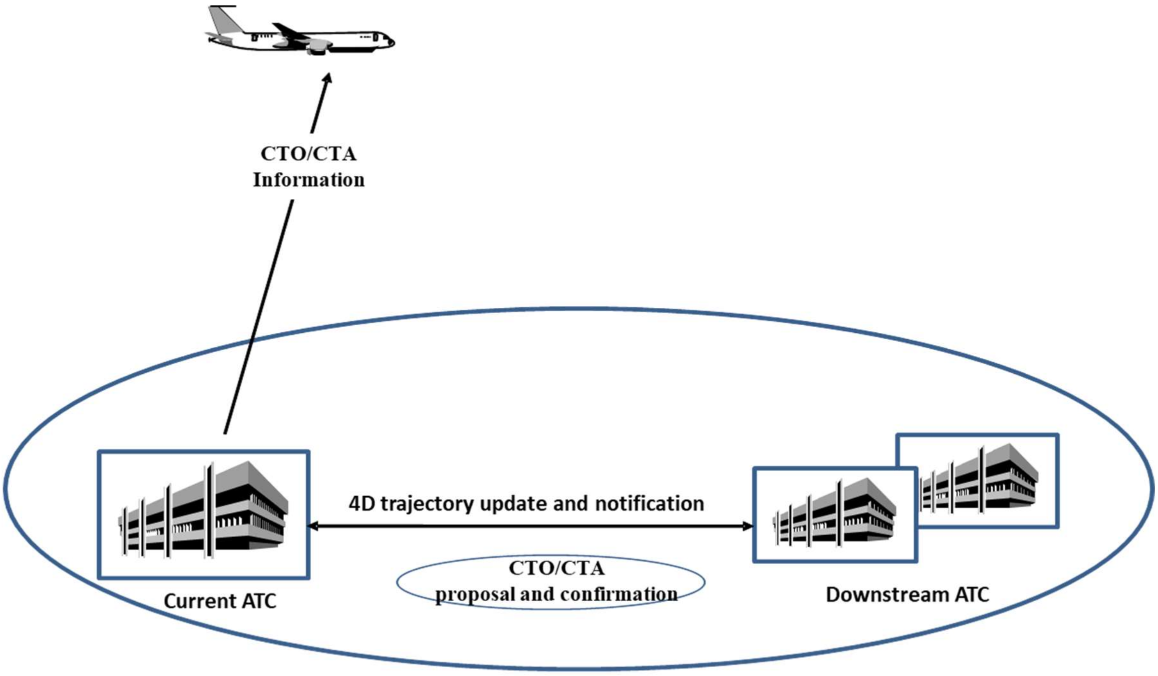

Figure 6-2 Diagram of 4D trajectory update and notification

Table 6-2 Operation process of 4D trajectory update and notification

Step	Description
1	The ground ATC center shares the latest 4D trajectory data to the relevant ground ATC unit for update and notification
2	The CTO/CTAs on waypoints are proposed by each relevant ATC unit according to its operating conditions, if necessary
3	The current ground ATC center will count which waypoints have proposed CTO/CTA
4	The current ground ATC center sends CTO/CTA constraints to aircraft

5	The current ground ATC center will notify the relevant ATC units of the confirmed CTO/CTA constraints information
6	The aircraft downloads the EPP data again according to the constraint's information

- **4D trajectory negotiation and notification.** When the 4D trajectory of the flight cannot meet the ATC operation requirements, a trajectory negotiation process is required.

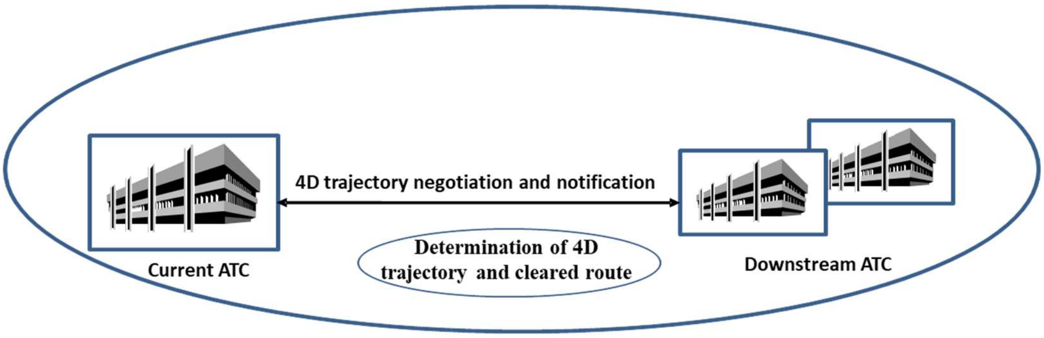

Figure 6-3 Diagram of 4D trajectory negotiation and notification

Table 6-3 Operation process of 4D trajectory negotiation and notification

Step	Description
1	The ground ATC center sends the proposed or requested 4D trajectory to the relevant ATC unit for negotiation
2	The relevant ATC center/controller discusses the proposed 4D trajectory until the trajectory is fully approved
3	Revise the trajectory according to Table 6-4

- **4D trajectory revision.** After the 4D trajectory negotiation is completed, the 4D trajectory will be revised as needed to re-synchronize the air and ground participants.

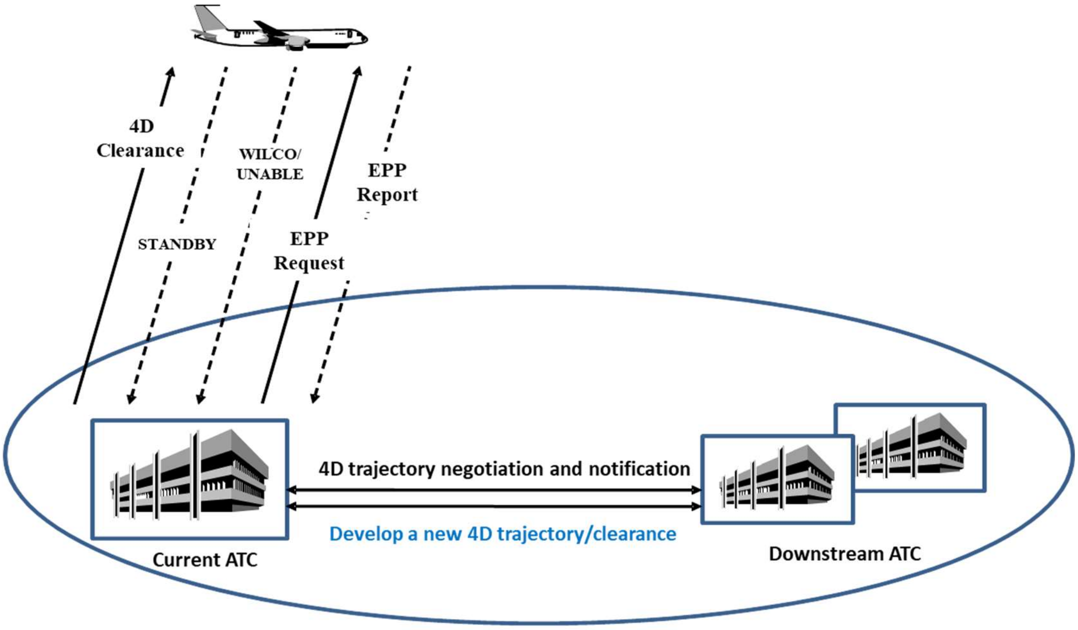

Figure 6-4 Diagram of 4D trajectory revision

Table 6-4 Operation process of 4D trajectory revision

Step	Description
1	When the 4D trajectory needs to be revised: 1) Need to coordinate among the related ATC centers 2) The new 4D clearance information is uploaded by the current ATC center
2	The ground current ATC center uploads 4D clearance information
3	The airborne communication system receives the clearance information and informs the crew members
4	The crew may feedback that the information has been received and needs to be evaluated (STANDBY)
5	The 4D clearance information is loaded into the airborne FMS and the crew members evaluate it
6	When the crew member confirms that the received 4D clearance information can be executed, the crew returns a WILCO message to activate the received clearance
7	The ground ATC center receives the WILCO message from the crew and notify the controller
8	The ground ATC center requests airborne 4D trajectory data
9	The aircraft downloads the airborne 4D trajectory data
10	The latest 4D trajectory information will be communicated to relevant units
11	The ground ATC center monitors the synchronized 4D trajectory
7U	If the crew confirms that the received 4D clearance information cannot be executed, the crew returns an UNABLE message

8U	The ground ATC center receives the UNABLE message from the crew and notify the controller
9U	Notify relevant ATC units
10U	If necessary, the ground ATC center maintains coordination to formulate a new 4D trajectory

Clearance request and issue

- **Clearance request for a new route**. Before initiating the clearance request, the flight crew had received the flight plan route from the AOC. The flight crew will only request a clearance request that differs from the filed trajectory for major reasons，such as sudden thunderstorm.

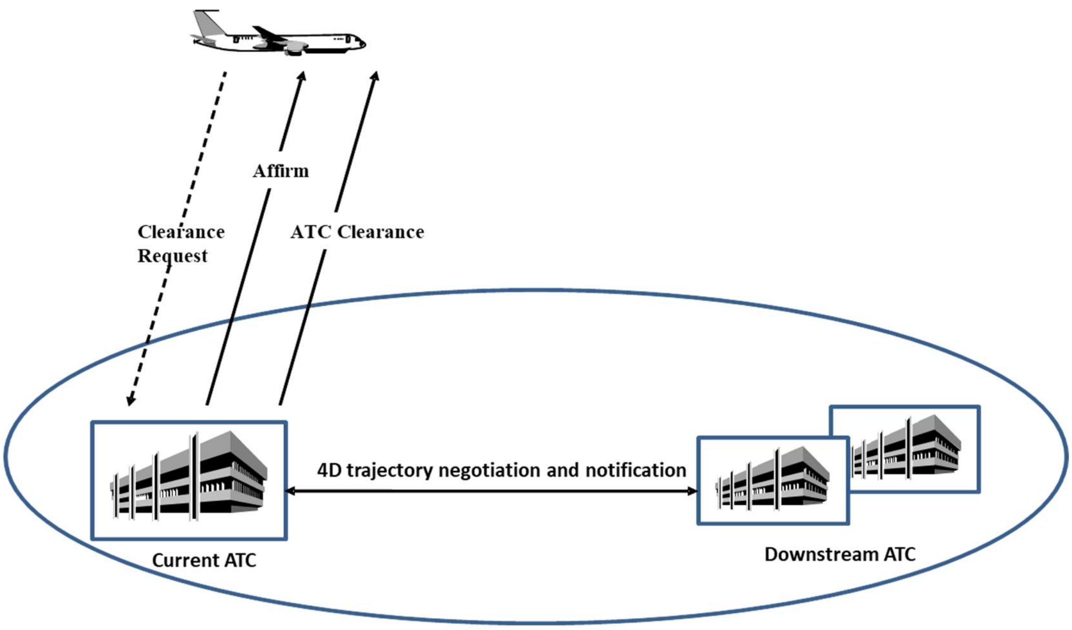

Figure 6-5 Diagram of clearance request

Table 6-5 Operation process of clearance request

Step	Description
1	The flight crew generate a clearance request according to the flight intention and downloads it
2	After receiving the information, the ground ATC center sends a Affirm message to the crew
3	Follow the steps in Table 6-3 to start the ground negotiation procedure
4U	If the result of the negotiation is that the controller cannot provide the requested clearance, the controller uploads an UNABLE message and sometimes provides the reason for rejection

4C	If the controller can provide the related clearance, upload the corresponding ATC instructions

- **CTO/CTA issue**. The CTO/CTA issue is to implement time constraints on the basis of 3D trajectory to meet the ETA requirements.

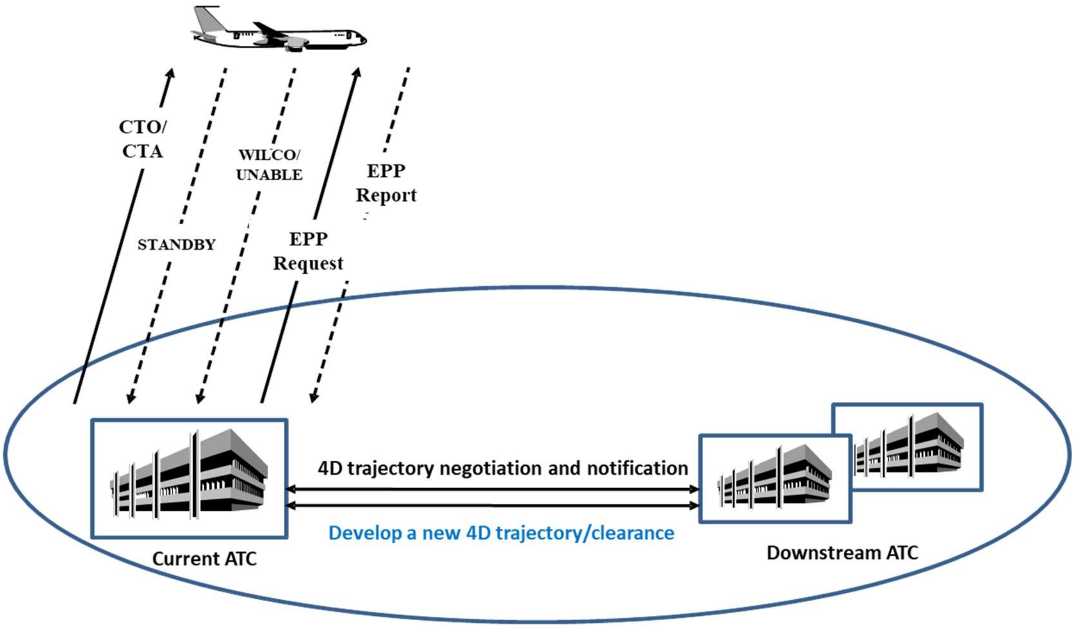

Figure 6-6 Diagram of CTO/CTA issue

Table 6-6 Operation process of CTO/CTA issue

Step	Description
1	The current ATC center shares the latest 4D trajectory information to other relevant ATC units
2	The ground ATC centers maintain coordination to confirm reasonable CTO/CTA constaints
3	The current ATC center uploads CTO/CTA constraints via CPDLC
4	The airborne communication system receives the CTO/CTA information and informs the crew members
5	The crew may feedback that the information has been received and needs to be evaluated (STANDBY)
6	The CTO/CTA is loaded into the FMS and the crew members evaluate it
7W	When the crew member confirms that the received information can be executed, the crew returns a WILCO message to activate the received CTO/CTA information
8W	The aircraft downloads ADS-C EPP data
9W	Synchronized trajectory information will be notified to relevant units

10	The ground ATC center monitors the synchronized 4D trajectory
7U	If the crew confirms that it cannot execute the received CTO/CTA information, the crew returns an UNABLE message
8U	The ground ATC center receives the UNABLE message, then notify the controller and relevant ATC units
9U	If necessary, the ground ATC center maintains coordination to formulate new CTO/CTA constaints

- Consistency monitoring of 4D trajectory

The established 4D trajectory and flight constraints are based on the common understanding of the situation, without considering the influence of unknowable factors. The consistency monitoring is to monitor the difference between the expected flight trajectory and the constraints in advance, and ensure the consistency with the 4D synchronization trajectory to the greatest extent.

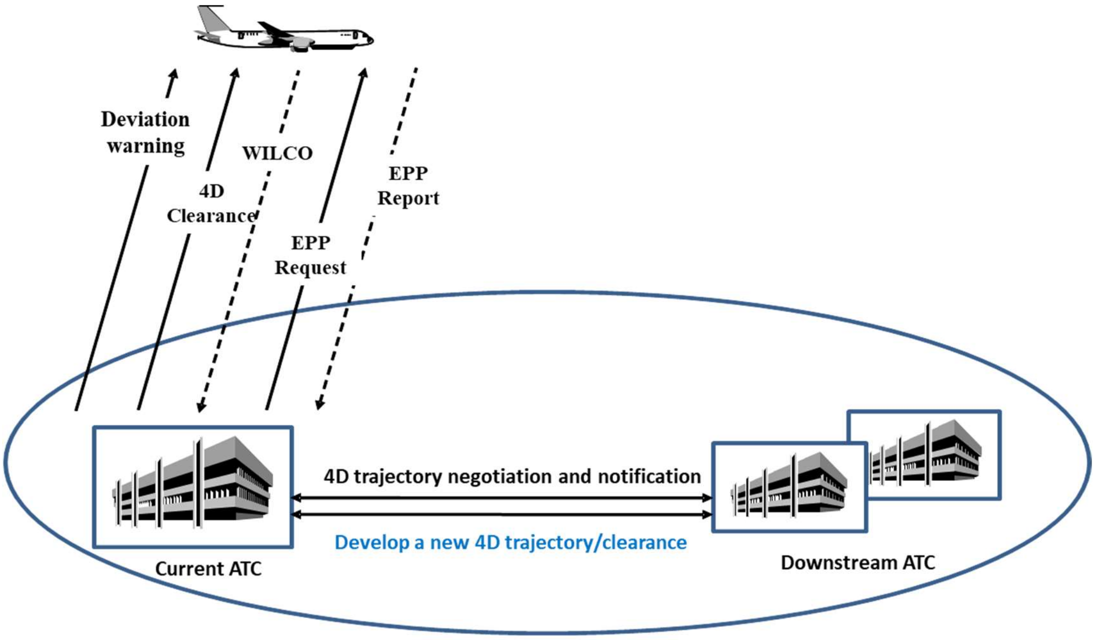

Figure 6-7 Diagram of consistency monitoring

Table 6-7 Operation process of consistency monitoring

Step	Description
1	The ground ATC center found that the aircraft deviated from the 4D trajectory, and sent a deviation warning to the aircraft
2	The ground ATC center initiates the trajectory coordination and negotiation procedure, and generates a new clearance
3	The ground ATC center sends the latest clearance to the aircraft

4	The aircraft updates the 4D trajectory information according to the latest clearance and downloads EPP to the center

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