4D TRAJECTORY BASED OPERATION IN HIGH DENSITY TERMINAL CONTROL AREA CONSIDERING THE UNCERTAINTY OF WEATHER FORECAST DATA

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Keywords: *Aircraft Trajectory Prediction, Meteorological Effects, Trajectory Based Operation, Continuous Descent Operation, Continuous Climb Operation*

Abstract

Imaging the near future air traffic management, realization of Trajectory-Based Operation (TBO) is expected to achieve an efficient and orderly air traffic flow. In order to introduce TBO, it is necessary to consider the effect of the meteorological influences to the aircraft trajectory prediction. In order to clarify the difference of the wind between Meso-Scale Model (MSM) datasets and real flight, three descent flights along the same route within 10 minutes were extracted. The data demonstrated the deviation from the MSM data around certain range of pressure altitude.

This may mean that, by the implementation of weighted-average method, we can demonstrate the wind model which is closer to the real wind than MSM data. Here, Haneda airport approach trajectory was focused on because many flight data along the same flight trajectory can be obtained. The obtained wind data are classified into weighted-average winds and perturbations. We can easily distinguish the wind shear condition from the time and altitude variation of the weighted-average wind profile. The increase in the wind perturbation, which is considered to be caused by the wind shear, was also demonstrated.

In this paper, we focus on the Tokyo terminal control area which shares the departure and arrival routes of Haneda and Narita airports. Supposing the Continuous Climb Operation (CCO) and Continuous Descent Operation (CDO), the altitude separation at the crossing points of the routes are demonstrated, and the wind effect is also discussed. The results indicate the possibility to lift the altitude restrictions of arrival and departure route by applying the Trajectory based CCO and CDO.

1 Introduction

The global Air Traffic Management (ATM) operational concept is presented in the ICAO vision as an integrated, harmonized and globally interoperable ATM system[1]. In order to establish and maintain a safe, orderly and efficient flow of air traffic, the concept of dynamic four-dimensional trajectory (4-DT) control and negotiated conflict-free trajectories is demonstrated. Long-term visions based upon the ICAO Concept have been formulated in the U.S. (NextGen: Next Generation Air Transportation System), and in Europe (SESAR: Single European Sky ATM Research) in order to meet regional needs. In Japan, CARATS (Collaborative Actions for Renovation of Air Traffic Systems) is being discussed[2].

Following points are considerable characteristics in Japan. Air traffic is concentrated in the airports and airspace of the Tokyo Metropolitan Area. Because high-speed transportation competitors, such as Shinkansen (Bullet Train) exist, high level of convenient and punctual service is also required to aviation. Therefore, it is desired that the arrival time is precisely predicted when the airplane departs from airport. For minimizing operational restrictions and optimizing the performance of air traffic, it is considered necessary shifting from the traditional airspace-based ATM operation to a strategic Trajectory-Based Operation (TBO). Reducing fuel consumption is also the target of the CARATS. It is also pointed out that meteorological phenomena are significant uncertainty when predicting air traffic flow and air traffic control capacity.

In this paper, a 4D TBO with considering meteorological uncertainty and reducing fuel consumption is proposed (Fig. 1). In the climb phase, the departure time from the airport is adjusted so that the airplane can arrive at the merge point on time by Continuous Climb Operation (CCO). Considering the ideal fuel consumption flight in the cruise phase, each airplane can select the best cruise Mach number. The meteorological uncertainty will be integrated during the cruise flight. In the descent phase, the flight path to the airport is controlled so that the airplane can arrive at the airport on time by Continuous Descent Operation (CDO).

1.1 TBO with considering the meteorological uncertainty

For simulating and discussing the proposing 4D trajectory based operation, we have to demonstrate how large the meteorological uncertainty of the flight time is. Supposing the 4D-TBO, the trajectory is estimated by utilizing the weather forecast information. However, the real trajectory will be deviated because of the meteorological uncertainty of the forecast data. By comparing the real flight data and weather forecast data, the meteorological uncertainty in the airspace of the Tokyo Metropolitan Area is clarified[3].

Roach & Robinson[4] have researched the airspace of Dallas/Fort Worth International Airport. The arrival airplanes level-off at 11,000ft and cross over the departure flow which level-off at 10,000ft. They have reported that CDO and CCO present the opportunity for lifting restrictions on departure climbs.

In Tokyo Metropolitan Area there are two main airports; Tokyo International airport (Haneda, RJTT) and Narita International airport (Narita, RJAA). SID (Standard Instrument Departure) are controlled by Tokyo terminal control. STAR (Standard Instrument Arrival) of each airport share the same area and the airspace is divided by altitude. In this paper the application of CDO and CCO is researched for Tokyo terminal control area with considering the meteorological uncertainty.

2 Analytical method

2.1 Mode S system data

The real flight data was obtained from the experimental Secondary Surveillance Radar (SSR) Mode S system which is managed by the Electronic Navigation Research Institute in Japan. The mode S system obtains the flight data every 10 seconds. The contents of data are as follows:

Time (Japan Standard Time: JST), Latitude, Longitude (Rader Measured Values), Pressure Altitude, Ground Speed (GS), True Airspeed (TAS), Indicated Airspeed (IAS), Mach Number, True Track Angle, Magnetic Heading, Roll Angle, Track Angle Rate, Barometric Altitude Rate, Inertial Vertical Velocity, Barometric Pressure Setting, MCP/FCU Selected Altitude.

One-third of the data in year 2013 are selected with consideration of including all four seasons' data.

2.2 Japan Meteorological Agency Meso-Scale Model

As for the weather forecast data, Meso-Scale Model (MSM) Grid Point Value (GPV) data was used, which was provided by Japan Meteorological Agency (JMA). JMA provides a 3-hour intervals forecast of MSM at a time, and the forecast including the initial dataset is updated every three hours. In order to obtain the meteorological values of temperature and wind at a certain point of specified time, linear interpolation is performed on the latitude, longitude, pressure altitude and time.

2.3 Flight time estimation using weather forecast data

The GS estimated by MSM data is calculated by adjusting the heading so that the true airspeed and true track angle becomes consistent with the Mode S data. The flight path length is calculated by integrating the GS of Mode S with respect to time. The flight time predicted by MSM data is calculated by integrating the ratio of real flight GS reported by Mode S system to predicted GS calculated by MSM data with respect to time. The averaged value of the ratio of real flight GS to predicted GS becomes the flight time ratio of weather forecast estimation to real flight.

2.4 Error of side wind in turning

The increase in the error of the wind has been reported when we calculate the wind vector by subtracting the ground speed from airspeed at turning[5,6]. Direction of the airspeed vector is determined by the heading of the aircraft. It is pointed out that when the aircraft is turning, the aircraft rolls and may cause a sideslip in the orthogonal direction to the nose; that is considered as the reason of the wind error.

During the holding flight, the latitude, longitude and altitude of the location is considered almost the same. This indicates that the wind speed is not to vary significantly. Examination of the wind in the direction orthogonal to the nose yields the deviation of the wind speed around 5 to 15kt[7]. Therefore, in this study, the data whose roll angle is more or less than ± 2 degrees are eliminated.

2.5 Comparison of wind data along the same path

In order to verify the differences of the wind between the real flight and MSM model, the multiple flight data whose flight path are almost the same were extracted from the Mode S data.

Wind speed varies substantially depending more on the altitude than the latitude and longitude. Therefore, we decided to plot the data by wind speed versus altitude. Further, since the flight altitude differs among the same flight path data, the latitude and longitude at the same altitude also differs. In order to distinguish the difference of the latitude and longitude, trihedral figure of the flight path is also plotted.

2.6 Smoothing of wind data by the weighted average method

MSM data is updated every three hours, but, when we consider how a sudden change of weather condition affects to the flight time and the separation control of arriving aircraft, high time resolution model is required.

In the linear stability analysis of flow, unsteady flow is classified into averaged value and fluctuation. The ‘tanh’ type velocity distribution is known as Kelvin-Helmholtz instability and vortex structure is formed around the inflection point of the velocity profile. This is the reason that wind share accompanies large velocity fluctuation in addition to the change of the average wind speed. If such sudden change of weather conditions caused by wind share is analyzed and accurately predicted, the air traffic safety is expected to be improved.

In the wind tunnel experiments, we can measure the average and fluctuation value of wind speed by an anemometer which is fixed in space. But the airplane continues flying and the data acquired by Mode S do not yield such fixed-point values. Therefore, in this paper, the wind data obtained by the Mode S system is smoothed by the spatial and temporal direction, and classified into the smoothed value and the fluctuation.

Considering the flight along the approach trajectory, the latitude and longitude becomes almost the same position when the altitude is given. Arrival routes will be varied when the wind direction changes; however, the runway operation cannot be frequently changed. The trajectory is essentially the same if the time is near. In this paper, we do not consider the differences in latitude and longitude, and wind data is smoothed as variables of time and altitude.

Gaussian function $\exp(-d^2)$ is introduced for a weighting function. The function is multiplied to the wind and the wind data are smoothed. The variable d, which demonstrates the norm of the separation from current value to each data, is calculated by the difference of pressure altitude H and time t, whose value is divided by the scale conversion parameters H_{ref} and t_{ref} as follows:

$$d = \sqrt{\left(\frac{H - H_i}{H_{\mathrm{ref}}}\right)^2 + \left(\frac{t - t_i}{t_{\mathrm{ref}}}\right)^2}$$

3 Results and Discussions

3.1 Uncertainty of flight time for trajectory prediction using MSM data

Using the initial value and every three hours forecast values of MSM data, GS values estimated by MSM are calculated. The histograms of the GS ratio of Mode S to MSM are demonstrated in Fig, 2. The flight time uncertainty is evaluated that if we use the initial value of MSM data, 96% of flights are estimated within the accuracy of ±2%. If we use the 15-hour forecast value, the number of flights is reduced to 87%. The flight time uncertainty is increased when we use the long term forecast value.

Considering that the flight time of domestic flight is around 1.5 hours, 3-hour forecast data will be used for 4D-TBO. The flight time of long haul international flight is around 12 hours, which indicates that the 15-hour forecast data will be used before the departure. If we can update the weather forecast data during the flight, the trajectory will be adjusted to cope with the change of weather forecast data. When we consider the application of 4D-TBO, 3-hour forecast data will be used for trajectory prediction. In such case, the uncertainty of flight time prediction is approximately 2σ~2%.

3.2 Wind deviation of MSM data from real flight data

In order to clarify the difference of the wind between MSM data and the real flight, we have extracted the three descent flights whose route are the same and the time difference is within 10 minutes. Figure 3 presents the altitude versus wind plot with the trihedral figure of flight path for three descent flights.

As for the wind speed at the altitude around FL050, the wind speed shows the local maximum, and the wind speed of MSM data deviates from the real flight about the speed of 10kt. Though the reason that deviation is caused is unclear, by creating the data which can simulate the wind under the conditions that such deviation occurs, we can propose a more realistic wind model of approach trajectory than the MSM data.

3.3 Comparison of MSM data and actual wind for Haneda Airport approach trajectory

In order to predict the wind using MSM data, the values which are updated every three hours are interpolated. When the wind velocity is rapidly changed, the interpolated MSM data seems to be deviated from the real wind. In order to check this assumption, the interpolated MSM data and real wind on March 7, 2013 are compared in Fig. 4. In each pressure altitude zone of 3,000ft and 5,000ft, the data within the pressure altitude of ± 250ft are plotted.

Figure 4(a) demonstrates that, in the pressure altitude zone around 3,000ft, the real wind speed is larger than the MSM data almost all time period. In the pressure altitude zone around 5,000ft, which is shown in Fig. 4(b), the real wind speed is larger than the MSM data in the time periods from 8 hours to 12 hours and 14 hours to 17 hours, whereas the real wind speed is smaller than the MSM data in the time periods from 12 hours to 14 hours and 17 hours to 23 hours.

In addition, the variance of the wind speed is large in the time periods around 18 hours and after 20 hours. The model of MSM does not capture the condition that the wind speed is rapidly changed by time and altitude.

3.4 Wind model generated by the weighted average method

In order to obtain the wind model of Haneda airport approach trajectory, the real wind data calculated by using the Mode S data is smoothed by weighted average method. Figure 5 is a result of the March 7, 2013. The parameters of the scale conversion for the weighted average method are set as H_{ref} = 500[ft] and t_{ref}= 1800[sec].

Figure 5(a) demonstrates the result of the pressure altitude around 3,000ft. During the time period from 8 hours to 17 hours, the smoothed wind values of the same time zone are almost the same, whereas the distribution of smoothed wind values is observed during the time period from 17 hours to 23 hours. For applying the weighted average method, the parameters of the wind are selected as time and pressure altitude. Therefore, if the smoothed values are not consistent at the same time zone, the actual wind is considered to be changed by the pressure altitude.

The wind speed data around 23 hours demonstrate relatively large fluctuations from the smoothed values. In this time period, the wind speed is reduced approximately by 20kt when the pressure altitude rises from 3,000ft to 5,000ft (Fig. 5(b)). The fluctuation of the wind speed is considered to be increased by the wind shear, which demonstrates the steep variation of wind speed according to the increase in time or altitude.

It is considered to be possible to show the relationship between the wind shear and fluctuation of the wind speed, by smoothing the wind speed and comparing the wind speed of each value.

3.5 Designing a figure of one day wind condition for approach flight

The number of the figure like as Fig. 5 becomes large if we plot the wind speed by classifying the several pressure altitude zones. It becomes easy to understand the daily wind conditions if we can design a figure that demonstrates the whole day wind condition data. Here, grid is generated in time and altitude directions in the interval of time every 10 minutes and altitude every 100ft. The smoothed wind speed and wind direction values on each nodal point are demonstrated in Fig 6. Furthermore, the root mean square values of the fluctuations from the smooth value are calculated using the data which is in the vicinity of each nodal point, and plotted by the color points.

Figure 6 shows the results of the March 7, 2013. In the time period from 18 hours to 23 hours of Fig. 6(a), we can distinguish the wind shear that demonstrates the decreasing wind speed according to the increase in pressure altitude. The fluctuation of the wind speed becomes greater in the wind shear region. In the wind shear, a change of wind direction accompanying with the change of wind speed might also be seen. In the plotted result which is shown in Fig. 6(b), the wind direction is not changed so much with respect to the pressure altitude.

4 Applying CDO and CCO to the flight route that share the airspace

In the SID and STAR of RJTT and RJAA of north wind operation, there are crossing points of departure and arrival routes (Fig. 7). At present, the airspace of the departing and arriving aircrafts is divided by altitude zone and the separation at the crossing point is ensured. For applying the TBO, if the airspace around the crossing point is shared, we should ensure the separation by time management.

Typical flight time of Japanese domestic flight is roughly 1.5 hours. Assuming that arriving airplane passes through between the departing airplanes which fly every 2 minutes, it becomes impossible to ensure sufficient time separation, because the uncertainty of 2% flight time prediction after 1 hour flight becomes around 70 seconds. It considered difficult to share the airspace by time management.

4.1 Liftof the altitude restrictions by CCO & CDO

In the case of applying CCO and CDO, it is necessary to ensure the altitude separation at the crossing point of the routes. To examine this, the flight path is calculated supposing that the flight path angles of departing and arriving aircrafts are 4º and 2.5º, respectively. These value are estimated from the B773 airplane BADA PTD file[8]. The results are plotted in Fig. 8. The crossing flight paths of SID and STAR are plotted by solid circles, and these of CDO and CCO are plotted by dashed circles.

Because the diameter of the circles corresponds to the pressure altitude of 1,000ft, the flight path profile intersects the circles, if the vertical separation is lower than 1,000ft.

CACAO Arrival Route intersects with JYOSO FOUR Departure and TETRA FOUR Departure Route. PLUTO ONE Departure and JYOSO FOUR Departure Route intersect at JYOSO. In addition, considering the influence of the north wind, the trend of change in flight path, that means, arriving profile becomes shallow and departing profile becomes deep, is also demonstrated. The arrow shows the 20% variation in the angle of climb or descent. The flight profiles do not intersect the circles which demonstrate the vertical separation of 1,000ft from the crossing flight route. It is considered possible to cross the route with ensuring the altitude separation more than 2,000ft. Same as the Dallas/Fort worth airport case[4], we can lift the flight path altitude by application of the CCO and CDO.

4.2 Adjustment of the flight time caused by uncertainty of weather forecast

Fluctuation of the flight time due to the uncertainty of weather forecast becomes around 70 seconds after one hour flight. To examine whether we can adjust the delay or early passing during the CACAO Arrival course, the difference of flight time between CDO and STAR profile is calculated.

In order to simplify the calculation, TAS, which is changed by altitude, is fixed at the averaged speed, which is calculated from the average of the TAS at both ends of the pressure altitude. The flight time is calculated by dividing the flight distance by the TAS value. The required time for the deceleration in level flight is calculated from the equation:

$$\frac{T-D}{m}=\frac{dv}{dt}$$

where T is thrust, D is drag, and m is mass, respectively.

Using the values of Medium mass descent of B773 in BADA PTD file[8], the required time and distance for deceleration from 310kt to 250kt at the pressure altitude of 11,000ft is estimated as 1 minute and 5 NM.

Figure 9 shows the results. The flight time of CDO becomes 11 minutes, and the flight time of STAR becomes 13.1 minutes. Therefore, if the standard profile is selected in the intermediate of CDO and STAR profiles, the standard flight time becomes 12 minutes, and the flight time adjustment around ±1 minute becomes possible. Furthermore, if the altitude of flight profile at STONE is reduced from 20,000ft to 11,000ft, the distance from STONE to the top of descent becomes longer and the airplane fly lower altitude than that of the CDO in enroute area. At low pressure altitude, TAS value of the same CAS becomes lower than high pressure altitude, if the flight altitude at STONE is lowered, the flight time until STONE increases. We can absorb the fluctuation of arrival time due to the uncertainty of the weather forecast.

When aircraft is controlled to fly along the altitude of STAR for absorbing the earlier fluctuation of arrival time, the vertical separation for JYOSO FOUR Departure is reduced. In this case, it is necessary to lower the flight profile of JYOSO FOUR Departure than the CCO flight profile.

It should be pointed out that the effect of the wind share over 20kt to the airplane speed of 250kt becomes nearly 10% and it would reduce the time adjustment flexibility. Detailed research of meteorological effect and the simulation of flight paths are necessary. Improving the prediction accuracy of wind speed and detecting the wind shear using up-to-date information become important keys in applying the TBO.

5. Conclusions

The application of CDO and CCO is researched for Tokyo terminal control area with considering the meteorological uncertainty. JMA MSM data are used for predicting the effect of weather to the trajectory prediction. The uncertainty of the flight time becomes around 2%, and if we suppose the airplane enters into Tokyo terminal control area after one hour flight the uncertainty becomes around 70 seconds. Considering this, it is difficult for arrival flights to passes through between the departing airplanes which fly every 2 minutes without control.

Figure of the wind variation with time and altitude is designed to present the smoothed and fluctuation of the wind speed. We can easily distinguish the wind shear and the fluctuation of the wind. The wind shear of increasing wind speed of 20kt according to the decrease in the pressure altitude of 2,000ft is demonstrated.

In the case of applying the CCO and CDO, it is necessary to ensure the altitude separation at the crossing point of the routes. To examine this, the flight path is calculated supposing that the flight path angles of departing and arriving aircrafts are 4° and 2.5°, respectively. We can lift the flight path altitude by applying the CCO and CDO. The flight time of CDO and STAR profiles are compared. If the standard profile is selected in the intermediate of CDO and STAR profiles, the standard flight time becomes 12 minutes. The flight time adjustment around ±1 minute becomes possible. When aircraft is controlled to fly along the lowered flight path, the flight path of departing airplane might also have to be lowered than CCO, because of maintaining the vertical separation.

It should be pointed out that the effect of the wind share over 20kt to the airplane speed 250kt becomes nearly 10% and it would reduce the time adjustment flexibility. Improving the prediction accuracy of wind speed and detecting the wind shear using up-to-date information become important keys in applying the TBO.

Acknowledgments

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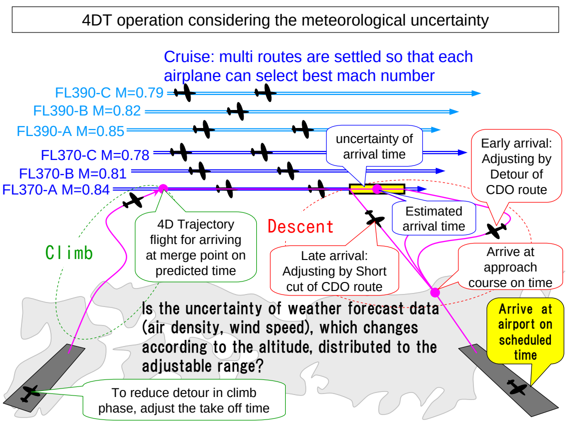
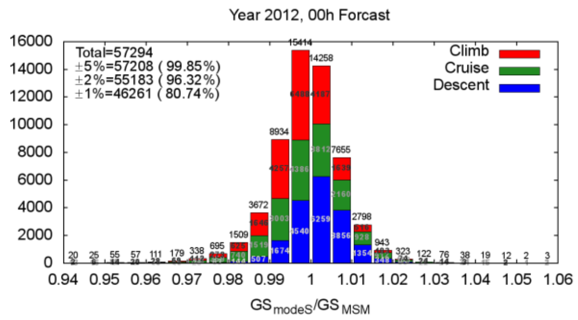
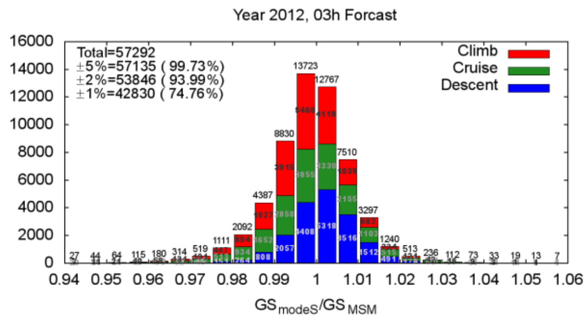


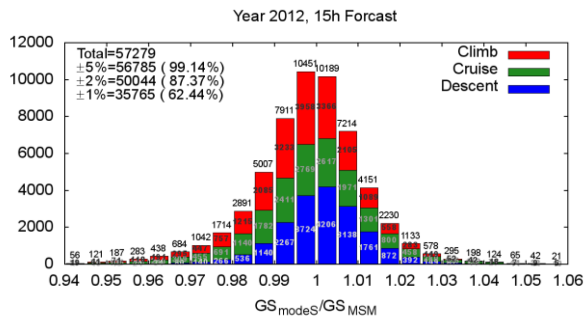
Fig 1. Concept of 4-Dimensional trajectory based operation considering the meteorological uncertainty



(a) initial data



(b) 3-hour forecast data



(c) 15-hour forecast data

Fig.2 Uncertainty of the Ground Speed estimated from the MSM data

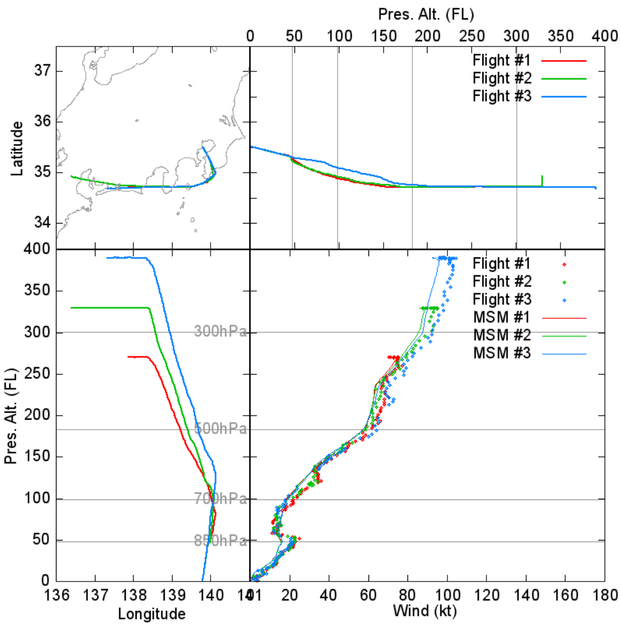
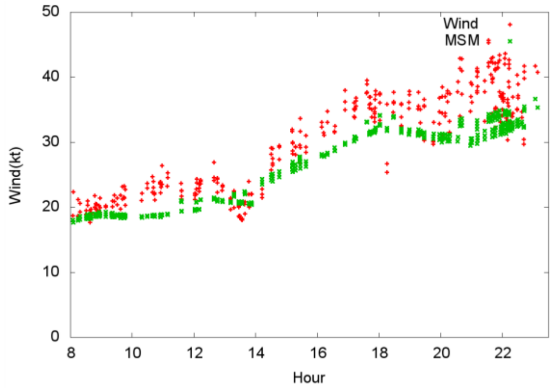
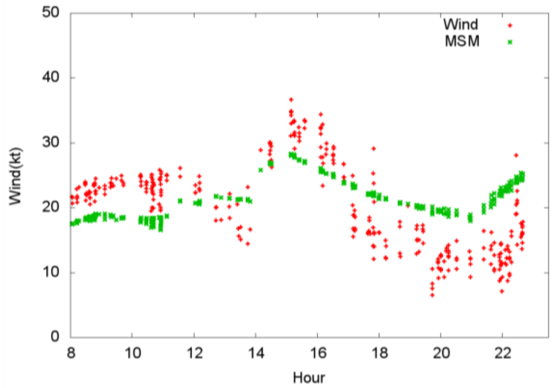


Fig.3 Variation of wind speed with position and pressure altitude

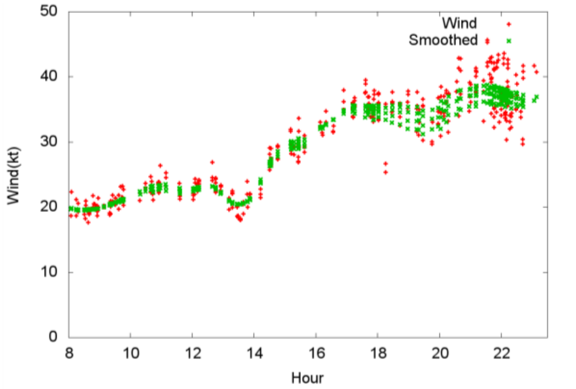


(a) Pressure altitude around 3000ft

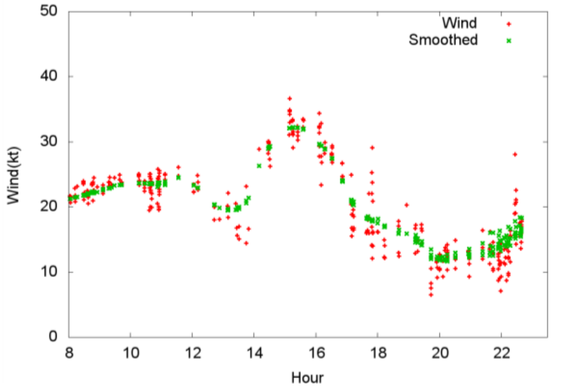


(b) Pressure altitude around 5000ft

Fig.4 Comparison of real wind speed with MSM data at each altitude zone of RJTT approach trajectory.

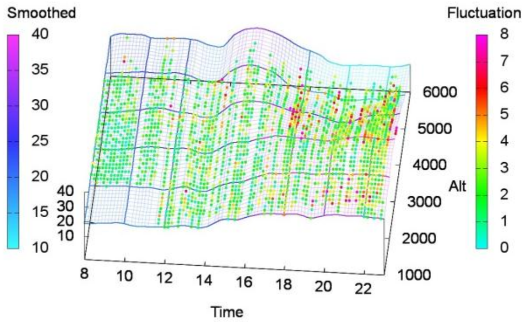


(a) Pressure altitude around 3000ft

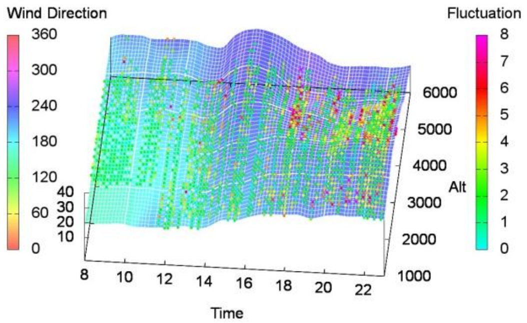


(b) Pressure altitude around 5000ft

Fig.5 Comparison of real wind speed with smoothed data at each altitude zone of RJTT approach trajectory.



(a) March 7th 2013 Wind Speed



(b) March 7th 2013 Wind Direction

Fig.6 Variation of the smoothed wind speed and fluctuation of wind speed with time and pressure altitude

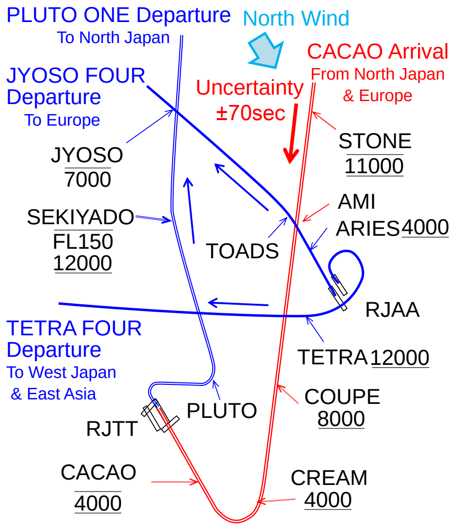
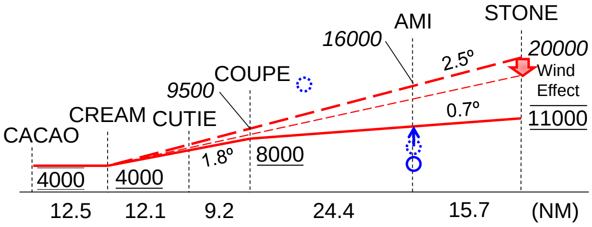
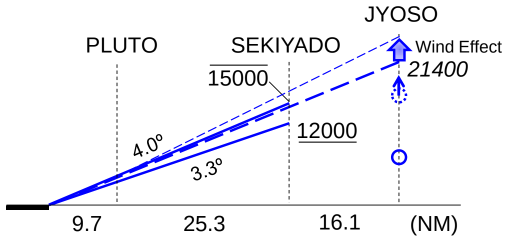


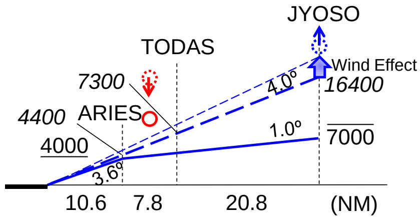
Fig. 7 Schematic of STAR and SID of RJTT and RJAA at north wind operation



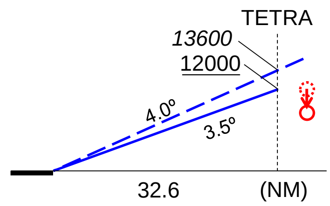
(a) CACAO Arrival



(b) PLUTO ONE Departure



(c) JYOSO FOUR Departure



(d) TETRA FOUR Departure

Fig. 8 Increase in Altitude with applying CDO and CCO and the change of altitude caused by north wind effect

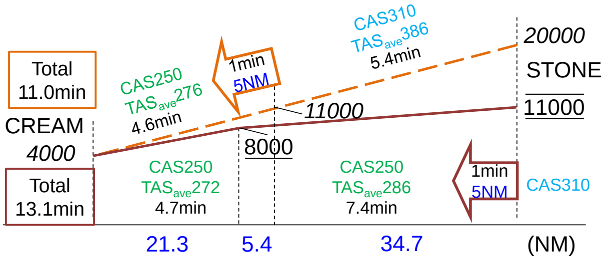


Fig. 9 Difference of flight time between CDO and STAR