CONFLICT AND SEPARATION SYMBOLS IN CDTI FOR SMALL AIRCRAFT OPERATION

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Abstract

This paper describes a simulation study of CDTI symbologies designed for trajectory-based operations of small aircraft.

Although presenting a pilot with traffic information enhances situation awareness and enables self-separation, it may increase workload and affect other tasks. A series of pilot-in-the-loop flight simulations was carried out to investigate the relationship between traffic awareness and workload. Two types of separation symbology were devised and compared in manually flown tasks with self-sequencing and self-separation. The results show that although the newly introduced symbologies were accepted by the pilots, they did not reduce pilot interactions with the CDTI — on the contrary, pilots tended to pay more attention to the CDTI, sometimes resulting in degraded flight path tracking performance.

1 Introduction

The Japan Aerospace Exploration Agency (JAXA) and the Electronic Navigation Research Institute (ENRI) have been conducting a research program called NOCTARN (New Operational Concept using Three-dimensional Adaptable Route Navigation) aimed at developing an aircraft operations concept that can reduce noise impact on communities while enhancing the capacity and operational efficiency of airports by using precisely-defined trajectories shared between aircraft and air traffic control [1][2]. The focus is on improving the efficiency of regional airports, and so NOCTARN is targeted at small aircraft and helicopters and is designed for single-pilot operation.

NOCTARN is assumed to be operated in two modes: a Ground Separated Mode (GSM) and an Airborne Separated Mode (ASM). In ASM, pilots are responsible for approach sequencing and separation assurance, which are carried out a using Cockpit Display of Traffic Information (CDTI). In earlier experiments, introducing a self-separation task induced higher workload and reduced flight path tracking performance, although overall pilot task performance was still acceptable [3]. Although it was obvious that pilots paid much attention to other traffic when CDTI monitoring and related tasks were introduced, the mechanism of the degraded flight path tracking performance was not clear. Investigation of this phenomenon might provide a means of reducing workload. On the other hand, after examining the results of these experiments, new CDTI symbols were introduced to provide traffic awareness for airborne self-sequencing and separation assurance, and these were generally welcomed by the pilots. This paper describes a simulation study to investigate the effects of these symbols, and to clarify the relationship between pilot workload and traffic awareness.

2 Operations Concept and System Design

2.1 Operations Concept

NOCTARN is a trajectory-based future operations concept for small aircraft proposed by JAXA and ENRI. It currently focuses on the area around small airports or heliports serving commuter or general aviation traffic. The basic concept of NOCTARN is illustrated in Fig. 1.

An airport is surrounded by a "control zone" or "airfield area" of airspace, which aircraft enter and leave through "gates" situated around its edge. Each runway has one or more predefined approach routes from each gate to its approach end, and one or more predefined departure routes from its departure end to each gate. These routes are defined by continuous 3D paths. ATC (Air Traffic Control) instructions and clearances and pilot requests and responses, including 4D trajectory information, are communicated over a digital data link. Aircraft also broadcast their position and assigned trajectory over the same data link, similar to the ADS-B concept, and the position and assigned trajectory information are displayed both on the air traffic controller's console and on the CDTIs of suitably equipped aircraft operating within the zone.

To use NOCTARN trajectories, an aircraft must have suitable equipage, including a Multi-Function Display (MFD) and a data link transceiver, and operates under NOCTARN flight rules. Aircraft intending to enter the control zone under NOCTARN flight rules, either to transit the zone or to land, enter through one of the gates and then fly along a route negotiated with the controller. Conventional aircraft operating under VFR (visual flight rules) are also permitted to operate in the NOCTARN control zone, and are separated from NOCTARN traffic by an altitude "buffer" while being monitored by secondary surveillance radar.

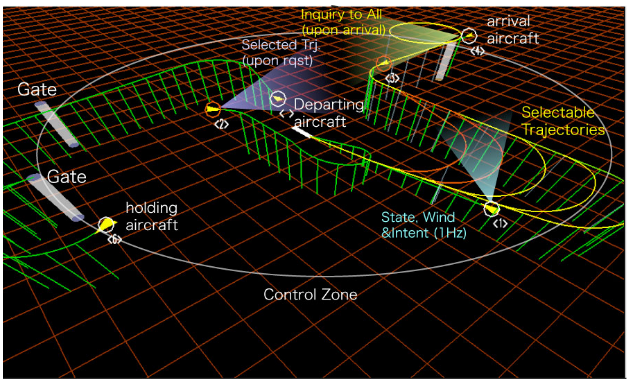


Fig. 1. NOCTARN Overview

2.2 Procedure

In the ASM mode of operation, aircraft assume responsibility for route selection, approach sequencing and separation using the MFD. The proposed communication procedure in ASM mode is as follows. The pilot first activates the NOCTARN system before entry into the zone while the aircraft is approaching one of the gates. The NOCTARN on-board system automatically initiates communication with other aircraft in the area, and the position of the aircraft is displayed on the CDTI of these other NOCTARN-equipped aircraft.

Figure 2 shows a snapshot of the NOCTARN MFD. After receiving information on the runway in use, runway condition and winds, displayed on the MFD, the pilot selects one of the approach routes to the active runway from a menu. The system automatically detects possible traffic conflicts for each route, and these are indicated on the CDTI as well as in the route selection menu.

The pilot then proceeds to fly along the chosen trajectory to the runway while maintaining separation from other aircraft by controlling airspeed. A nominal airspeed is set when the pilot selects a trajectory, and may be modified by the pilot. The nominal airspeed is also broadcast to other aircraft and used to update conflict estimation.

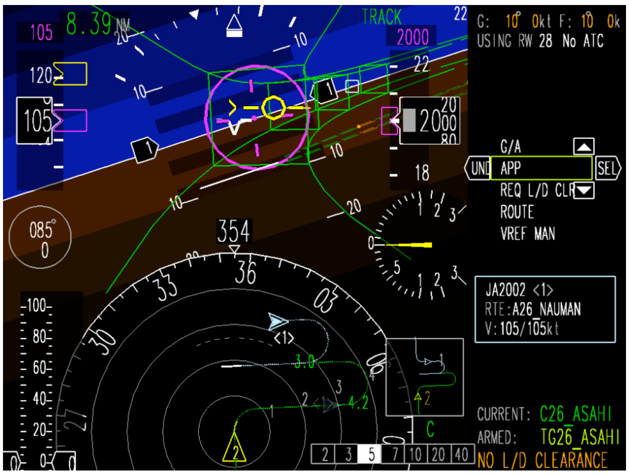


Fig.2. MFD for NOCTARN

2.3 CDTI Design

The CDTI is designed to provide pilots with traffic awareness and the necessary information to select conflict-free trajectories and to maintain separation from other aircraft. Most of the basic symbols and the conflict estimation method are adopted from "PARTI" [4][5]. The CDTI symbology is presented in Fig. 3.

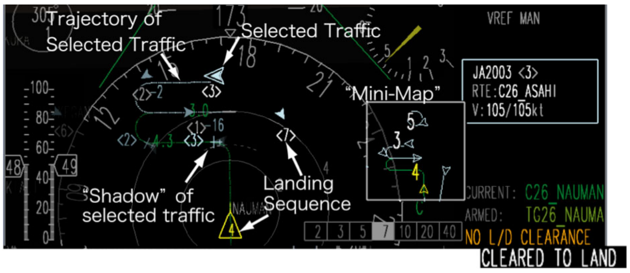


Fig. 3. CDTI Symbology

Like most other proposed CDTI formats [6], other aircraft are displayed as triangles with relative altitude. A vertical motion (climb / level / descent) arrow is omitted as long as the target is flying along its assigned trajectory. Symbols of other aircraft may be "selected" in turn by the pilot pushing a thumb switch on the control yoke. When an aircraft is selected, its callsign, assigned trajectory, and current and intended speeds are presented in a separated box in the left column of the CDTI. The geometry of the displayed trajectory is generated from a set of current position, route identifier and wind information broadcast by other aircraft, and an on-board database of nominal trajectory geometries.

Aircraft symbols are colored according to their conflict status with the ownship. For each aircraft, its CPA (Closest Point of Approach) to the ownship, the time to CPA, and horizontal and vertical separation at CPA are calculated at least once a second. If the horizontal and vertical separation at the CPA are less than threshold values, provisionally set at 1.0nm horizontally and 250ft vertically, or if the estimated time separation at landing is less than 90s, the aircraft is classified as "Conflicting Traffic", and the color of its symbol is changed to amber. If the time to CPA is less than 25 seconds and the predicted horizontal separation is less than 0.6nm, the traffic is classified as "Avoidance Required" and is displayed in red. Otherwise the target's symbol is colored sky blue, indicating no conflict. The name of each trajectory shown in the trajectory selection menu is similarly colored according to its conflict status.

The landing sequence number of each aircraft is calculated and appended to the corresponding aircraft symbols, including that of the ownship.

This study examines the effect of two features added to the CDTI to improve traffic awareness for self-sequencing and self-separation: a "Shadow" symbol and a "Mini-map". The Shadow symbol was introduced to show the separation status between the ownship and the currently selected aircraft, and represents the projected position of the opponent aircraft on the ownship's trajectory to show how these aircraft will be separated after their trajectories merge. The Mini-map is a sub-window that shows the overall traffic situation by always displaying preceding and following aircraft and their landing sequence numbers. With the aid of the Mini-map, it was expected that the pilot would not have to change the display range so often to grasp the traffic situation.

Although both the Shadow and Mini-map can both be presented on the CDTI at the same time, in this experiment only one was displayed in any scenario.

3. Simulation

3.1 Objectives and Hypothesis

A series of pilot-in-the-loop simulations was conducted to investigate the effects of the Shadow and Mini-map and to clarify the relationship between pilot workload and traffic awareness. There were three hypotheses regarding CDTI functions.

1. The greater the pilot's awareness of the traffic situation, the less attention he will pay to the CDTI and the less he will interact

with the display (i.e. range control, traffic selection).

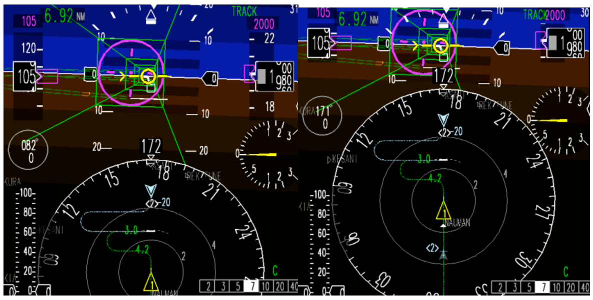
2. Path tracking performance will be degraded if too much attention is focused on the CDTI.
3. Path tracking performance will be degraded by frequent operation of display switches.
4. Although the Shadow and Mini-map are both useful for the task, one of these will be preferred by the majority of pilots.

3.2 System Environment

The evaluation was carried out using JAXA's FSCAT-A research flight simulator programmed with the non-linear flight dynamics of a Dornier Do-228 twin turboprop aircraft. Four JAXA research pilots, all of whom were well experienced with the aircraft and with the NOCTARN tunnel-in-the-sky display and CPDLC operation, participated in the simulation study. Figure 4 shows the simulator cockpit. The cockpit layout is similar to that of a modern jet transport airplane with three liquid crystal display (LCD) screens. The flight controls are electrically loaded.

The MFD is located in the front of the pilot on the main instrument panel. A four-way switch mainly used for trajectory selection and pushbutton switches for traffic selection are mounted on the control yoke for thumb operation, and pushbutton switches for display mode selection, range selection and reference speed change are located beside the display bezel. By using "up" and " down" switches, a desired range is chosen from 7 values. Figure 5 shows two pilot-selectable display modes: "half-arc" and "full-arc". The shortest display range and the half-arc mode were pre-selected at the start of each simulation run.

Fig.4. Simulator Cockpit



Half-arc Full-arc

Fig. 5 Display Modes

3.3 Scenarios and Display Parameters

Three scenarios were prepared. Each scenario had a maximum of 8 aircraft, and contained both arrival and departure traffic. The wind condition was manipulated such that the separation between the ownship and preceding aircraft would decrease during the flight even if the pilot successfully maintained the trajectory and reference speed.

Three types of display were prepared, with four cases.

A. No traffic
B. Basic (no Mini-map or Shadow)
C. Mini-map
D. Shadow

In the "No traffic" (A) case, the Mini-map was not presented.

3.4 Procedure

The airport used in the scenarios had a single 1,000m east-west runway. Each simulation run began with the aircraft located 1nm north of an entry gate to the airport's NOCTARN control zone, and stopped when the aircraft reached 500ft above ground on final approach. As soon as a simulation run started, the simulated data link system was activated and other traffic were shown on the MFD. The pilot was asked to start approach trajectory selection after the system had received traffic information from other aircraft. The pilot was free to change the reference airspeed and the currently selected other aircraft at any time, and any horizontal display range and display mode could be selected. No changes to the aircraft's configuration (undercarriage or flap settings) were supposed to occur during the flights. The pilots were required to capture and track the selected trajectory without excessive maneuvers. A total of 12 runs, one for each combination of a scenario and a display type, were flown by each pilot.

From the recoded flight parameters, flight path and speed tracking errors, and the number of CDTI-related switch operations were analyzed. Pilot comments were recorded in interviews after each simulation run. Pilots were also asked to fill in a comment sheet regarding information acquisition from the CDTI (Table 1).

4. Results

Figures 6–10 show results for each case. Figure 6 shows path tracking error versus the number of display mode and range changes. Figure 7 shows the number of display mode and range switch operations. Figures 8 and 9 show time-accumulated average values of selected display range and display mode. Figure 10 shows horizontal path, vertical path and airspeed error. Table 1 shows a summary of questionnaire responses.

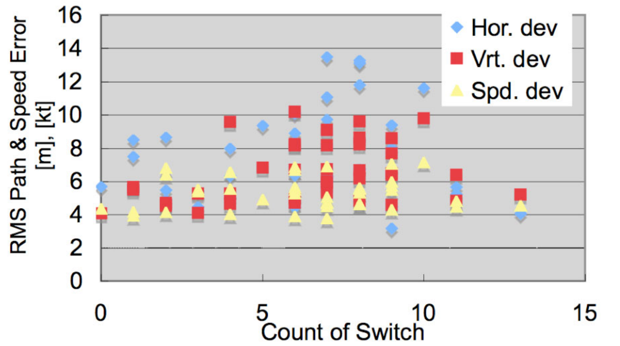


Fig. 6. Tracking and Speed Error v.s. SW Manipulation Count

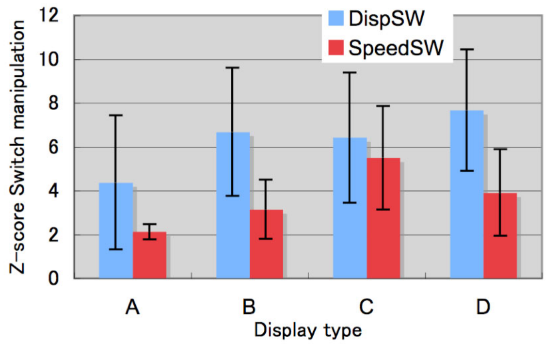


Fig.7. Switch Manipulation Count

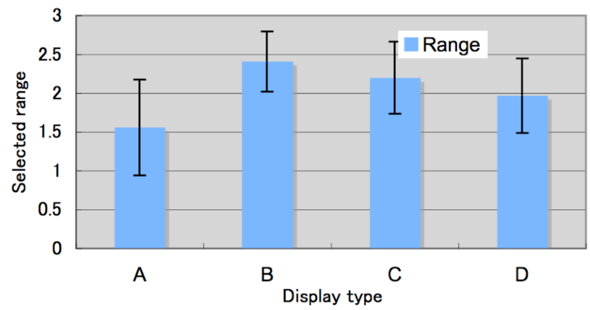


Fig. 8. Selected Display Range

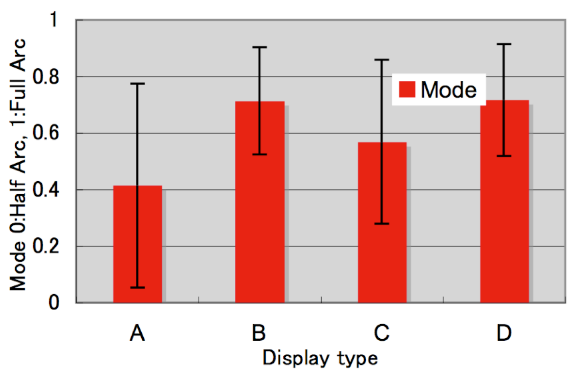


Fig. 9. Selected Display Mode

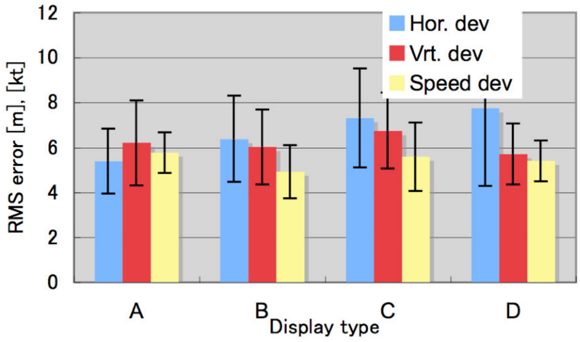


Fig. 10. Tracking and Speed Error

Table 1. Summary of Questionnaires

Question	Summary of response
Mini-map provides usable information	Agree Disagree ☑☑☑ ☐☑☐
Information is easily acquired from the Mini-map	Agree Disagree ☐☑☑ ☑☑☐
Shadow provides usable information	Agree Disagree ☐☑☒ ☐☐☐
Information is easily acquired from the Shadow	Agree Disagree ☐☑☒ ☑☐☐
Actual position and Shadow are clearly related	Agree Disagree ☐☒☑ ☐☑☐
Either of Shadow or Mini-map is necessary	Agree Disagree ☐☒☑ ☐☐☐

☒ Majority of response ☑ One scored

5. Discussion

5.1 Effect of Display Switch Manipulation

No clear correlation was found between path tracking error and number of display switch operations from Fig. 6. However, if analysis is conducted with the data for less than nine switch operations discarded, there is a significant relationship between horizontal and vertical tracking error and the number of switch operations. This basically supports Hypothesis 3, that path tracking performance is affected by switch operation. On the other hand, Fig. 6 also shows that a higher number of switch operations (more than 8) did not necessarily degrade tracking performance. It can be supposed that when the aircraft was sufficiently stable and required less attention to control, pilots could divert the remainder of their attention to the traffic situation; in other words, if flight control workload were too great pilots would not pay attention to traffic. Unless the "necessary level of traffic awareness" is defined, it seems to be difficult to clarify relationship between traffic awareness and number of display switch operations.

5.2 Display Range and Mode Selection

Figure 8 shows that the pilots selected the longest display range in Basic (B), and shortest range in Shadow (D). It was often observed that the pilots selected a longer range at the beginning of a session to identify preceding aircraft. On the other hand, Fig. 9 shows that the pilots changed the display range and mode in Shadow (D) most frequently. This means that the pilots re-selected a shorter range after checking the overall traffic situation. This supports the hypothesis that Shadow provides better situation awareness than Basic and Mini-map.

Figure 9 shows that the pilots preferred the half-arc to the full-arc display mode in Basic (A) and Mini-map (C). It can be considered that the Mini-map provides pilots with the "big-picture", and successfully provides information not shown by the half-arc display mode.

Figure 7 shows that the pilots changed the reference speed most frequently in Mini-map (C). This is thought to be because unlike Shadow, the Mini-map shows the relative positions of following aircraft as well as preceding aircraft and although the pilots were instructed only to care about preceding aircraft in the experimental sessions, they may also have paid attention to, and maintained separation from, the following aircraft shown on the Mini-map display.

5.3 Path and Speed Errors

The acquired data for tracking error versus display type show no significant correlations, and few differences are observed between the cases. Fig. 10 indicates that Basic (A) gave the lowest cross track error but relatively large values of vertical and speed error. It is supposed that the pilots had to pay more attention to speed control in scenarios with traffic than in cases without traffic. Some narrative pilot comments supported this supposition.

5.4 Summary of Results

Hypothesis 1 (less attention will be paid to the CDTI when the pilot has adequate traffic awareness) was not supported by the results. The results of the Mini-map case indicate that pilots paid *more* attention to the CDTI if they had additional information. The relationship between traffic awareness and the number of display interactions (switch operations) is not clear, because the pilots seemed to interact with the CDTI when the aircraft was stable. Path tracking performance degradation could not be related to traffic awareness— although the pilots stated that their traffic awareness was increased by the additional symbols, there was no observed reduction in path tracking error.

For Hypothesis 2 (path tracking performance will be degraded by excessive attention to the CDTI), the results failed to give any direct clue as to the reason for the traffic awareness differences between display types. As discussed in the former paragraph, the pilots tended to have better awareness when their workload was not high.

Hypothesis 3 (path tracking performance will be degraded by frequent switch operation) was partly supported by the results. In general, path tracking performance degraded when the pilot operated display switches too often. On the other hand, the pilots also interacted with the display when the aircraft was stable.

Hypothesis 4 (there will be a preference for either the Shadow or the Mini-map) was not supported by the results. From narrative pilot comments and answers to the questionnaires, the pilots stated that both the Mini-map and Shadow enhanced their traffic awareness. As it is difficult to tell which of these should be chosen, a function to allow pilot selection would be appropriate for an actual implementation.

In addition, presentation of the Mini-map on the CDTI enabled pilots to easily grasp the surrounding traffic situation, and they were able to monitor and separate from not only preceding aircraft but also from following aircraft. It is, however, difficult to tell whether the Mini-map is beneficial because it may induce unnecessary workload by drawing the pilot's attention to non-critical traffic, unless such low-priority traffic information is appropriately masked.

6 Summary

A series of pilot-in-the-loop flight simulations was conducted to investigate how pilots interacted with a CDTI in single-pilot trajectory-based, self-sequenced and self-separated operations. Two types of separation symbology were devised and compared. The results show that although the newly introduced symbologies were accepted by the pilots and did not reduce interaction with the CDTI; on the contrary, pilots tended to pay more attention to the CDTI, sometimes resulting in degradation of flight path tracking performance. A "Mini-map" successfully provided pilots with surrounding traffic information, but tempted pilots to pay attention to following aircraft in the landing sequence.

As future work, objective methods to assess the situation awareness should be introduced into the experiment to identify the level of traffic awareness directly.

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