SUMMARY OF NOCTARN RESEARCH PROJECT

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Abstract

This paper gives an outline of NOCTARN research activity that aimed at developing and demonstrating a trajectory-based air traffic management and operation system for small aircraft.

This research focused on developing technologies to generate and share 4D flight trajectories among aircraft and between air and ground, and to use this information to enable high-density operations and for noise abatement while maintaining pilot workload at the same level as conventional operation. A pilot display, ATC console and data link system have been developed during the course of this research, and a flight experiment involving multiple aircraft was accomplished in the final stage, demonstrating the concept's feasibility.

1 Introduction

While the growing demand for air travel is putting pressure on many airports to increase their capacity, many airports are located near noise-sensitive residential areas that constrain such increases. The use of three-dimensional (3D) flexible approach patterns in addition to the conventional straight-in approach is an effective means of increasing the number of aircraft movements while limiting the impact of noise. Moreover, by sharing four-dimensional trajectories between aircraft and an air traffic control ground station, capacity and safety around such airport will be enhanced.

The Japan Aerospace Exploration Agency (JAXA) and the Electronic Navigation Research Institute (ENRI) have been conducting a research activity called NOCTARN (New Operational Concept using Three-dimensional Adaptable Route Navigation) aimed at developing an aircraft operations concept that can reduce the noise impact on communities while enhancing the capacity and operational efficiency of airports, by using precisely-defined trajectories which are shared between aircraft and air traffic control [1]. The focus is on regional airports and small aircraft and helicopters, and the concept is designed with single-pilot operation in mind. The goal of the research was to accomplish a flight demonstration with multiple aircraft and to show the feasibility of the proposed operations concept.

Figure 1 shows the research structure of the NOCTARN project. Three technologies were identified as key issues to be prototyped in the system: (1) A multi-function pilot display for single pilot operation; (2) an ATC (air traffic control) workstation that handles 4D trajectories and ground noise data; and (3) a data link communication protocol for providing services similar to ADS-B (Automatic Dependent Surveillance – Broadcast), FIS-B (Flight Information Service - Broadcast) and CPDLC (Controller-Pilot Data Link Communication), as well as trajectory generation and sharing algorithms.

Although most of the regional airports in Japan that suffer from noise or capacity issues have a controller or traffic service, it was expected that the proposed system would also be used for non-towered aerodromes and heliports. Therefore, the system has been developed to function in two modes: a Ground Separated Mode (GSM) and an Airborne Separated Mode (ASM). In the former mode, a controller on the ground assures separation using the ATC workstation display. In the latter mode, aircraft assume responsibility not only for self-separation but also for approach or departure sequencing [2]. In the course of this research, a HLA (High Level Architecture)-based network simulation environment was identified as a key technology for the overall activity [4]. This paper describes the proposed operations concept, prototyped system and flight demonstration.

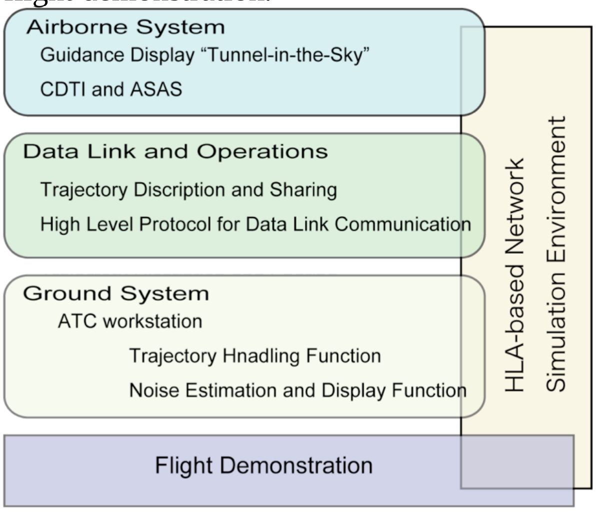

Fig. 1. NOCTARN Research Structure

2 Operations Concept

2.1 General Concept

The basic NOCTARN operations concept is illustrated in Fig. 2. An airport has a "control zone" which aircraft enter or leave through "gates" situated around its periphery. 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 trajectories that are designed to reduce noise impact on the surrounding community. ATC instructions and clearances and pilot requests and responses, including 4D trajectory information, are communicated over a digital data link using a CPDLC-like service. Aircraft also broadcast their position and assigned route over the same data link, similar to the ADS-B concept, and this position information is displayed both on the air traffic controller's console along with corresponding assigned trajectory information and on the CDTIs (Cockpit Display of Traffic Information) of other suitably-equipped aircraft operating within the zone.

To use NOCTARN trajectories, an aircraft must have suitable equipage and operate under NOCTARN flight rules. NOCTARN equipage comprises a digital data link transceiver, a GPS (Global Positioning System)-based navigation and guidance system, and a cockpit MFD (Multi-Function Display) that displays trajectory information, CDTI and Tunnel-in-the-Sky flight guidance information, and also acts as a CPDLC terminal. 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 must then fly along a selected or assigned route.

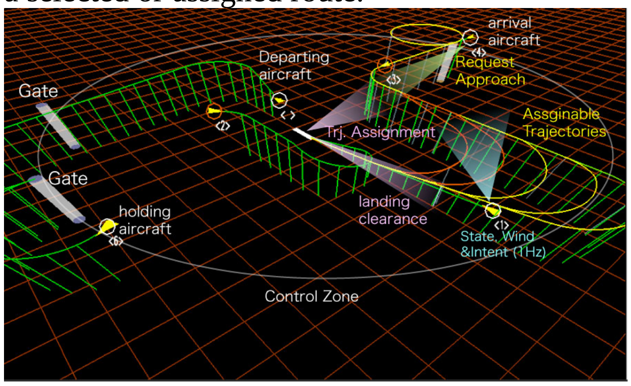

Fig. 2. NOCTARN Overview (GSM)

2.2 Procedure in Ground-Separated Mode

In GSM, for airports with a manned control tower, the procedure is as follows. While an aircraft is inbound approaching one of the control zone "gates", the pilot activates the system, which establishes a data link communication session with the controller's ground station. After this, the aircraft's ADS position is displayed on the controller's workstation and on the CDTI displays of other NOCTARN-equipped aircraft flying in the control zone.

After receiving uplinked runway in use, runway condition, and wind information, the pilot selects one of the approach routes using the MFD and a request for the route is downlinked to the controller by the CPDLC function. If the controller approves the requested route, it is assigned to the aircraft. Otherwise, the controller may offer an alternative route using the CPDLC function. Negotiation may continue until the aircraft crosses the gate. If the negotiation is still in progress when the aircraft enters the NOCTARN zone, the last route offered by ATC is assigned automatically; otherwise, the aircraft must cancel the approach and restart the procedure. The pilot cannot land without receiving landing clearance by CPDLC. The data link session is terminated by the pilot, either when instructed by the controller or when the aircraft has stopped at its spot. The controller cannot terminate the session, although he or she can remove information related to the aircraft from the console.

When a missed approach is initiated, the pilot reports it to the controller either by voice or by CPDLC. If CPDLC is utilized, the nominal missed approach pattern becomes active both on ATC console and on the pilot's MFD.

For departures, the system works in a similar manner. When the pilot initializes the NOCTARN avionics on the ground, a communication session is again initiated and the pilot and controller negotiate a departure route. The aircraft cannot taxi for departure without an assigned departure route. After leaving the control zone, the pilot terminates the data link session.

2.3 Procedure in Airborne-Separated Mode

The proposed communication procedure in ASM, where there is no air traffic controller so the most suitable approach route must be selected by the pilot, 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 ADS position of the aircraft is displayed on the CDTIs of these other NOCTARN-equipped aircraft.

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

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

3 System

3.1 Overall System

Figure 3 depicts overall NOCTARN system. From a hardware point of view, the system is constructed from airborne and ground sub-systems. From a functional point of view, the pilot display, ATC console, data link and trajectory generation algorithm are essential parts of an integrated system. Each function is described below.

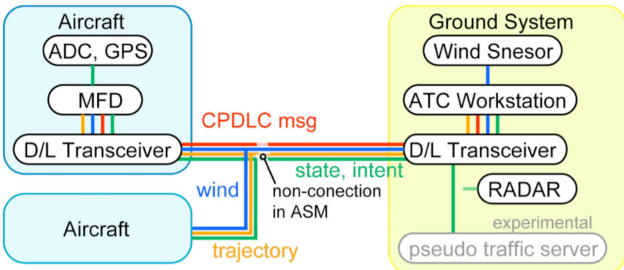

Fig. 3. NOCTAN System

3.2 Pilot Display

3.2.1 Display Function

When fully developed, the NOCTARN avionics package will be an integrated system consisting of an MFD (Multi-Function Display), a GPS-based navigation system, and a data link communication system. The NOCTARN MFD will have three main functions: navigation and guidance, CDTI, and data link communication terminal. These are elaborated upon below.

3.2.2 Navigation and Guidance

An example of the navigation and guidance display format is presented in Fig. 4. The guidance display is in the form of a “Tunnel-in-the-Sky”, which presents the nominal flight path as a perspective image of a “tunnel” [5-8]. Although it was anticipated that conventional Flight Director (FD) and Navigation Display (ND) may supports the pilot task to follow the curved trajectory, we decided to use the Tunnel-in-the-Sky Display as the basis for the NOCTARN piloting task. The display format has been optimized for precision tracking for both airplanes and helicopters by several flight experiments [9,10].

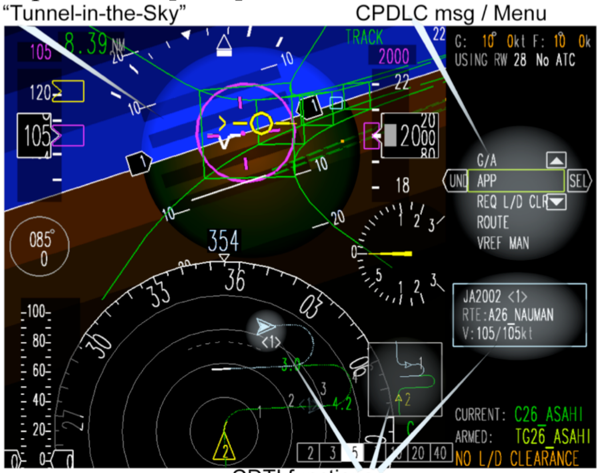

Fig. 4. MFD for NOCTARN

3.2.3 CDTI

The CDTI was designed to provide the pilot with traffic awareness and the necessary information to select conflict-free trajectories and to maintain separation, particularly in ASM [11].

Like most other proposed CDTI formats [12], other aircraft are displayed as triangles with relative altitude. Vertical motion (descent or climb) is not displayed so long as the other aircraft is following its assigned trajectory. When the symbol of another aircraft is “selected”, its callsign, assigned trajectory and speed are presented in separated box in the left column of the display. The pilot can cycle the “selected” state among the displayed aircraft by pushing thumb-operated switches mounted on the control yoke.

The conflict status of each aircraft with the ownship is calculated by comparing its trajectory with that of the ownship at least once a second. If the horizontal and vertical separation at the estimated CPA (Closest Point of Approach) are within threshold values, provisionally set at 1.0nm horizontally and 250ft vertically, or if the difference in estimated time at runway threshold is less than 90 seconds for landing aircraft, the aircraft is classified as “Conflicting Traffic”, and the color of its symbol is changed to amber. If the time until conflict 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. The name of each trajectory shown in the CPDLC trajectory selection menu also is colored according to its conflict status. The landing sequence number of each aircraft including the ownship is calculated and appended to the aircraft symbols.

3.2.4 Data Link Interface Function

ATC-assigned routes and pilot requested routes are exchanged as four-dimensional trajectories, and the presentation of the routes on the MFD is designed so that the pilot can distinguish between the current and alternative routes and can comprehend the assigned route without needing to refer to charts [13]. The CPDLC menu structure is shown in Fig. 5. The menu structure is designed to be less than two levels deep. Only a limited number of messages were selected for the message set in consideration of single-pilot operation.

When an uplinked message from the aerodrome’s controller arrives, a menu of downlink messages normally displayed on the MFD is removed and the incoming message shown in its place, and the message is read-out by a synthetic voice. The system also verbally annunciates messages selected by the pilot for downlink.

For the trajectory display, a trajectory under selection or negotiation is shown in yellow and is overlaid onto the current/assigned trajectory, which is shown in green. Four thumb-operated buttons on the control yoke are used for message composition and CPDLC response: "Down" and "Up" buttons are used for selecting a message or a route, and "Cancel (left)" and "Select (right)" buttons are used for message activation, cancellation and moving between menu levels.

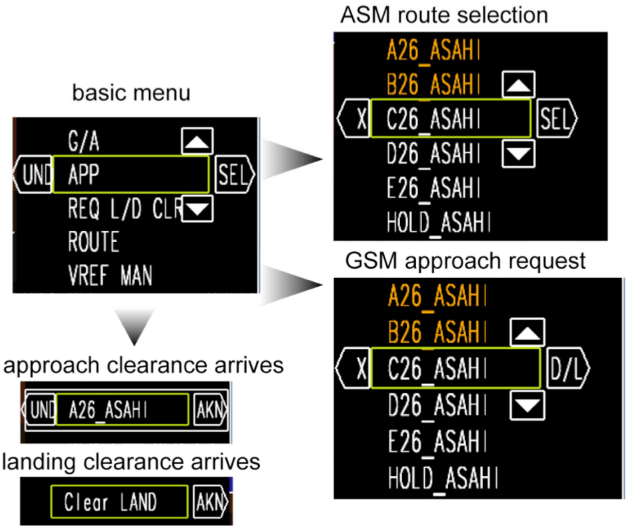

Fig. 5. CPDLC Menu in MFD

3.3 ATC Console

3.3.1 Functions

An essential function of the NOCTARN ATC console is to enable a controller to select a desired trajectory and to uplink it to the aircraft. Trajectories that may be shared between aircraft and the ground station include approach, take off, and holding patterns. There are also data link messages without associated trajectory information, such as take off and landing clearances. If more complex communication is required, the controller reverts to voice.

Figure 6 shows a snapshot of the ATC console with CPDLC menu. To send a message, the controller selects the target aircraft and then chooses the desired message from a pull down menu. If a trajectory is associated with the message, the possible assignable trajectories are graphically shown on the display, and the controller can select one of these candidates. Arrival of a downlink message is notified by the corresponding target symbol flashing and an audio alert.

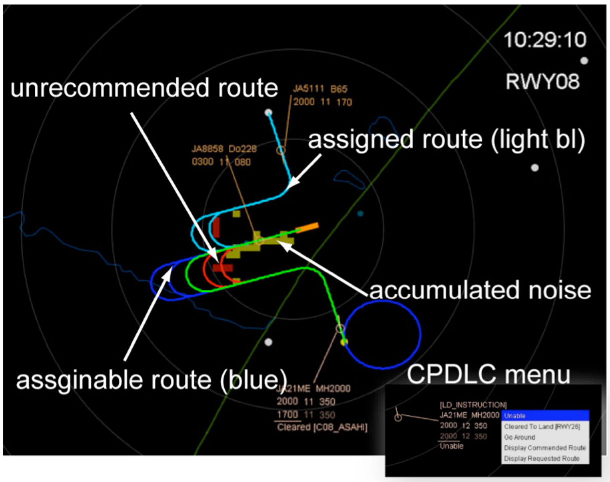

Fig. 6. ATC Console

3.3.2 Noise Estimation and Advisory

There are two methods of noise abatement by using specially designed trajectories: static and dynamic. The former method has been used for decades by designing steep approach paths and/or curved trajectories to avoid noise-sensitive areas. In the latter method, different trajectories may be assigned at different times considering wind conditions and previous noise distribution (that is, the distribution of noise experienced on the ground accumulated over time).

The NOCTARN ATC console has an integrated function that advises the controller which trajectory will have the least noise impact on the surrounding community. Figure 6 shows a snapshot of the ATC console showing noise contours of noise sustained on the ground over time, and the color-coded noise impact status of different trajectories. The noise estimation and advisory system works as follows: During the trajectory selection process, estimated ground noise contours for each candidate trajectory are calculated taking into account the measured wind conditions and the aircraft type. When a candidate trajectory is selected, its corresponding noise contour is considered as actual generated noise and is added to a memory of accumulated noise on the ground. At the same time, warning levels for ground areas are calculated by comparing the accumulated noise with threshold levels set for each area (with low thresholds for noise-sensitive sites such as hospitals and residential areas, and high thresholds for less sensitive sites such as industrial parks and bodies of water). If the threshold for any area is exceeded, the color of the trajectory on the display is changed to warn the controller that assigning the trajectory may cause a noise problem.

Although this function has been successfully integrated into the ATC console and demonstrated in flight experiment, actual evaluation by air traffic controllers has not been accomplished. Whether or not the controller's separation assurance task can include noise considerations is still under discussion.

3.4 Data Link System

NOCTARN did not assume a specific data link technology (i.e., VDL, UAT), but assumed a generic data link capable of supporting ADS-B and FIS-B applications and air-ground message exchange. In addition to conventional ADS-B reports, aircraft transmit current trajectory information, CPDLC messages and trajectory inquiry messages. Except for CPDLC messages, all information is sent automatically, either periodically or upon request from other station. The ground station transmits CPDLC, FIS-B, and TIS-B messages.

Upon receiving a non-periodic message, a low-level acknowledgment message is transmitted back to the sender. If the sender does not receive this acknowledgement within a predetermined time, it re-transmits the same message. If this also times out, a data link disconnection message is shown on the sender's display.

Wind information downlinked from aircraft is stored in the ATC workstation, and the average value is broadcasted to all aircraft as an "area wind". This information is utilized for trajectory optimization, as discussed in the following section.

In the current experimental implementation of the system, no radar-based ground surveillance system is available to provide TIS-B information. Instead, "pseudo" aircraft could be generated on the ground and used to simulate a variety of traffic situations.

3.5 Trajectory Generation and Sharing

Trajectory description is the most essential issue for the NOCTARN system. From a traffic management and noise abatement point of view, trajectories should be designed as flexibly as possible. For example, to satisfy the noise abatement requirements of airports located in residential areas, curved approach paths with short final straight legs should be assigned, while keeping pilot workload at an acceptable level. As the trajectory is fixed in inertial space, significant deviation from the nominal route may occur when attempting to track it in strong wind, and there is the risk that tracking the nominal route may require maneuvers close to the performance limits of the aircraft, with a consequent risk of loss of control.

In order to improve aircraft trajectory tracking performance while avoiding requiring maneuvers that could lead to loss of control, the system incorporates a periodic route modification function. The following trajectory generation and modification algorithm is considered to avoid such problems [12].

A trajectory is described by connecting straight legs and circular arcs. In order to reduce deviation and pilot workload, the original low-order trajectory is replaced by a high-order trajectory generated from it using fast-time simulation assuming a scheduled roll rate. When route modification is applied, estimated and uplinked winds are included in the fast-time simulation. The estimated wind is utilized to alter the flight path angle so that the aircraft maintains a constant "flight path relative to air mass". Figures 7 and 8 show respectively an example of original and modified trajectories generated in an actual flight experiment, and the recorded time histories of a flight simulation comparing those trajectories. Figure 8 shows that whereas tracking the original trajectory would require greater than 20 degrees of bank, with the modified trajectory the required maximum bank angle is less than 20 degrees.

Once the modified trajectory is assigned, it is shared with other aircraft and the ground station.

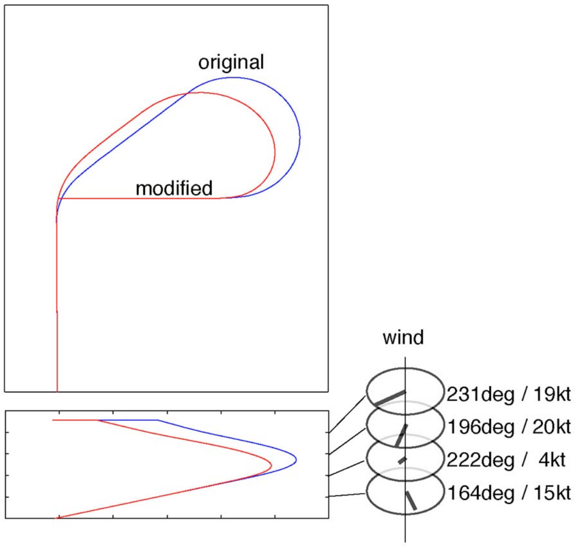

Fig. 7. Example of Trajectory Modification

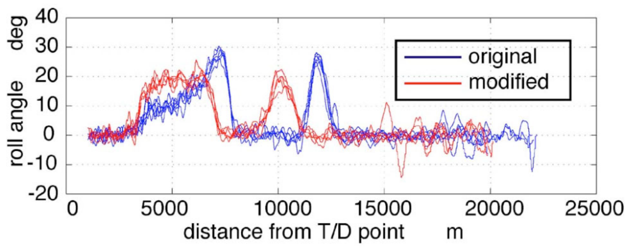

Fig. 8. Time History Flying Modified Trajectory

4. Evaluation

4.1 System Functionality

A series of flight experiments to confirm the system's functionality and to demonstrate the feasibility of the NOCTARN operations concept was conducted in September 2005. Two NOCTARN-equipped aircraft, one helicopter and one fixed-wing, were used. A total of 13 trials were flown, most scenarios including four pseudo-aircraft generated on the ground. Two helicopter pilots and three airplane pilots participated the experiment. Figure 9 depicts the aircraft and their display installations.

Figures 10 and 11 show examples of flown trajectories in ASM. In Fig. 10, two aircraft, JA8858 and JA21ME, departed from separate "standby" patterns almost simultaneously, and initiated the trajectory selection process. After JA8858 had selected a trajectory, the CDTI on JA21ME proposed a longer trajectory to give sufficient separation from the preceding aircraft.

In Fig. 11, as there was a northerly wind of nearly 20kt, the flown trajectories were modified to avoid excessive bank angle.

Fig. 9. Aircraft and Display Installation

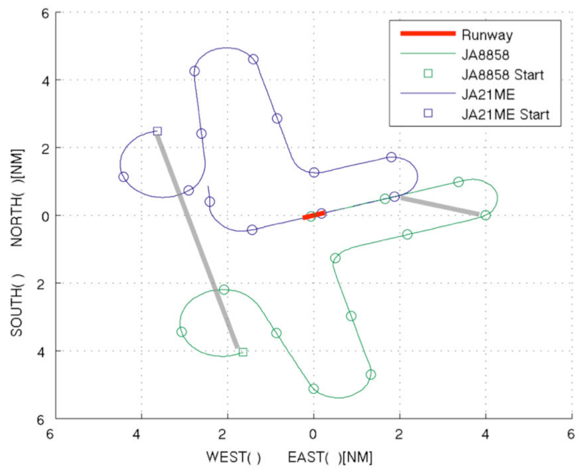

Fig. 10. Example of Flown Trajectory (1)

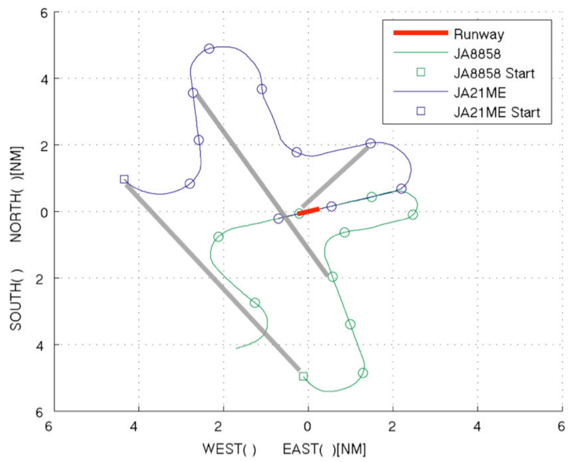

Fig. 11. Example of Flown Trajectory (2)

4.2 Pilot Workload

Pilot workload was evaluated compared with conventional instrument approaches. Figure 12 shows relative workload scores based on NASA-TLX [14] for GSM and ASM. For GSM, Operation Performance (OP) and Frustration Level (FR) were significantly reduced (at α=0.05) in NOCTARN approaches, and for ASM, (OP, Time Pressure (TP) and Effort (EF) were significantly reduced. All participating pilots agreed that comparative workload was reduced for ASM, but not necessarily for GSM. From the workload reason code corrected with the TLX score [15], it was revealed that CPDLC response delay, which was mainly due to the controllers' task time, caused an increase of workload, especially for Mental Demand (MD). It was also revealed that OP workload reduction was due to better flight path tracking performance and the clear presentation of conflict-free status by the CDTI.

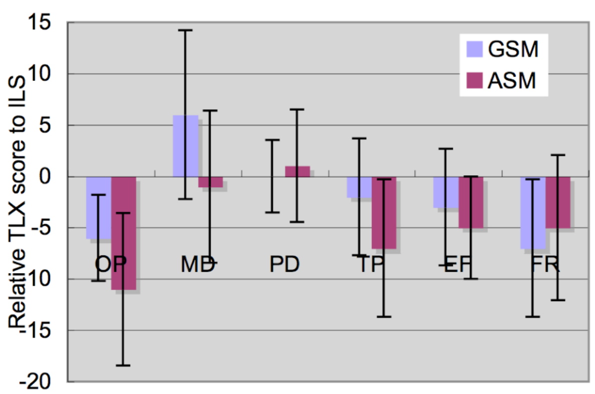

Fig. 12. NASA-TLX Score

5. Summary

This paper has presented a summary of NOCTARN research activity that aims at developing and demonstrating a trajectory-based air traffic management and operation system for small aircraft. The research focused on developing technologies to generate and share 4D trajectories among aircraft and between air and ground, and to use the information for enabling high-density operations and noise abatement while maintaining pilot workload at the same level as conventional instrument flight operations. A pilot display, ATC console and data link system have been developed in the course of this research.

Flight experiments with multiple aircraft were accomplished at the final stage of the research, and the feasibility of the operations concept was demonstrated.

As future activities, a high-level data link protocol for trajectory information exchange will be studied, and more detailed considerations of the effects of temporary link disconnection will be required. In parallel, implementation of the original NOCTARN data link messages into existing data link hardware and protocols, such as VDL (VHF Digital Data Link) or UAT (Universal Access Transceiver) is planned.

Acknowledgment

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References

[1] Funabiki, K., Muraoka, K., Iijima, T. and Shiomi, K.; *NOCTARN: Trajectory Based CNS/ATM Concept for Small Aircraft*, proc. Of 21st Digital Avionics Systems Conference, 2002

[2] Williams, D., Consiglio, M., Murdoch, J. and Adams, C.; *Preliminary Validation of the ASTS HVO Concept*, proc. of 24th International Congress of the Aeronautical Sciences, 2004.

[3] Yokota, M., Ikeuchi, K., Kuraya, N., Mizuno, H. and Morita, Y.; *TDMA Air-to-Air Surveillance System for Helicopter Safety*, SAE 2001-01-2995, 2001.

[4] Muraoka, K. and Funabiki, K.; *Distributed Simulation for NOCTARN*, AIAA Modeling and Proc. of Simulation Technologies Conference and Exhibit, 2001.

[5] Grunwald, A.J., Robertson, J.B. and Harfield, J.J.; *Experimental Evaluation of a Perspective Tunnel Display for Three-Dimensional Helicopter Approaches*, AIAA Journal of Guidance and Control, NOV-DEC 1981, 1981.

[6] Grunwald, A.J.; *Tunnel Display for Four-Dimensional Fixed-Wing Aircraft Approaches*, AIAA

Journal of Guidance and Control, MAY-JUNE 1984, 1984.

[7] Theunissen, E., and Mulder, M.; *Error-Neglecting Control with Perspective Flightpath Displays*, Proc. of Eighth International Symposium on Aviation Psychology, 1995.

[8] Mulder, M., *Cybernetics of Tunnel-in-the-Sky Displays*, Delft University Press, 1999.

[9] Funabiki, K., Muraoka, K., Terui, Y., Harigae, M. and Ono, T.; *In-flight Evaluation of Tunnel-in-the-Sky Display and Curved Approach Pattern*, AIAA Guidance, Navigation and Control Conference and Exhibit, 1999.

[10] Funabiki, K., Muraoka, Iijima, T.; *Tunnel-in-the-sky Display for Helicopters*, AIAA Guidance, Navigation and Control Conference and Exhibit, 2001.

[11] Funabiki, K., Iijima, T. and Nojima, T.; *CDTI design in a Trajectory-based Operations Concept for Small Aircraft*, proc. of 23rd Digital Avionics Systems Conference, 2004.

[12] RTCA Special Committee-18; *Draft Minimum Operational Performance Standards for Cockpit Display of Traffic Information*, 1998.

[13] Funabiki, K., Iijima, T. and Nojima, T.; *Evaluation of a Trajectory-Based Operations Concept for Small Aircraft: Airborne Aspect*, proc. of 22nd Digital Avionics Systems Conference, 2003

[14] S. G. Hart, and L. E. Staveland; *Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research*, In P. A. Hancock and N. Meshkati (eds.): Human Mental Workload, 139–183, Elsevier Science Publishers B. V., Amsterdam, 1988.

[15] Iijima, T, Funabiki, K. and Nojima, T.; *Pilot Workload Assessment method in a new CNS/ATM Environment*, System Man and Cybernetics Conference, 2004.