A Distributed Air Traffic Information
Display Simulator: Design and Results

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Abstract

The National Airspace System (NAS) is vested in the interaction of multiple partners. Effective simulations of NAS require the participation of multiple operators. One reason why such an integrated simulation facility would be useful lies in its potential to test various proposed changes in NAS operations that have accompanied the introduction of impact technologies. Autonomous self-separation by pilots is close to one end of a continuum of operational concepts known as 'free flight', which could compose an evident paradigm change for global air operations. The configuration of autonomous control has been explored in our Laboratory in a programmatic series of research studies. We created a purpose-specific simulation system especially focused on the issue of pilot-ATC interaction and the respective changes in functioning due to greater distribution of control. The present paper describes this effort, its structure, function, and results, which have shown a consistent use of a time-to-contact threshold by pilots in resolving conflict situations.

A Distributed Air Traffic Information Display Simulator (DATIDS).

To support the design of autonomous control in commercial aviation, our collective research group, then at the University of Minnesota, created the DATIDS (Distributed Air-Traffic Information Display Simulator) system. DATIDS was purpose-designed to be a user-friendly research tool that provided a flexible array of experimental workstations for exploration of the decision-making, communication, and actions of any combination of (1) pilots, (2) pseudo-pilots, (3) air traffic controllers, and (4) airline dispatchers. Creation of this facility was supported by

Grant funding from the Federal Aviation Administration and represented an experimental environment which was employed to support a number of experiments (e.g., Knecht, & Hancock, 1999; Murphy, Smith, & Hancock, 2004; Smith, Hancock, & Scallen, 1996; Smith, Scallen, Knecht, & Hancock, 1998). The DATIDS suite is shown in Figure 1.

One pilot, or multiple pilots, could be employed as participants in the distributed cockpit facilities. In the original instantiation of DATIDS, there was only a single pilot seated in a mockup of the captain's side of a Boeing 757 cockpit. Pilot controlled one of the aircraft in the simulated airspace. The paths of all other aircraft in the experimental scenario were scripted and under the real-time control of one or more 'pseudo-pilots.' An experimenter could assume the role of 'pseudo-pilot' for up to as many as thirty other aircraft ('targets') in the scenario. Alternatively, this function could be handed off to single, or multiple, associates. The DATIDS pseudo-pilot interface on the server enabled the experimenter to maneuver any of the target aircraft realistically in real time.

Figure 1. The Human Factors Research Laboratory's (HFRL, Univ. of Minnesota) Aviation Research Facilities. At the left, with the staircase, is a single-seat cockpit that housed a single (pilot) participant. Behind is a two-seat cockpit configuration. At right, one of the creators of the DATIDS system is seated at the ATC workstation.

An 'air traffic controller' could be designated as another experimental participant, seated at a mockup of an ARTCC sector controller's workstation. Again,

there was the opportunity for the interaction of a single or multiple sector controllers with each other and with aircraft (and the pilot in the mockup of the cockpit). Finally, other experimental participants could act as 'airline dispatchers.' Further, single or multiple operator configurations were available. In the original DATIDS, this individual was seated at a mockup of a dispatcher's workstation at Northwest Airline's Systems Operations Center (SOC).

Simulation Functionality

In its initial configuration on a high-end Silicon Graphics machine, DATIDS supported en route flight scenarios with as many as thirty aircraft anywhere in the continental United States. DATIDS was also able to support either arrival or departure scenarios if files and routes were created to supply the graphics for the necessary "background" data, i.e., arrival fixes, runways, etc. The restriction to thirty aircraft was actually arbitrary, as was the decision to limit the data files of waypoints and jet ways to those in the contiguous forty-eight states. In principle, there is no reason why the whole, global airspace could not have been represented on the DATIDS system. In the second-generation of DATIDS, advances in PC technology allowed us to expand the simulation to include multiple glass cockpits and ATC workstations networked together to form a distributed array. The tasks of calculating aircraft movement, accepting inputs from several participants, recording data, and displaying graphic representations of a number of different electronic devices were separated and assigned to individual computers. The computers communicated over a local network to form a unified simulation. The PC-based system was significantly more cost-effective than its predecessor.

DATIDS Workstations

The Air-Traffic Control Workstation. The DATIDS simulation of an ARTCC sector controller's workstation recreated a circular composite radar screen (the Plan View Display, PVD), a computer read-out display (CRD), a panel of buttons and five dials. As shown in Figure 2, aircraft, routes, waypoints, and sector boundaries were drawn on the PVD. Each waypoint was accompanied by its name. Each aircraft had a configurable data tag that conformed to the standard format used by controllers of high-altitude sectors. The experimental participant used a trackball to re-center the radar field by clicking on a waypoint. Position and flight plan data, from the last aircraft the user clicked on, was displayed in the CRD in the upper right of the display. By clicking on the first dial (labeled RANGE), the user could zoom in or out by adjusting the radius of the displayed area. To mimic real ATC screens, aircraft were drawn as short lines perpendicular to their headings. To portray the refresh rate of ATC radar data realistically, the locations and data tags for aircraft on the screen were updated once every six seconds. This is slower than the sweep at an ARTCC and closer to the timing of a TRACON facility. It was chosen here in relation to the experimentation on future implementation of autonomous self-separation. Positions from previous updates remained on the screen and faded to black over time. The number of previous updates that remained visible could be manipulated using the HISTORY dial. An aircraft's filed flight plan and its projected path along its current heading could optionally be

displayed as a thick lines extending in front of the aircraft on the radar screen using the bottom three dials. In Figure 2, the user elected to see the next 32 minutes of the flight plan for Delta 3220.
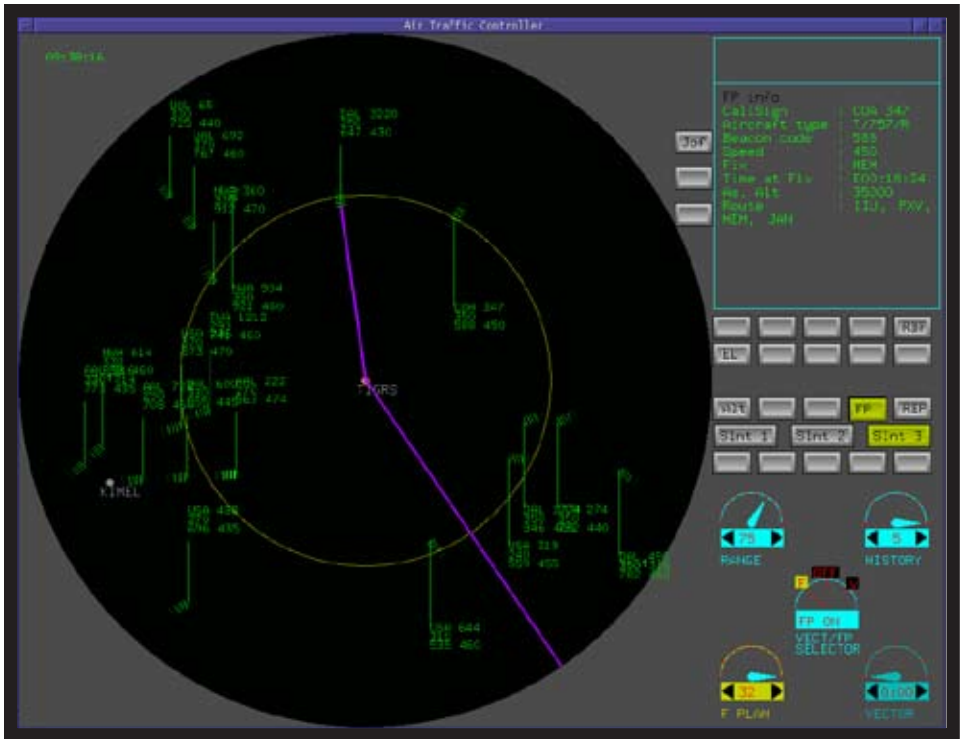

Figure 2. The DATIDS Air Traffic Control Display. The circular PVD shows a representation of flights in the sector with their data tags. The CRD in the box at upper right displays selected information about a specific flight. The ranks of buttons below the CRD are used to select the displayed information. Dials, at lower left, control the display on the PVD.

The Cockpit Workstation. With respect of the pilot position, DATIDS could be best described as a "mid-fidelity" simulation facility. It emulated only those controls and displays used in glass-cockpit aircraft to inform decisions about routing and (self-) separation and to execute flight maneuvers. The aircraft responded like a Boeing 757 with all the associated flight dynamics and response capacities. DATIDS did not emulate any of the controls used to sustain an aircraft in the air, e.g. fuel management, engines, etc. Three displays made up the cockpit workstation, (a) Primary Flight Display (PFD, Figure 3); (b) Cockpit display of traffic information (CDTI, Figure 4); and (c) Flight Management System (FMS) control screen and Multi-Control Display Unit (MCDU) panel.
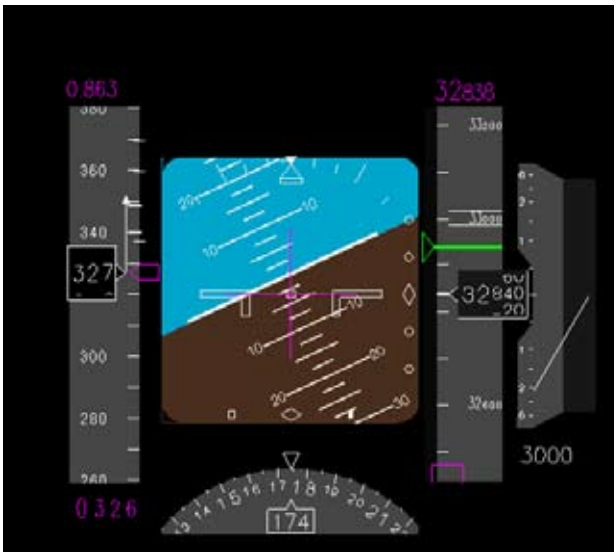
Figure 3. The Primary Flight Display. The portion of the compass rose at the base of the display shows the heading. The ladder at left shows the indicated airspeed in the present case is 327 knots. The ladder at right shows current altitude, being almost 33,000 ft. The pitch ladder in the center shows the horizon line and bank angle. The horizon, shown as the transition between blue and brown, indicates that the own-ship is very slightly nose down (since the magenta cross is below the horizon) and is banking to the right (at the angle shown by the solid white line on the horizon).

Figure 4. The Cockpit Display of Traffic Information (CDTI) used in the experiments supported by DATIDS. The illustration shows the ownership at the center of the display. The magenta line shows the own-ship's plotted path as derived

from its filed flight plan. As evident from the figures at the base of the display, the present altitude of the ownship is 29,000 ft. (flight level 290) with a speed of 272 knots. The information at the top indicates that the waypoint 'Lando' is approximately 4 minutes ahead. This fix is also shown on the central display area. In this version of the display, other aircraft were color-coded to reflect the severity of a potential violation of separation rules (5 nm horizontally and 2,000 feet vertically). Thus, the yellow data tags and aircraft symbols indicated that both Delta Air Lines (DAL 043) and American Airlines (AAL 333) are within a specified distance (which had been set by the experimenter). The use of a blue highlight for United Airlines (UAL 200) indicates a greater distance from its potential conflict with the ownship. Aircraft at a different altitude are not in potential conflict with the ownship and are represented in white.

Anticipating the arrival of ADSB communications, the radar screen of the CDTI displayed all the aircraft in its own (referred here as 'own-ship') vicinity within a pilot-selectable range. The PFD showed the aircraft's heading, pitch, roll, speed, and altitude. Piloting commands were entered on a FMS button pad (Honeywell MCDU). The FMS control screen echoed the command being entered. The participant pilot could request data about other aircraft through the FMS pad. These Data were then displayed on the FMS display. We have not illustrated the FMS here since it was a piece of standard operating equipment, used in its standard mode.

The "Pseudo Pilot" and Experimenter Workstation. The pseudo-pilot and experimenter's workstation, shown in Figure 5, was a simplified version of the cockpit workstation. It displayed a list of all aircraft in the simulation. When an aircraft was selected, its current altitude, speed, heading, and flight plan are displayed. The user could then issue heading deviations, speed alterations, altitude changes, and flight plan corrections just as a pilot could using the MCDU in the cockpit workstation(s).

Figure 5. The 'Pseudo-Pilot's' and Experimenter's Workstation enables real-time control of aircraft in the traffic scenarios. At left is a listing of all the aircraft in the scenario. Generally, only a subset of the aircraft on the list is present in the sec-

tor at any one time. The boxes along the top of the display are editing panels that echo the current operational data of the aircraft highlighted at left (i.e., AAL 222). Editing the data in these panels changes the operational parameters for the selected aircraft. The flight plan for the selected aircraft is shown below the heading, speed, and altitude panels. This window allows the 'pseudo-pilot' or experimenter to change the plan of any flight at any time during the scenario.

DATIDS Data Collection Capacities

The DATIDS server recorded and time stamped all the commands received from each workstation. After the completion of an experiment, the server could be employed in a "playback" mode using only the recorded commands as input. In playback mode, the server wrote to file the records of events that occurred during the session. The types of events recorded varied with the nature of the research. New data extraction and analysis routines were routinely developed, added, or changed, and implemented simply by modifying specific software modules and running in playback mode. As a result, any experimental session conducted previously could be used to test novel hypotheses. Information about participant behavior that was not reflected in aircraft performance was recorded at that participant's workstation. For example, ATC workstations recorded the dial settings selected by the participant for display on the PVD. Cockpit workstations recorded CDTI settings, range and view, and how long each respective screen remained in a setting. This construction was designed to capture the requisite data to facilitate analysis of pilot and controller strategies for free-flight operations.

Hardware Requirements

Hardware requirements for the second and subsequent versions of DATIDS included a server-client network of PCs with high-speed processors running Linux and connected by Ethernet. The graphical displays were programmed to run in the X11 Windows environment and use an OpenGL-compliant graphics library package. The X server used MetroLink's MetroX software. Some of the stations required more than one display. For each display monitor, a Matrox Millennia video card was required. The X server could then be configured to display on up to four monitors. Each computer also required an ISA Ethernet network adapter.

The mockup of the Boeing 757 cockpit contained three 640x480 VGA monitors, a Honeywell MCDU FMS keypad, and a dashboard with six buttons aligned vertically along the rightmost screen, three lighted buttons, and two rotary dials. The FMS pad, the buttons, and the dials on the dashboard were wired into the computer through an analog/digital input/output circuit board. The ATC workstations used one 17" or larger monitor and one trackball. The experimenter's workstation presented the ATC workstation on one monitor and the pseudo-pilot workstation on a second.

Findings Using DATIDS

The DATIDS simulation was used in a number of experiments investigating the decision making and maneuver selection by currently certified commercial airline pilots (e.g., Knecht, & Hancock, 1999; Murphy, Smith, & Hancock, 2004; Smith, Hancock, & Scallen, 1996; Smith, Scallen, Knecht, & Hancock, 1998). In

these experiments, the pilots exercised autonomous control of all decisions regarding routing and conflict avoidance with no assistance from air traffic control (and see Scallen, Smith, & Hancock, 1997). The exercise of autonomous control by pilots is an end-member of the continuum of operational concepts known as 'free flight' (Smith, Hancock & Scallen, 1996). One of the more remarkable findings that emerged from the DATIDS system concerned the timing of pilots' detection of potential conflicts with other aircraft. Here we present these previously unpublished results.

Experimental Participants

Ten highly experienced and currently certified commercial airline pilots (flight hours: mean 9,177, range 6,000 to 24,000; age: mean 51.9, range 38 to 63) volunteered to participate. Participants were certified to fly one or more of the following glass-cockpit aircraft types: Airbus 320, DC9/10, MD80/90, Boeing 474-400, 757, and 767. The pilots received instructions, signed an informed consent form, and became familiar with the DATIDS cockpit and its displays in a series of practice scenarios; afterwards, the pilots individually flew a series of twelve realistic but challenging en-route flight scenarios.

Experimental Design and Procedure

Pilots were instructed to maintain standard FAA aircraft separation (5 nm. horizontally and 1,000 feet vertically) between their aircraft and 6 to 16 other aircraft. They were free to make all decisions about routing and separation without the support or intervention of air traffic control. In all but 1 of the 12 scenarios, pilots encountered realistic but challenging traffic conditions including crossing traffic, merging traffic, and being overtaken by other traffic.

Table 1 shows the incomplete block design of the 12 En Route scenarios. The design manipulated (a) two dimensions of airspace complexity; (b) traffic count at three-distinct levels and; (c) relative bearing of traffic at five levels. Traffic count, a common metric of airspace complexity (e.g., Hopkin, 1980; Smith, Scallen, Knecht, & Hancock, 1998) was defined as the total number of aircraft within 150 km of the pilot's aircraft prior to and during the scheduled conflict. Relative bearing is defined with reference to the direction of flight of the pilot's aircraft. Thus, traffic with a relative bearing of 0° is flying in the same direction as the pilot and traffic with a relative bearing of 180° is approaching the pilot head-on. Roughly, half of the traffic with intermediate values of relative bearing approached from the left and half from the right.

Table 1
The manipulations of traffic count and relative bearing in the 12 en-route air traffic scenarios.

Traffic count	Relative bearing of conflicting traffic					No conflict
	0°	45°	90°	135°	180°	
6		X	X	X		
9	X	X	X	X	X	X
16		X	X	X		

In a series of shake-down flights, the pilot who volunteered to serve as our subject matter expert commented that the 0° values of relative bearing (being

overtaken) and 180° value (head-on collision at the same altitude) were unrealistic but challenging. To reduce the time participants would have to spend in the simulator, we retained only one instance of each of these bearings. The 11 conflict scenarios developed violations of minimum separation rules within 6 minutes if the pilot followed the preprogrammed flight plan. The twelfth scenario, a control condition, contained no scheduled conflict.

Pilots were asked to think aloud as they navigated through traffic in the En Route scenarios. Their concurrent verbal reports were recorded on a Dictaphone recorder with a Telex hands-free headset. Separation and relative velocity for each aircraft were calculated with respect to the pilot's aircraft and recorded at approximately 5 Hz throughout the scenario. A Sony 8 mm camcorder with audio input from the Telex system was used to record trials and add a time stamp for correlation of the verbal protocol and flight data. The verbal reports and videos were scored to determine when a pilot first indicated detection of an impending conflict (detection time). The target aircraft that motivated the pilot's conflict detection and subsequent action was determined by verbal recording and confirmed in subsequent computer playback of the session. The separation and relative velocity for each target aircraft at its detection time are the data used in the analysis.

Experimental Results
Grouping across participants and scenarios, the pilots were able to maintain the FAA separation criteria in 84 of the 110 conflict scenarios. In 28 of these 84, the pilot did not verbalize with sufficient clarity to identify the detection time or target unambiguously. Each circle in Figure 6 represents the separation and relative velocity between the pilot's aircraft and a target aircraft at its detection time for 1 of the 56 conflicts that were clearly detected and successfully resolved. The fuzziness of some circles reveals where data overlap. The relatively high percentage of successful resolutions (84/110 = 76%) reveals that the pilots were generally able to extract time-to-contract information from the flat-panel CDTI. The potentially troubling failure rate of 24% (26/110) only derives because these scenarios were purposed-developed to present such intense challenges that they might not be resolvable without augmented support (e.g., Knecht, 2007). The resolution rate in this experiment should not be interpreted as predictor of failure rates of self-separation in fully functional, free-flight conditions.
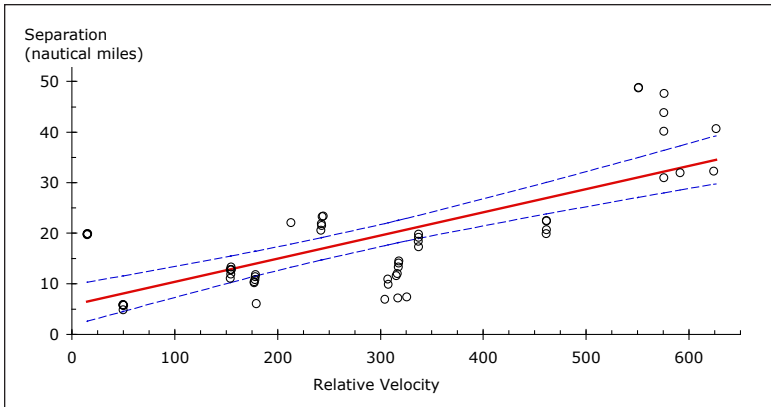
Figure 6. Pilot conflict detection times and least-squares linear regression analysis. Curves represent ±95% confidence interval for the regression line. Plotted points may overlap.

Figure 6 is a phase plane representation of en route air-traffic dynamics (Phatak & Bekey, 1969; Smith & Hancock, 1995). A phase plane is a state space in which one of the axes is the time derivative of the other (Jagacinski & Flach, 2003). In Figure 6, the vertical axis is separation, the distance between the locations of the pilot's aircraft and the target aircraft in nautical miles. The horizontal axis is its derivative, velocity in knots. Here, velocity is the relative velocity of the two aircraft, the sum of the components of their velocities in the direction of their separation. Points near the vertical axis represent conflicts in the overtaking scenario that unfolded slowly. Points at the far right represent conflicts with aircraft approaching nearly head-on and, accordingly, with high relative velocity. Points close to the horizontal axis represent conflicts that occurred within two minutes of the beginning of the scenario.

The data shown in Figure 6 are collapsed across the manipulations of traffic count and relative bearing. In spite of this diversity of conflict opportunity and the variation, which results from intrinsic individual differences, the data exhibit a significant linear trend. Least-squares linear regression defined a line with an intercept of 5.8 nautical miles and a slope of 0.046 hours = 2.75 minutes (r^2 = .52, n = 56). The 95% confidence interval for the line, shown with dashed curves in Figure 6, indicates that the Y-intercept is statistically indistinguishable from the 5-mile FAA criterion for minimum horizontal separation.

Discussion

In this experiment, the pilots were instructed to maintain standard FAA aircraft separation and were free to make all decisions about routing and separation. A necessary component of decision making about self-separation is the detection of impending potential conflicts. For the pilots in our experiment, the only source of this information was the flat panel CDTI of Figure 4. The critical information was the rate of closure of the gap separating the soon-to-be-coincident objects (the ownship and the target). These pilots were able to extract information about gap closure from the flat-panel display. Here, they did not rely upon the direct perception of the expanding optic array (Gibson, 1954, 1979; Lee, 1974, 1976); rather

they were able to extrapolate time-to-contact information from the representational display. However, the notion that time-to-contact information is critical in conflict avoidance is still preserved and represents the most remarkable outcome of this procedure. It is here as if the pilots have used a very primitive avoidance strategy, derived from terrestrial navigation, and transposed this self-same property into the representational space of commercial flight. This transposition of maneuvering strategy has extremely important implications for the design and operations of a national Airspace System predicated on distributed self-separation. This finding is consistent then with the proposition that pilots monitor gap variations as symbols representing traffic move across a flat-panel display. It further reveals a common linkage between ecological and information-processing based approaches to spatio-temporal navigation (and sees Hancock & Diaz, 2001). This result is but one example of how a comprehensive simulator facility such as DATIDS can encourage both pragmatic efforts in relation to practical objectives (e.g., free flight) and yet still invoke fundamental theoretical issues.

Acknowledgements

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