ISSN 2320 -2602

**International Journal of Advances in Computer Science and Technology (IJACST)**, Vol.2 , No.8, Pages : 12-17 (2013)
*Special Issue of ICCECT 2013 - Held during 16-17 August, 2013, Thailand*

# Downlink Aircraft Parameters (DAPs) Based Interacting Multiple Model Tracking System for Air Traffic Surveillance

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**Abstract :** With the rapid increase in air traffic, the more reliable and accurate tracking technologies for aircraft surveillance is required to improve the capacity, safety and efficiency of ATC services. Interacting Multiple Model (IMM) estimator is a suboptimal hybrid filter that has been widely applied in a lot of tracking applications. However, if the aircraft has the maneuvering motion during initial tracking period or later tracking period, it is difficult to estimate precisely the target state since the mode probabilities have a bias or become uniform. In the Mode S Enhanced Surveillance (EHS), the Downlink Aircraft Parameters (DAPs) are available for obtaining updated and detailed information from aircrafts. In this paper, for improving the accuracy, a DAPs based IMM tracking system is proposed. The system consists of an IMM filter with 3 different models and a maneuver detector which is able to dynamically revise the mode probabilities according to the different motions of aircraft. The results of computer simulations and practical experiments show the effectiveness of proposed system by comparing with the conventional IMM filter.

**Key words :** Mode S Enhanced Surveillance (EHS); Downlink Aircraft Parameters (DAPs); Interacting Multiple Model (IMM).

## INTRODUCTION

Air traffic surveillance systems are required to obtain updated and detailed information from aircrafts in order to provide safe and efficient air traffic control (ATC) services. Civilian aircraft have two basic modes of flight: the uniform motion and maneuver. The former refers to the straight and level flight with a constant speed and heading, and the latter refers to turning or climbing/descending. A good tracking algorithm must provide accurate and reliable estimates of the aircraft state for both modes even in measurement errors and outliers situations.

Interacting Multiple Model (IMM) estimator is a suboptimal hybrid filter that was shown to achieve an excellent compromise between performance and complexity [1][2]. IMM calculates likelihood functions from residual vectors and integrates smoothed state of all target models using mode probabilities obtained from likelihood functions ratio. However, if the aircraft has the maneuvering motion during initial tracking period or later tracking period, it is difficult to estimate precisely the target state since the mode probabilities have a bias or become uniform. The main reason is that the detection of maneuvers is often delayed by the response of Kalman filters.

With the advancement of the sensor and communication technologies, the extensive deployment of air-to-ground data links leads to the emergence of complementary means for aircraft tracking system. Known as Mode S radar, there are two possible configurations, the first one is called the Mode S Elementary Surveillance (ELS) and the other one is the Mode S Enhanced Surveillance (EHS) [3]. The fundamental concept of the former is the assignment to each aircraft of a unique ICAO 24-bit address by the State Registration Authority [4]. This address is the one used for selective interrogation, which permits the obtaining of the flight ID and the altitude in 25 feet steps. On the other hand, the latter consists of Mode S ELS supplemented by the extraction of downlink aircraft parameters (DAPs) which will be delivered to the air traffic controllers.

The equipage of aircraft with Mode S transponders which have the functions of Autonomic Dependent Surveillance-Broadcast (ADS-B) and EHS gets more and more widespread. Mode S transponder is not only an equipment to send out surveillance data, but also a platform to exchange automatically data with other airborne and ground stations. More efficiency, more capacity and a higher traffic throughput of ATC system can be achieved if the transmitted DAPs could be used operationally. As a result, the air traffic controllers can access directly these essential data without delay by inquiring ATC system, instead of using R/T voice. Moreover, these parameters can also be used for safety improvement by cross-checking or double-checking data which are safety-relevant for the ATC services. In the air traffic surveillance systems, DAPs based tracking system can server as a backup for ADS-B in the event of loss of Global Navigation Satellite System (GNSS) information.

For the performance evaluation of Mode S EHS, Electronic Navigation Research Institute (ENRI) has constructed an aircraft surveillance system which is composed of two SSR Mode S radars. In [5], Roll-Angle is used to assist trackers during maneuvers to improve accuracies during straight-line flight. And in [6], the DAPs information is applied to calculate the control noise for a Kalman filter. In this paper, for improving the accuracy, a DAPs based IMM tracking system is proposed. The system consists of an IMM filter with 3 different models and a maneuver detector which is able to dynamically revise the mode probabilities in real time according to the different motions of aircraft by using DAPs information. Moreover, as the availability and certification cannot be guaranteed, the integration of ELS and EHS is also implemented.

The paper is structured as follows. In the next section, the Mode S and DAPs concept are described. In section 3, a DAPs based IMM tracking system is presented. The results of computer simulations and practical experiments are shown and discussed in section 4, and the paper is concluded in section 5.

## MODE S EHS

### Mode S Radar

SSR Mode S includes two elements: an interrogative ground station (GS) and a transponder on board of the aircraft. Each GS has its own interrogation code which permits the configuration of the target answers, as they know who is interrogating them. Currently, most of Mode S radars are using the multisite surveillance protocol [7][4].

Networked Mode S radars also can be configured as a monosite for aircraft tracking to reduce RF pollution. This is gained grouping radars in sets called "clusters". All radars that belong to the same cluster are given the same interrogation code. Thus, when a target is captured by one of these radars, it stops answering "all calls" from the rest of the Mode S radars of the cluster.

In order to guarantee track continuity, radars are provided with responsibility maps, so when an aircraft leaves the coverage of a radar and enter the coverage region of the contiguous one, both know how to exchange the appropriate data to manage tracking information. These maps depict areas where targets are responsibility of one radar and transitioning areas where the radar must allow the target acquisition by a contiguous radar. In this point, there are two possible options to transfer the control and management information depending on the radar network, which can be summarized as centralized or distributed [8][9].

Besides, Mode S radars can be configured for working with overlapped coverage, but using each one its own interrogation code. In this case, the fusion center will receive data related to the same aircraft coming from different Mode S radars. In this situation, a multisite fusion, which will increase trajectory update rate and will reduce the error during maneuver period, will be performed.

### Downlink Aircraft Parameters

Mode S has two operational modes, the elementary surveillance (ELS) and the enhanced surveillance (EHS). The differences between them fall on uplink and also downlink data transmissions. The data items sent by a Mode S ELS are the following ones:

- ICAO 24-bit address
- Data-link capability reporting
- Common usage airborne parameter register capability reporting
- Aircraft identification reporting
- Mode 3/A code reporting
- Mode S pressure altitude reporting
- Special position identification reporting/Flight status reporting

From a tracking point of view, the most important aspect of ELS is the height measurement improvement (measured in 25 feet steps), which allows a better vertical tracking.

Mode S EHS delivers further information. Thus, aircraft can send to the ground station several aircraft registers or BDS with flight information. The decision of what BDSs are sent depends on the local configuration and also on the ATC Authority. The ones that seem to be more useful from an Air Traffic Control point of view are:

BDS 4.0:
- Selected Altitude

BDS 5.0:
- Roll Angle
- Track Angle Rate (or True Airspeed)
- True Track Angle
- Ground Speed

BDS 6.0:
- Magnetic Heading
- Indicated Airspeed or Mach Number
- Vertical Rate
- True Airspeed (if Track Angle Rate is not available)

Some parameters are for display to the controller, known as controller access parameters (CAPs) and others are for ATM system function enhancement, known as system access parameters (SAPs) [10]. According to several documents from Eurocontrol, the DAPs are classified into two groups:

- Vector state DAPs, which show the current value of the aircraft movement parameters.
- Intention DAPs, which show the intention of the crew for the future, such as waypoints, estimated times of arrival, etc.

The intention DAPs have an operational utility and are also useful for a collision detection system. For the tracking function, the useful parameters are the vector state DAPs, which tell the ground station what movement the aircraft is performing in that moment. Even though, not all of them are useful for the tracking function. As our task is to track aircraft in a ground-fixed coordinate system, the most suitable DAPs are the ones referred to the ground system (BDS 5.0). Four parameters are directly related to the ground based tracking system.

- Track Angle Rate
- True Track Angle
- Ground Speed
- Roll Angle

The rest of the parameters referring to the horizontal movement depend on the wind direction and speed, which are useless due to the difficulty of knowing the relationship between them and the ones referred to the ground system, when they are fused at the ground station. According to the results provided by an Eurocontrol report [3], where DAPs monitored from two different aircraft are compared with the actual ones recorded by the aircraft avionics. The conclusions obtained are:

- The parameters related to the horizontal tracking (Track Angle Rate, True Track Angle, Ground Speed) when are received through the Mode S link

**Table 1:** Characteristics of DAPs

| DAPs | Units | Update Rate | Precision | Range |
|---|---|---|---|---|
| Roll Angle | degrees | 1s | 45/256 | 90 |
| True Track Angle | degrees | 90/512 | 1s | 180 |
| Ground Speed | knots | 1s | 2 | [0, 2046] |
| Track Angle Rate | degrees | 1s | 8/256 | [-16, +16] |
| True Air Speed | knots | 1s | 32 | [0, 2046] |
| Barometric Altitude Rate | feet/min | 1s | 32 | [-16384, +16352] |

are representative of the ones measured in the aircraft.

- The "Roll Angle" is always much more noisy than the angular velocity (Track Angle Rate), so the only use is when no measurement of the "Track Angle Rate" is available.

The characteristics of the DAPs considered for the tracking function are given in the Table 1. Regarding error analysis, it has been found two main error sources: one related to the quantification performed before sending the chosen DAPs through the Mode S downlink and the other to a delay due to update rates [11].

## DAPS BASED IMM TRACKING SYSTEM

Safe and effective operation of the ATC relies on accurate and timely airspace situational awareness supported by surveillance systems. However, there are at least two problems that should be considered for designing the DAPs based tracking system. One is that DAPs are not always available, even if the aircraft has the ability to send them. This depends on the channel congestion and on the ATC Authority. Thus, it is difficult to guarantee that the DAPs data can be continuously processed. The other problem is the reception of corrupted or erroneous DAPs, which is even more dangerous than the former. Since, it can easily lead to wrong predictions and consequently to wrong estimates. Therefore, one appropriate approach is to construct a tracking system taking ELS data as primary, and EHS data as complementary.

### Motion Models

The models in the horizontal and vertical are treated separately, due to the fact that the target motions in horizontal plane and vertical plane are comparatively independent. The motion models used in the IMM filter are defined in this section. The uniform motion can be described by a second-order kinematic (constant velocity) model. The maneuver motion can be described by a third-order kinematic (constant acceleration) model and a coordinated turn model.

### *A. Constant Velocity Model*

The state vector corresponding to the constant velocity model is defined as:

$$x = [x\,\dot{x}\,y\,\dot{y}]^T$$

with $x$ and $y$ denoting the orthogonal coordinates of the horizontal plane. And the discrete-time state equation is given by:

$$x(k) = \begin{bmatrix} 1 & T & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & T \\ 0 & 0 & 0 & 1 \end{bmatrix} x(k-1) + \begin{bmatrix} \frac{T^2}{2} & 0 \\ T & 0 \\ 0 & \frac{T^2}{2} \\ 0 & T \end{bmatrix} v(k-1)$$

where $T$ is the sampling interval, and $\nu$ is a zero-mean Gaussian white noise used to model accelerations with an appropriate covariance $Q$, which is a design parameter.

### *B. Constant Acceleration Model*

The state vector corresponding to the constant acceleration model is defined as:

$$x = [x\,\dot{x}\,\ddot{x}\,y\,\dot{y}\,\ddot{y}]^T$$

The state equation is given by:

$$x(k) = Fx(k-1) + Gv(k-1)$$

where

$$F = \begin{bmatrix} 1 & T & 0 & 0 & \frac{T^2}{2} & 0 \\ 0 & 1 & 0 & 0 & T & 0 \\ 0 & 0 & 1 & T & 0 & \frac{T^2}{2} \\ 0 & 0 & 0 & 1 & 0 & T \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \qquad G = \begin{bmatrix} \frac{T^2}{4} & 0 \\ \frac{T}{2} & 0 \\ 0 & \frac{T^2}{4} \\ 0 & \frac{T}{2} \\ 1 & 0 \\ 0 & 1 \end{bmatrix}$$

### *C. Coordinated Turn Model*

A coordinated turn is a turn with a constant turn rate (rate of angle change) and a constant speed. Although the actual turning of a civilian aircraft is not exactly coordinated since the ground speed is the airspeed plus the wind speed, the kinematic behavior of the aircraft during the turn is suitably described by the coordinated turn model plus a fairly small noise representing the modeling error. This will be referred to as the nearly coordinated turn model in the sequel. Such a model is necessarily a nonlinear one if the turn rate is not a known constant. The state vector corresponding to this model is

$$x = [x\,\dot{x}\,y\,\dot{y}\,\omega]^T$$

where $\omega$ is the tum rate. The coordinated tum model is then given by:

$$x(k) = \begin{bmatrix} 1 & \frac{\sin(\omega(k)T)}{\omega(k)} & 0 & -\frac{1 - con(\omega(k)T)}{\omega(k)} & 0 \\ 0 & con(\omega(k)T) & 0 & -\sin(\omega(k)T) & 0 \\ 0 & \frac{1 - con(\omega(k)T)}{\omega(k)} & 1 & \frac{\sin(\omega(k)T)}{\omega(k)} & 0 \\ 0 & \sin(\omega(k)T) & 0 & con(\omega(k)T) & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} x(k-1) + \begin{bmatrix} \frac{T^2}{2} & 0 & 0 \\ T & 0 & 0 \\ 0 & \frac{T^2}{2} & 0 \\ 0 & T & 0 \\ 0 & 0 & T \end{bmatrix} v(k-1)$$

Note that the process noise $\nu$ has in general different noise statistics to reflect different modeling errors.

**System Architecture**

(1) Data Field

Fig.1 represents the adaptive tracking system architecture which consists of Mode S Radar, Tracker, DAPs Monitor and Position Monitor. The nodes in the system are connected through Data Field (DF) that serves as a communication medium of coordination between the nodes. It can be a Local Area Network (LAN) or LANs connected by Wide Area Network (WAN). All necessary data is broadcast into the DF, where the data logically circulates in the DF.

(2) Radar and Monitors

Mode S Radar gets targets' information from its own surveillance area. Then it sends the target report message which contains the position, identification number, time and DAPs information to the DF.

DAPs Monitor stores the DAPs information of each aircraft, and shows the values of each parameters of the selected aircraft in the figures. Position Monitor displays and updates the measurement, smoothing and predicted positions of each aircraft.

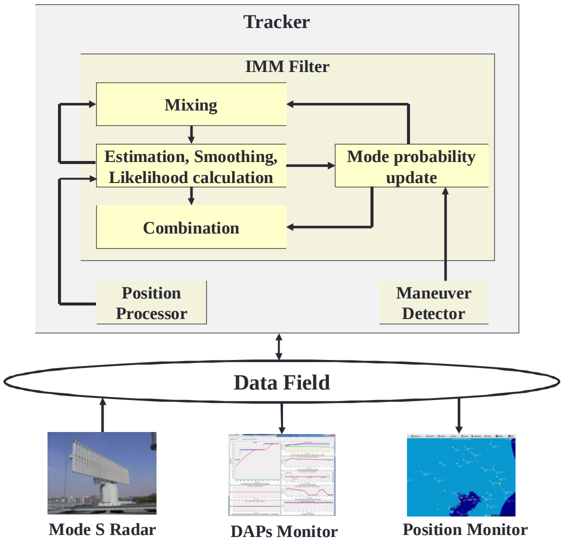

**Fig 1:** System Architecture

(3) Tracker

Tracker is composed of Position Processor, Maneuver Detector and IMM Filter. Position Processor is in charge of storing and updating the position information of aircrafts. When receiving the target report message, processor extracts the aircraft position information, and converts from North-East-Up (NEU) coordinates (Rang, Azimuth and Flight Level) to earth-centered earth-fixed (ECEF) coordinates (Latitude, Longitude and Altitude).

Maneuver Detector is responsible for extracting and storing DAPs information from the target report message. And based on this information, it detects the motion model changes of aircraft. The equations of detection are as follow:

$$C_v = V_{gs}(k) - V_{gs}(k-1)$$

$$C_a = R(k-1) \cdot W(k-1)$$

where $V_{gs}(k)$ is ground speed at time $k$, $R(k-1)$ is roll angle at time $k-1$, and $W(k-1)$ is track angle rate at time $k-1$. If the Track Angle Rate is not available, we can calculate the angular velocity which is related to the Roll Angle and True Air Speed by following expression:

$$\omega = g\frac{\tan(\theta)}{v}$$

where $g$ is gravity acceleration, $\theta$ is roll angle, and $v$ is true air speed.

One computational cycle of IMM filter consists of four major steps: interaction (mixing), filtering, probability update, and combination. At each time, the initial condition for the filter matched to a certain mode is obtained by mixing the state estimates of all filters at the previous time under the assumption that this particular mode is in effect at the current time. This is followed by a regular filtering (prediction and update) step, performed in parallel for each mode. Then, the mixing and model probabilities are updated by using the likelihood function. Finally a combination (weighted sum) of the updated state estimates of all filters yields the state estimate. The probability of a mode being in effect plays a key role in the weighting of the mixing and the combination of states and covariances.

In the conventional IMM filter, the default mode probabilities are used for initialization since it is difficult to predict the motion model of aircraft at the beginning. Therefore, if the default mode probabilities do not match the motion model or the motion model changes during the initial tracking period, the prediction accuracy is degraded. Moreover, during the later tracking period, each mode probability becomes uniform since the difference of residual vectors between modes decreased through mixing process. As a result, if motion model changes during the later tracking period, the prediction error increases because the response of filters is often delayed. To solve this problem, based on the DAPs information, the predictions of each mode probability during the initial tracking period are presented below:

$$\text{if } (C_a \neq 0), \text{ then}$$
$$\mu_1(k-1) = \min\{\mu_1(k-1), \mu_2(k-1), \mu_3(k-1)\}$$
$$\mu_2(k-1) = \text{mid}\{\mu_1(k-1), \mu_2(k-1), \mu_3(k-1)\}$$
$$\mu_3(k-1) = \max\{\mu_1(k-1), \mu_2(k-1), \mu_3(k-1)\}$$
$$\text{if } (C_a = 0 \,\&\, C_v \neq 0), \text{ then}$$
$$\mu_1(k-1) = \text{mid}\{\mu_1(k-1), \mu_2(k-1), \mu_3(k-1)\}$$
$$\mu_2(k-1) = \max\{\mu_1(k-1), \mu_2(k-1), \mu_3(k-1)\}$$
$$\mu_3(k-1) = \min\{\mu_1(k-1), \mu_2(k-1), \mu_3(k-1)\}$$

where $\mu_1(k-1)$, $\mu_2(k-1)$ and $\mu_3(k-1)$ are mode probabilities for constant velocity model, constant acceleration model and coordinated turn model at time $k-1$ respectively.

In addition, during later tracking period, since each mode probability becomes uniform they can be revised as follows:

$$\text{if } (C_a \neq 0 \,\&\, \mu_3(k-1) < 0.5), \text{ then}$$
$$\mu_1(k-1) = \min\{e_1(k-1), e_2(k-1), e_3(k-1)\} - 0.2$$
$$\mu_2(k-1) = \text{mid}\{e_1(k-1), e_2(k-1), e_3(k-1)\} - 0.1$$
$$\mu_3(k-1) = \max\{e_1(k-1), e_2(k-1), e_3(k-1)\} + 0.3$$
$$\text{if } (C_a = 0 \,\&\, C_v \neq 0 \,\&\, \mu_2(k-1) < 0.5), \text{ then}$$
$$\mu_1(k-1) = \text{mid}\{e_1(k-1), e_2(k-1), e_3(k-1)\} - 0.1$$
$$\mu_2(k-1) = \max\{e_1(k-1), e_2(k-1), e_3(k-1)\} + 0.3$$
$$\mu_3(k-1) = \min\{e_1(k-1), e_2(k-1), e_3(k-1)\} - 0.2$$

where $e_1(k-1)$, $e_2(k-1)$, and $e_3(k-1)$ are prediction error rate in latitude and longitude at time k-1 of each model, which are defined as:

$$\varepsilon_i(k-1) = | x_m(k-1) - x_p(k-1) | + | y_m(k-1) - y_p(k-1) |$$

$$e_i(k-1) = \frac{\varepsilon_i(k-1)}{\sum_{i=1} \varepsilon_i(k-1)}$$

where $x_m(k)$ and $y_m(k)$ are measurement position in latitude and longitude at time $k$, and $x_p(k-1)$ and $y_p(k-1)$ are prediction position in latitude and longitude at time $k-1$.

## EVALUATION

### Parameters

The performance of proposed DAPs based IMM tracking system is compared with conventional IMM filter on the real-time radar measurement data. To obtain the best possible results, the system has to be properly designed to meet the special requirements of the particular sensor. Based on the preliminary study, the design parameters are given in Table II.

The model transition probabilities for IMM filter is designed as follows:

**Table 2:** Parameters

| Model | Process Noise | Measurement Noise (m) |
|---|---|---|
| Constant velocity | 0.01g | 60 |
| Constant acceleration | g | 60 |
| Coordinated turn | 0.1g | 60 |

$$P = \begin{bmatrix} 0.95 & 0.025 & 0.025 \\ 0.025 & 0.95 & 0.025 \\ 0.025 & 0.025 & 0.95 \end{bmatrix}$$

### Results

The evaluation results are based on the real-time practical experiments and one aircraft trajectory is selected to show in the Fig.2 and Fig.4. Fig.2 shows the measurement position in latitude and the prediction position in latitude of conventional IMM and proposal. We see that the proposed system is effective to improve the tracking performance through maneuvers compared with the conventional IMM filter. The results shown in Fig.3 reveals that proposed system permits to significantly leverage the prediction error through maneuvers in latitude not only during the initial tracking period (from 5 to 15) but also during later tracking period (from 45 to 50). The average improvement of the prediction error in latitude is 60% compared with the conventional IMM filter. And we can get the same result from the Fig.5 in which the prediction error in longitude is shown.

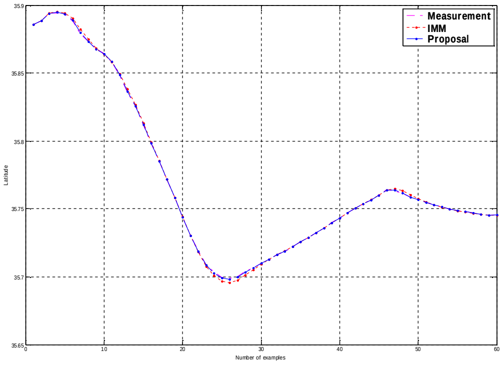

**Fig 2:** Aircraft trajectory in latitude

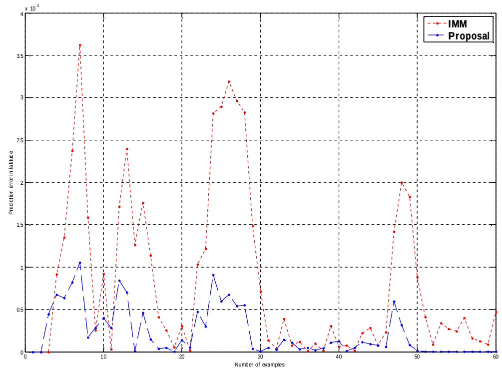

**Fig 3:** Prediction error in latitude

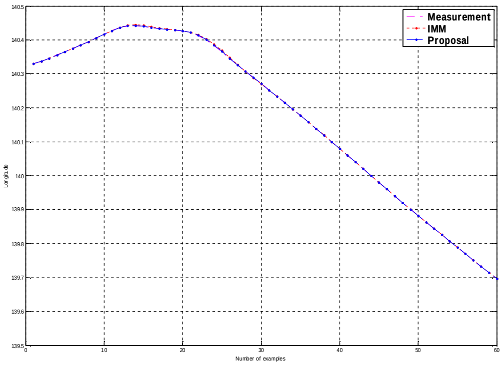

**Fig 4:** Aircraft trajectory in longitude

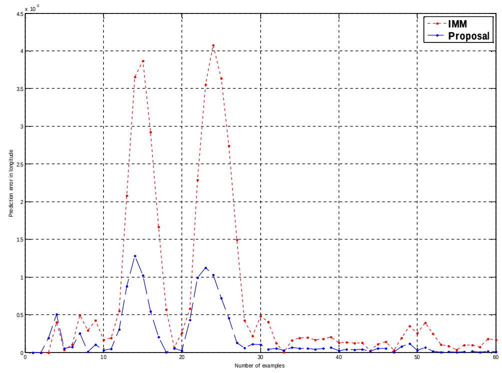

**Fig 5:** Prediction error in longitude

## CONCLUSION

In this paper, the development and practical experiments of DAPs based IMM tracking system for aircraft surveillance are proposed. From the obtained results, the performance of proposed system is confirmed and the effectiveness for real application is shown. Compared with the conventional IMM filter, the proposed system significantly reduces the prediction error through maneuvers not only during the initial tracking period but also during later tracking period. For satisfying the desired level of accuracy, it is required to further improve the performance for changing refresh rate and scattering measurement conditions.

## ACKNOWLEDGEMENT

This work is supported by Electronic Navigation Research Institute, Japan under Grants-in-aid for Priority Research on Hybrid Surveillance System.

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