Study on Trajectory Prediction Model

Yutaka Fukuda, Masayuki Shirakawa, Atsushi Senoguchi
Air Traffic Management Department
Electronic Navigation Research Institute (ENRI)
Tokyo, Japan
[fukuda | shirakawa | senoguchi]@enri.go.jp

Abstract: International Civil Aviation Organization (ICAO) has created the global Air Traffic Management (ATM) operational concept scoping to 2025. Trajectory-based operation is introduced in the concept. The future vision of NextGen and SESAR has progressed it. Electronic Navigation Research Institute (ENRI) has defined trajectory management as a core subject in its future research vision. A trajectory prediction system is required for trajectory management. This paper discusses a trajectory prediction model developed at ENRI. Firstly, general information on trajectory management is explained. Secondly, the trajectory prediction model as a means to predict and estimate the trajectory of an aircraft, is discussed. Finally, a comparison of estimated trajectory with flight data measured by aircraft is given.

Keywords: Air Traffic Management, Trajectory Management, Air Traffic Control

1. Introduction

International Civil Aviation Organization (ICAO) recommended the global Air Traffic Management (ATM) operational concept at the Eleventh Air Navigation Conference in 2003 [1]. The concept scopes to 2025. ATM is the dynamic, integrated management of air traffic and airspace – safely, economically and efficiently – through the provision of facilities and seamless services in collaboration with all parties [2]. It is made up of 7 components, including demand and capacity balancing, traffic synchronization, and conflict management. It aims to realize the expectations of the ATM community such as safety, efficiency, and capacity. Trajectory-based operation is introduced in the concept.

Long range visions such as the United States' NextGen and Europe's SESAR have been proposed to realize this concept [3], [4]. These plans aim for trajectory-based operation.

Trajectory management was defined as a core subject in the long term research vision of Electronic Navigation Research Institute (ENRI) [5]. ENRI has been studying the trajectory prediction model as a key element of trajectory management. The study is developing a system to predict trajectory and evaluate it with operational data.

This paper covers the trajectory prediction model that is being developed. Estimated trajectory is compared with actual measurement values recorded by aircraft.

2. Trajectory Management

2.1 Trajectory

Trajectory is defined by providing a series of pieces of information on the position (latitude, longitude, and altitude), speed and time over waypoints and trajectory change points. It is made by considering weather and restriction of airspace and airports. Trajectory management is a method for future ATM. It makes trajectories, taking into consideration safety separation, air traffic controller workload, airspace and airport capacity, aircraft performance, and meteorological conditions. Information exchange and mathematical calculation are necessary.

It is necessary to manage trajectory information for prediction, update, and sharing. There are a lot of subjects to be developed. For example, as follows:

1) Wide range information sharing and coordination

2) Trajectory prediction and estimation

3) Coordination and rescheduling of trajectory

4) Accurate surveillance of aircraft trajectory executed

5) Communication, navigation, and surveillance infrastructure to support all of these

2.2 Trajectory Management

Aircraft fuel saving is important for environmental reasons. New aircraft are equipped with a new type of Flight Management System (FMS), which manages the optimum trajectory for fuel consumption and flight time. Trajectory optimization is limited to an individual aircraft. It doesn't work to optimize trajectories for all aircraft within airspace.

Aircraft equipped with the latest FMS have a highly accurate trajectory control function. Older aircraft do not have the function. A ground-based system is required to predict the trajectory for each individual aircraft to optimize trajectories for all aircraft in airspace.

There is an operational difference between the current air traffic control procedure and trajectory management. In the current operation, air traffic controllers keep separation of aircraft relatively, by controlling course, altitude, and speed of aircraft. Trajectory management controls absolute time of the trajectory. Therefore, it is necessary to introduce trajectory management gradually.

3. Trajectory Prediction Model

3.1 Trajectory Prediction

It is necessary to predict time, altitude, and speed at waypoints and trajectory change points of each aircraft for trajectory management. The following uncertainties exist for prediction:

1) There are many kinds of aircraft operated. The performance model for each aircraft is required, but detailed performance information for aircraft is not published.
2) Certain elements are not decided until the day or time of operation.
3) Flight conditions change even in the same aircraft, based on altitude, weather, weight, and configuration such as flaps and landing gears.
4) Changes in course, altitude, and speed are assigned by the air traffic controller for keeping safe separation between aircraft. This is not planned in advance.
5) Meteorological conditions such as wind and temperature are uncertain.

It will be possible to share state and intent information of aircraft through data communication, such as Automatic Dependent Surveillance-Broadcast (ADS-B), System Wide Information Management (SWIM), and Collaborative Decision Making (CDM) in the future. State information includes position, speed, and weather information, etc. Intent information includes control instructions by pilots and air traffic controllers. The above mentioned uncertainty can be reduced with this infrastructure for improvement of trajectory prediction.

Accurate time prediction of trajectory is necessary for trajectory management. Therefore, the prediction of ground speed is important. Ground speed is calculated according to the model shown below. It corresponds to estimation of the influences of 1) 3) 5) above.

3.2 Trajectory Prediction Model

A mass point model is used as simple model to predict trajectory. BADA performance model made by Eurocontrol is used as an aircraft performance and operational model [6]. It has been made public for research use only. The prediction model is composed of the following parts:

1) Calculation of CAS (Calibrated Air Speed) by operational model
2) Calculation of TAS (True Air Speed)
3) Calculation of ground speed by adding estimated wind from meteorological model
4) Calculation of vertical movement by energy conservation law
5) Calculation of fuel consumption, thrust, and drag, etc.

The model shows the relationship between various values of aircraft. Fuel consumption and altitude change rate can be predicted, in addition to ground speed.

3.3 Calculation of Ground Speed

It is assumed that air temperature, weight of aircraft, and altitude are already known in the calculation.

3.3.1 Calculation of CAS and Mach

Speed of aircraft is calculated based on operational model. Speed is provided by CAS and the Mach number at specified altitude. There is no significant difference between IAS (Indicated Air Speed) and CAS. CAS and the Mach number are more convenient than TAS from the viewpoint of controlling aircraft.

3.3.2 Calculation of TAS

TAS is converted from CAS at real speed in a calm atmosphere in correcting for the density of air.

3.3.3 Calculation of Ground Speed

The standard ICAO atmosphere model is used [7]. It is calculated by specifying air temperature. Moreover, the boundary between troposphere and stratosphere is calculated from air temperature and altitude.

Meteorological information is based on objective analysis data provided by Japan Meteorological Agency (JMA). Wind and temperature are defined on gridded points of three dimensions. Wind and temperature at the aircraft's position are calculated by interpolation. The along-track element of wind is added to TAS to obtain ground speed.

3.4 Calculation of Other Values

3.4.1 Calculation of Vertical Movement

Aircraft movement is caused by thrust and drag. Thrust is generated by engines, and drag is generated by air collision against aircraft. Aircraft altitude and speed result from these forces.

3.4.2 Expression of Energy and Control of Trajectory

Equation (1) is given from the law of conservation of energy.

$$(T-D)V_{TAS} = mg\frac{dh}{dt} + mV_{TAS}\frac{dV_{TAS}}{dt} \qquad (1)$$

where T is thrust, D is drag, V_{TAS} is TAS, m is mass of aircraft, h is altitude, t is time. There are three control elements of thrust, altitude change, and speed change. These three elements are interdependent. From the viewpoint of control, trajectory is decided by controlling two of the three elements. For example, it can be shown that only one element of speed or altitude is controlled at the same time when aircraft fly with idling thrust.

3.4.3 Calculation of Fuel Consumption

Fuel consumption can be calculated directly according to TAS and thrust.

3.5 Operational Model

An aircraft operational model is necessary to predict movement of an aircraft. Airlines often set operational procedure based on CAS. Aircraft can be modeled by the relationship between altitude and CAS.

Neither operational procedures nor aircraft performance data are published. However, it is assumed that almost the same operational procedures are carried out for aircraft of the same type. BADA standard model is used as a representative example. Figure 1 shows an example of air speed.

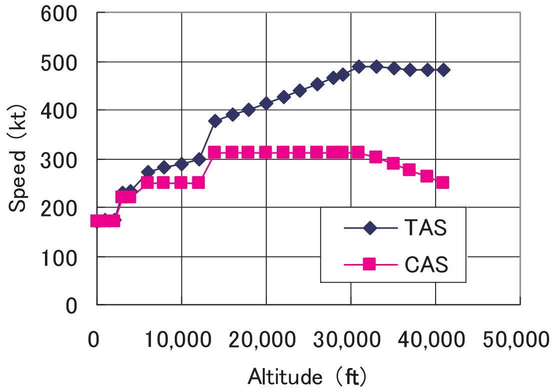

Figure 1 Example of Air Speed

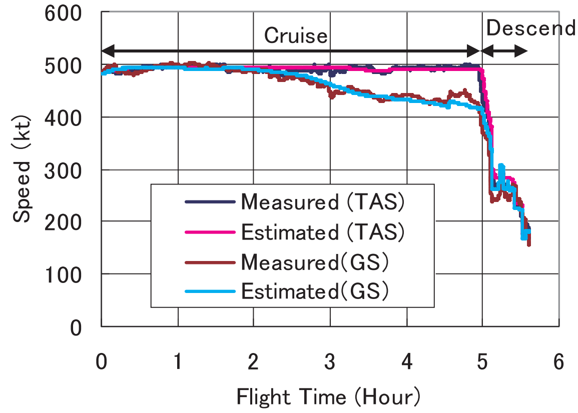

Figure 2 Comparisons of TAS and GS

4. Comparison with Flight Data

Ground speed and other values were estimated with the trajectory prediction model by using BADA aircraft performance data and operational model. It was compared with flight data measured by aircraft. JMA analysis data was used for wind and air temperature. In the calculation, route and altitude were assumed to be already known. The ground speed estimated value was compared with the measurement value at the same position.

4.1 Comparison of Ground Speed

Figure 2 shows TAS and ground speed as estimated and as measured by aircraft. It is for cruise and descent phase. JMA wind speed and air temperature data were used. Measured data of aircraft weight was used. As for TAS during cruise, measured and estimated values were almost the same. The difference was less than 1%.

Ground speed was obtained by correction with JMA wind data. Accuracy of ground speed estimation was less than 1% on average.

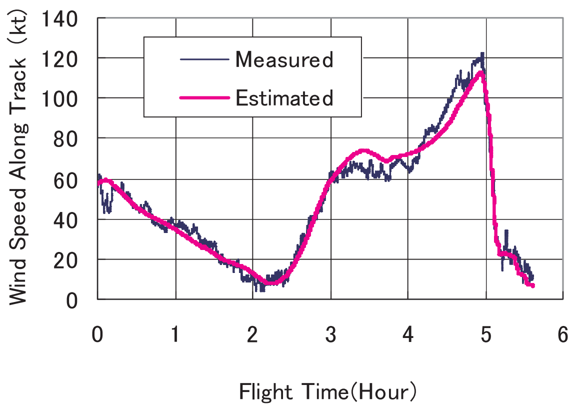

Figure 3 Comparison of Wind Speed

Figure 3 shows comparison of wind with actual measurement values recorded by aircraft. JMA wind data was observed about one hour before the beginning of the measurement. The estimated wind value agrees well with the measured value, though six or more hours had passed since it had been observed. In this case, atmosphere seemed to be stable. If the weather changes rapidly, the difference increases. JMA wind data is updated every six hours. Accurate forecast and update processing will be needed in the future.

Figure 4 shows variation of estimated time of arrival. The difference between estimated and actual ground speed is accumulated for the estimation. The time difference is less than 120 seconds. The total flight time is 5.5 hours (about 20,000 seconds). Time difference ratio is less than 1% over the flight time.

4.2 Comparison of Other Values

Figure 5 shows fuel consumption rate. It is assumed that aircraft weight is already known. Fuel consumption moves up and down on the right side, during the descent phase. Fuel consumption rises during the landing phase because of the effect of increasing drag as aircraft uses flaps and landing gears. Fuel consumption is one of the main indexes for operational efficiency of aircraft. If it can be estimated, the effect of fuel reduction can be calculated with the installation of trajectory management.

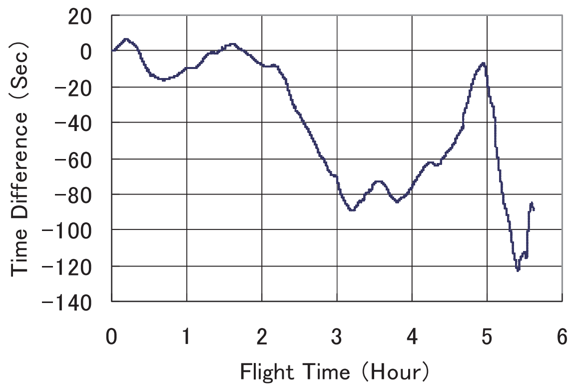

Figure 4 Difference of Estimated Arrival Time

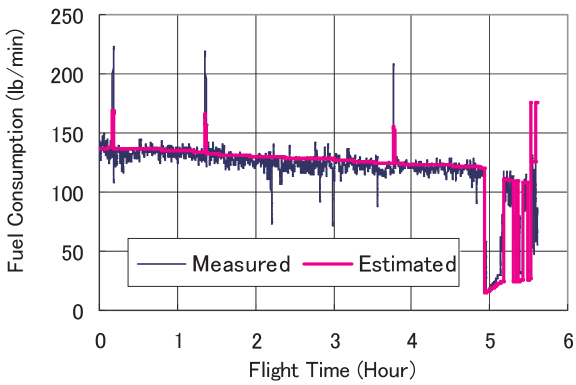

Figure 5 Comparison of Fuel Consumption

5. Summary

Trajectory management has been defined as one of the main subjects in the long term research vision of ENRI. ENRI started study on a trajectory model in 2008. The study is being carried out to develop a system to predict trajectory. BADA is being used for the prediction model.

An estimated trajectory was compared with flight data measured by aircraft. Accuracy of time prediction was examined. It shows less than 1% difference along flight time. Analysis of vertical movement and the improvement of the meteorological model are subjects for the future.

6. Acknowledgement

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