JOINT NASA AMES/LANGLEY EXPERIMENTAL EVALUATION OF INTEGRATED AIR/GROUND OPERATIONS FOR EN ROUTE FREE MANEUVERING

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Abstract

In order to meet the anticipated future demand for air travel, the National Aeronautics and Space Administration (NASA) is investigating a new concept of operations known as Distributed Air-Ground Traffic Management (DAG-TM). Under the *En Route Free Maneuvering* component of DAG-TM, appropriately equipped "autonomous" aircraft self separate from other autonomous aircraft and from "managed" aircraft that continue to fly under today's Instrument Flight Rules (IFR). Controllers provide separation services between IFR aircraft and assign traffic flow management constraints to all aircraft.

To address concept feasibility issues pertaining to integrated air/ground operations at various traffic levels, NASA Ames and Langley Research Centers conducted a joint human-in-the-loop experiment. Professional airline pilots and air traffic controllers flew a total of 16 scenarios under four conditions: mixed autonomous/managed operations at three traffic levels and a baseline all-managed condition at the lowest traffic level. These scenarios included en route flights and descents to a terminal area meter fix in airspace modeled after the Dallas Ft. Worth area.

Pilots of autonomous aircraft met controller assigned meter fix constraints with high success. Separation violations by subject pilots did not appear to vary with traffic level and were mainly attributable to software errors and procedural lapses. Controller workload was lower for mixed flight conditions, even at higher traffic levels. Pilot workload was deemed acceptable under all conditions. Controllers raised several safety concerns, most of which pertained to the occurrence of near-term conflicts between autonomous and managed aircraft. These issues are being addressed through better compatibility between air and ground systems and refinements to air and ground procedures.

Introduction

Background

Despite recent economic and security concerns, demand for air travel is already meeting or exceeding previous levels and is projected to increase further. In response to these demands, the National Aeronautics and Space Administration (NASA) is investigating a new concept of operations known as Distributed Air Ground Traffic Management (DAG-TM) [1].

One component of DAG-TM, *En Route Free Maneuvering*, represents a paradigm shift between a centralized ground-based system to a distributed system. DAG-TM has the goal of substantially improving capacity while maintaining or improving safety. Under this concept, flight crews of appropriately equipped "autonomous" aircraft fly under Autonomous Flight Rules (AFR). These aircraft are able to choose their own route and altitude, subject to maintaining separation from all other aircraft. Controllers continue to provide separation between "managed" aircraft unequipped for autonomous flight and traffic flow management services for all aircraft. En Route Free Maneuvering shares a common element with several other long-term operational concepts that call for delegation of some level of autonomy to flight crews, including those proposed by RTCA, Eurocontrol, and Boeing [2-4].

Over the past several years, NASA researchers have conducted several studies to investigate the feasibility and benefits of distributed separation responsibilities, focusing on both air and ground requirements [5-7]. As a continuation of this work, NASA Ames and Langley Research Centers conducted a joint human-in-the-loop experiment of integrated air-ground operations during the summer of 2004. This experiment investigated two key

features of the DAG-TM concept: mixed operations and scalability.

Experiment Motivation and Objectives

Mixed Operations

Under DAG-TM, AFR and Instrument Flight Rules (IFR) aircraft fly in the same airspace. Conducting mixed operations allows equitable airspace access to all users while providing benefits to those equipping for AFR. Concept feasibility requires that air and ground systems and procedures be able to accommodate this equipage mix.

Scalability

A primary anticipated benefit of DAG-TM En Route Free Maneuvering is its ability to substantially increase capacity without adversely affecting safety. Capacity is increased by adding autonomous aircraft while maintaining present levels of managed aircraft. In this way, each additional autonomous aircraft adds air traffic management capability to the system, thereby scaling capacity to meet demand.

Objectives

The experiment addressed the following research objectives:

- Investigate the safety and efficiency of mixed operations in high-traffic density sectors compared to operations with all managed aircraft.
- Investigate the ability to safely increase the number of total aircraft in a sector (beyond controller manageable levels) if the number of managed aircraft remains at or below current-day high-density levels.

Method

Simulation Facilities

The DAG-TM simulation environment was distributed across two NASA facilities and several laboratories as follows:

Langley Research Center:
- The Air Traffic Operations Laboratory (ATOL) housed 12 subject pilot workstations (including the Autonomous Operations Planner [8]) as well as the Traffic Manager system for handling multiple pseudo-piloted aircraft [9].

Ames Research Center:
- The Airspace Operations Laboratory (AOL) provided aircraft target generation and the Multi–Aircraft Control System (MACS), which supported controller workstations and multi-aircraft (pseudo-pilot) flight deck stations [10].
- The Flight Deck Display Research Laboratory (FDDRL) provided eight subject pilot workstations incorporating the three-dimensional Cockpit Display of Traffic Information (3D CDTI) [10-12].
- The Crew Vehicle Systems Research Facility housed the Advanced Concepts Flight Simulator (ACFS), a high fidelity full mission flight simulator that also provided the 3D CDTI on both map displays [10].

The Aeronautical Datalink and Radar Simulator (ADRS) served as the central hub for information exchange between pilot and controller facilities at Ames [10]. Data exchange between Ames and Langley occurred through the ADRS to Langley Gateway over a dedicated internet link. At Langley, information from the Gateway was distributed across a High Level Architecture and made available to all other components in the simulation.

Participants

Subject participants consisted of 5 professional controllers and 22 commercial airline pilots. Each of the four en route radar controllers was assigned to a single high or low altitude sector, with all positions located in the AOL (see airspace description in the next section). The fifth controller filled the role of a tracker, supporting the radar controllers during peak workload periods. All controllers had participated in several previous DAG-TM experiments conducted in the Ames AOL. Retired pseudo controllers monitored traffic within and assisted with handoffs to and from the adjoining "ghost" sectors.

All subject pilots at Ames and Langley were air transport rated and had glass cockpit experience. Twelve pilots were located in the Langley ATOL and operated the subject pilot workstations. They had never participated in a previous DAG-TM study. Eight other pilots were located in the Ames FDDRL and operated the single-aircraft MACS flight deck stations. Two additional pilots at Ames flew the ACFS as a captain and first officer pair. All Ames pilots had previously participated in DAG-TM experiments.

Non-airline pseudo-pilots at both centers monitored and interacted with the background aircraft in the simulation (those aircraft not flown by subject pilots). Pseudo pilots flying AFR aircraft used decision support tools to resolve traffic conflicts and

comply with traffic flow management constraints assigned by controllers. When flying IFR aircraft, pseudo-pilots implemented all controller instructions.

DAG-TM Airspace

The DAG-TM airspace (Figure 1) is a modified portion of the airspace in and around Dallas/Fort Worth (DFW) Air Route Traffic Control Center and DFW Terminal Radar Control (TRACON) facility. It was chosen and modified so that subject controllers could work continuous traffic streams from en route to final approach. The center's test area included three high altitude (Amarillo, Wichita Falls, and Ardmore) sectors and one low altitude (Bowie) sector. The merge point and TRACON boundary fix (BAMBE intersection) were within Bowie airspace.
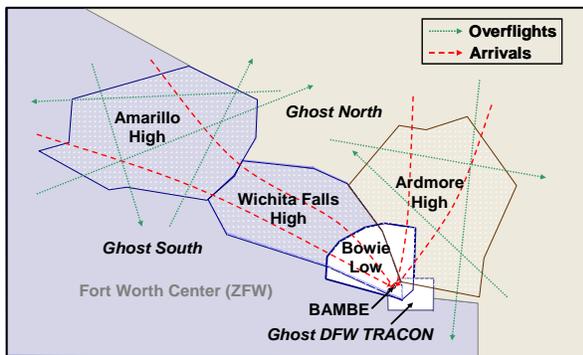

Figure 1. DAG-TM Airspace

Equipage and Flight Operations

Airborne Capabilities

Although Ames and Langley incorporated different aircraft simulations and flight deck decision support tools, all subject and pseudo-piloted aircraft at both centers had minimum capabilities consistent with their AFR or IFR status. All aircraft used Automatic Dependent Surveillance Broadcast (ADS-B) to exchange air-air and air-ground state and intent information. The centers employed two different ADS-B models. Langley aircraft broadcast target state information and up to four trajectory change points. Ames aircraft broadcast the entire flight plan. The Langley model incorporated several data link performance limits [13]. Controllers uploaded Required Times of Arrival (RTA) at the meter fix to AFR aircraft through Controller-Pilot Data Link Communications. AFR aircraft had airborne conflict management capabilities enabling self-separation and free maneuvering as well as the ability to meet assigned meter fix constraints.

Ground Capabilities

The meter fix arrival scheduler served a dual purpose. It prepared the traffic flow into the TRACON and provided slots for AFR aircraft to merge with IFR aircraft in an orderly manner. The scheduler automatically uplinked an RTA to each arriving AFR aircraft after it crossed the "freeze horizon" 160 NM from the meter fix. This RTA or a corresponding Scheduled Time of Arrival (STA) for IFR aircraft was held constant after this point. AFR aircraft were responsible for making necessary flight path changes to meet the RTA, whereas controllers issued speed and vector commands to IFR aircraft in order to meet the STA.

The ground stations incorporated conflict detection, using a 15-minute time horizon for IFR-IFR conflicts. As described previously, AFR aircraft were required to resolve all conflicts with IFR aircraft. Nonetheless, controllers were notified of IFR-AFR conflicts within 3 minutes of predicted separation loss as a safety back up. They were not required to act on this information nor were they alerted to AFR-AFR conflicts.

A trial planner allowed the controllers to determine the schedule impact and conflict status of proposed flight path changes for IFR aircraft.

Flight Operations

AFR pilots were required to maintain separation from all other aircraft and meet flow management constraints assigned by the controller. As in today's operations, controllers separated IFR aircraft from each other and provided traffic flow management services to all aircraft. Ames incorporated priority flight rules for AFR pilots [14].

In order to help prevent conflicts and minimize their impact, AFR aircraft had to comply with three maneuvering restrictions: 1) not maneuver in a way that would create a near-term conflict with another aircraft (within 4 minutes), 2) maneuver when in conflict with a managed aircraft, and 3) maneuver at least two minutes before a predicted separation loss. Similarly, controllers were not allowed to maneuver a managed aircraft such as to create a near-term conflict with an autonomous aircraft.

Experimental Design

The experiment investigated mixed operations and scalability issues by varying AFR/IFR traffic ratio and the total sector count. A "within-subjects" design was implemented for both pilots and controllers.

Figure 2 depicts the en route traffic load and equipage mix for each of the four experimental conditions (C1–C4). "T0" represents a traffic threshold that approximates the current-day monitor alert parameter for the simulated airspace. "T1" is a projected threshold above which managed-only operations cannot be achieved. T0 and T1 levels were determined in a prior controller-in-the-loop study at Ames. Traffic density increases were solely due to increases in overflight traffic. Arrival flows were kept at a constant, near-saturated level throughout the experiment.
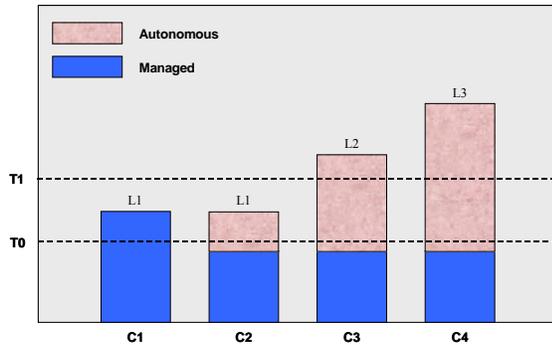
Figure 2. Experimental Design

Scenario Description

Each subject pilot scenario consisted of either an en route segment (level cruise across Amarillo or Ardmore sectors) or a descent to the terminal area meter fix (either through Amarillo and Wichita Falls or Ardmore). All aircraft were initialized with a flight plan and AFR pilots were asked to fly it unless it became necessary to resolve a conflict. Arrivals were given initial instructions to cross the BAMBE meter fix at 250 knots and 11,000 ft. AFR aircraft were also required to comply with the RTA issued when crossing the freeze horizon.

Subject pilots flew a total of 16 scenarios (two en route and two arrivals) per condition. As part of a separate investigation, half of the Langley subject pilot arrivals were conducted in a sector southeast of DFW airport. Therefore, each Langley pilot flew only one arrival in the subject controller sectors per condition. Pilots alternated between the Amarillo and Ardmore sectors. Scenario order and sector assignment were counterbalanced. All subject pilots flew as IFR aircraft for condition C1 and AFR aircraft for conditions C2-C4.

Due to differences in ADS-B models, airborne system requirements, and priority flight rules, subject pilots from Ames and Langley flew in different sectors and only interacted when arrival flights merged at the meter fix.

Scripted Conflicts for Langley Aircraft

To have a set of comparable conditions for analysis, carefully constructed conflicts were scripted in each scenario. This design allowed a focused assessment of key mixed operations and scalability performance metrics in a more repeatable and controlled environment. For each C1 scenario, six IFR-IFR conflicts were scripted for the subject controller to resolve (one per Langley subject-piloted IFR overflight). For each scenario in C2-C4, six AFR-IFR conflicts were scripted for subject pilots to resolve (one per Langley AFR overflight) in addition to one IFR-IFR conflict. The IFR-IFR conflicts in C2-C4 were included so that ground-resolved conflicts could be compared across traffic conditions in a similar manner as airborne-resolved conflicts.

The conflicts were all constructed using a similar geometry, with a co-altitude intruder converging at a 60-deg angle. In addition to globally scaling overflight traffic over an entire scenario, traffic was locally scaled in a structured manner around each scripted conflict via proximate but non-conflicting "flanking" aircraft. For C1 and C2 scenarios, one flanking aircraft was added at -1000 ft relative altitude. For C3, a second, opposite-direction aircraft was added at +1000 ft relative altitude. For C4, a third, co-altitude aircraft was added. Figure 3 shows the scripted conflict geometry. The flanking aircraft were IFR in C1 and AFR in C2-C4.
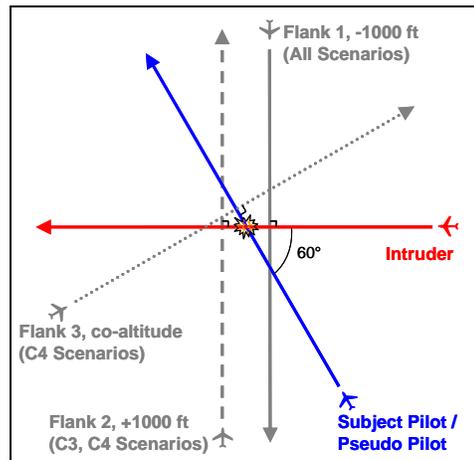

Figure 3. Scripted Conflict Geometry

Training

Pilots and controllers received 2 full days of training prior to running the data collection scenarios.

Training culminated with full mission scenarios conducted jointly between the two centers.

Performance Metrics and Data Analysis

Data collection focused on objective and subjective performance metrics related to concept feasibility in the areas of mixed operations and scalability. Primary objective metrics included the occurrence of separation violations (two aircraft closer than the minimum required spacing of 5 NM or 1000 ft) and conformance with assigned meter fix constraints (time (RTA or STA), altitude, and speed). Separation violations were only counted when they occurred in subject controller sectors and when the confederate controller did not contribute to the loss of separation (LOS). An aircraft was considered to "conform" to the meter fix constraints if it was within 15 seconds, 300 feet, and 10 knots of the assigned values. The three constraints were evaluated individually for each pilot. Subjective measures included pilot and controller workload and safety ratings for each run. Chi square analyses were performed on separation violation and meter fix conformance percentages.

Results and Discussion

Results are presented for Langley subject pilots, Ames subject pilots, and controllers. The two flight deck sections only include a discussion of subject pilot data for the indicated NASA Center. Because scripted conflicts were only conducted in sectors containing Langley subject pilots, ground-side scripted conflict results are presented in the Langley Flight Deck section.

Due to the system and experiment design differences described previously, results for each flight deck section should be evaluated on their own merit, without drawing performance comparisons between them.

Langley Flight Deck Results

Separation Violations

Separation violations for Langley subject-piloted aircraft as a function of flight rules type are shown in Figure 4.

Of the 13 total separation violations, 1 occurred between IFR-IFR aircraft, 10 between AFR-IFR aircraft, and 2 between two AFR aircraft. Six of the 13 separation violations occurred during C4. Three additional violations that occurred due to small simulation time discrepancies across the air/ground network were not included in this analysis.

Due to limited numbers in each category, a two-way chi square analysis was limited to the C3 and C4 conditions and AFR-IFR and AFR-AFR conflict types. This test revealed no significant differences between these traffic levels and operation types (X^2 (2) = 2.22, $p > .05$).
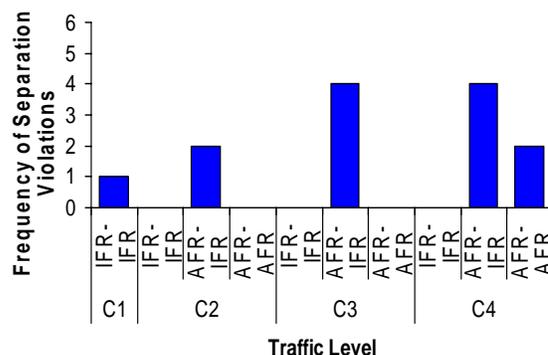

Figure 4. Langley Separation Violations by Condition

A detailed analysis was performed for each case to determine the likely contributing factors. Eleven out of the 13 cases were attributed to a "system" error. The most prominent of these errors was a software bug in the short-term, state-based conflict detection system that prevented short-term conflicts from being shown to the pilot until after the separation loss had occurred. This problem was the likely cause of six separation violations. Another problem included a known design problem where proposed tactical resolutions could exist within a displayed "no-fly" region, leaving the pilot with ambiguous guidance. A trajectory modeling discrepancy and Flight Management System (FMS) guidance problem rounded out the system issues.

Procedural or training problems were deemed to contribute to two violations. In both of these cases, a pilot maneuvered into a no-fly region. These maneuvers caused unrecoverable near-term conflicts and were in violation of AFR. Only one of the 13 events was partially attributable to an AFR "situation," defined to be a case where the system performed properly for the aircraft in question and the pilot followed proper procedures. Even on this case, a series of prior system errors helped create a difficult situation.

The lower occurrence of AFR-AFR separation violations (compared to AFR-IFR) suggests that pilots of other AFR aircraft used decision support

tools to recognize the impending conflict and take corrective action. Conversely, controllers were not asked to monitor AFR-IFR conflicts and they were de-emphasized on the ground displays.

Conformance

As described previously, the controller assigned a crossing time, altitude, and speed at the meter fix for each arriving aircraft. (En route overflight aircraft were not subject to constraints.) Figure 5 shows the percentage of Langley subject-piloted aircraft (across all arrival runs) that conformed with the time, altitude, and speed restrictions, respectively. These values only include arrival flights in subject controller sectors. For condition C1, the time reference was the STA when the aircraft crossed the freeze horizon.
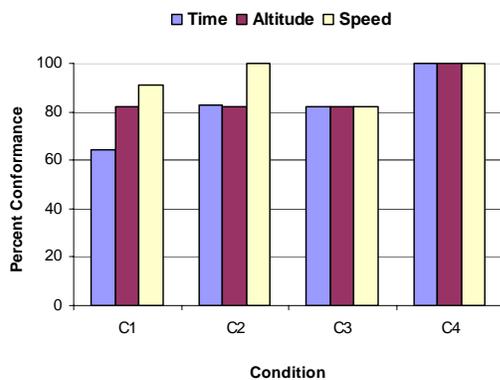
Figure 5. Langley Subject Pilot Meter Fix Conformance

Pilots were predominantly able to meet their assigned constraints and there does not appear to be a performance degradation as traffic level increases. Two of four RTA deviations for AFR runs were caused by the pilot entering the wrong RTA into the FMS. In one of these cases, the improper time entry led to a number of short term conflicts near the meter fix, and this pilot also deviated from the assigned altitude and speed restrictions.

Although there appears to be a slight trend toward better time conformance for AFR aircraft, this disparity may have been due to differences in controller procedures needed to accommodate different air/ground data link formats associated with Langley subject-piloted aircraft flying under IFR. These procedures were only needed under condition C1 (the only time these aircraft flew IFR.) Nonetheless, results from a chi square test indicated that no significant differences existed between the time conformance levels between C1 and C2 (X^2 (1)

= 1.15, p > .05), nor between C2, C3, and C4, (X^2 (2) = 2.18, p > .05).

Chi square tests performed on altitude and speed revealed no significant differences for mixed operations (C1 vs. C2) or scalability (C2 – C4).

After each AFR scenario (conditions C2, C3, and C4), pilots completed an arrival or en route questionnaire, as appropriate.

Scripted Conflicts

Sixty-nine of 72 AFR-IFR scripted conflicts occurred. While each aircraft trajectory was designed to be conflict-free until the scripted conflict, unpredictable traffic interactions prevented some conflicts from taking place. Objective data were used to assess the effects of traffic density on the following airborne performance measures: time before predicted LOS at which conflicts were resolved, the frequency of induced conflicts (defined as additional non-scripted conflicts caused by a resolution maneuver), and the frequency of conflicts requiring multiple maneuvers for resolution.

Mean times to predicted LOS when conflicts were resolved for subject pilot scripted AFR-IFR conflicts changed little as a function of traffic condition. The values were Mean (M) = 486 s, Standard Deviation (SD) = 87 s (C2); M = 473 s, SD = 97 s (C3); and M = 446 s, SD = 146 s (C4). A within-subjects ANOVA indicated that the slight decrease was not significant (F(2,22) = 0.82, p > 0.05). AOP provided a ten-minute conflict look-ahead time; under all traffic conditions tested, pilots were generally able to resolve conflicts before 5 minutes to LOS (at which time the AOP alerting level increased) and well before 2 minutes to LOS (minimum required time to commence maneuver).

Seven induced conflicts resulted from resolution maneuvers for AFR-IFR scripted conflicts. All of these occurred in C4. It is a concern that induced conflicts increased in the highest-density traffic condition, possibly indicating a reduction in system stability. However, it should be noted that all but one of these induced conflicts was caused by a manual maneuver, for which the pilot did not seek or use AOP resolution guidance. Thus, induced conflicts may be mitigated through more extensive pilot training and modifications to AFR procedures. Human factors issues have also been identified with the AOP conflict prevention tools, designed to alert pilots to potential conflicts along proposed manual maneuvers. For example, in the AOP version used in this experiment, computer limitations required the conflict prevention symbology to "time out" on the

aircraft displays, which occasionally masked the existence of potential conflicts.

Figure 6 shows, in each traffic condition, the percentage of AFR-IFR scripted conflicts that required multiple resolution maneuvers. While the rate of multiple resolutions increased slightly as traffic increased, a χ^2 test showed these differences were not significant ($\chi^2(2, N = 69) = 0.41, p > 0.05$). Improvements to AOP logic, such as the addition of spatial or temporal buffers for resolution maneuvers, may reduce the incidence of conflicts requiring multiple resolutions, especially near trajectory inflection points (such as top-of-descent) where aircraft dynamics are known to vary unpredictably. No such buffers were used for this experiment.
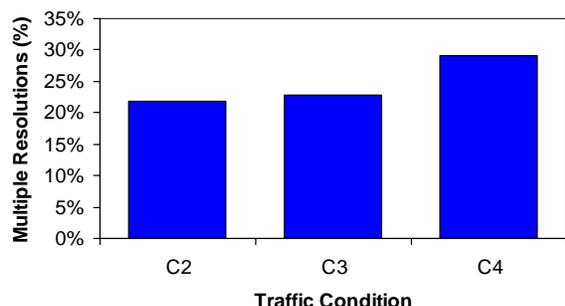
Figure 6. Conflicts Requiring Multiple Resolution Maneuvers (Pilot-Resolved Scripted Conflicts)

Overall, the AFR-IFR scripted conflict results support the hypothesis that airborne conflict resolution performance does not significantly degrade under high-density traffic conditions.

Thirty-one of 36 IFR-IFR scripted conflicts occurred. Due to the small number of data points in the mixed-operations scenarios (3 in C2, 3 in C3, and 2 in C4 vs. 23 at C1), statistical analyses were not performed on these data. However, using the same metrics previously presented for airborne-resolved scripted conflicts, the effects of mixed operations and traffic density on ground-side resolution performance can be qualitatively assessed.

Figure 7 shows a histogram of times to predicted LOS at conflict resolution for controller-resolved, IFR-IFR scripted conflicts in C2-C4. No consistent trend is observed across traffic conditions and resolution times are comparable to times in C1 (M = 490 s, SD = 111 s). Also, none of the IFR-IFR scripted conflicts required multiple resolution maneuvers, and no resolution maneuvers caused an induced conflict. Qualitatively, these results indicate that mixed operations (in C2) and increased AFR traffic (in C3-C4) had little effect on the ability of controllers to resolve IFR-IFR conflicts.

Pilot Questionnaires

Across all conditions, pilots overwhelmingly found that AFR flight operations did not adversely affect their workload. On a seven point scale ranging from 1 (completely acceptable) to 7 (completely unacceptable), average workload levels for overflights were 1.5, 1.5, and 2.3 for C2, C3, and C4 respectively. They were only slightly higher for arrival flights with means equal to 2.5, 2.2, and 2.4 for C2, C3, and C4 respectively.
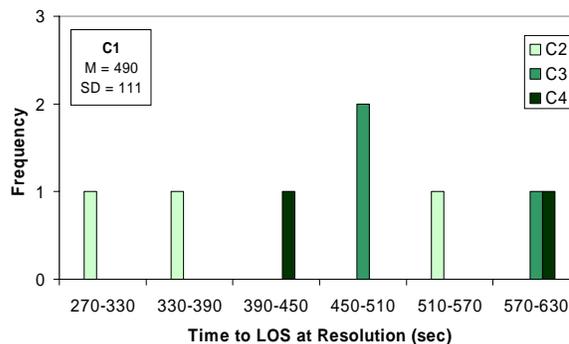
Figure 7. Time to LOS at Conflict Resolution (Controller-Resolved Scripted Conflicts)

Pilots also reported a high level of safety across all three AFR conditions. Traffic level and type of scenario (en route or arrival) had almost no effect on reported responses to this question. On a seven point scale ranging from 1 (completely unsafe) to 7 (completely safe), means were [C2, C3, C4] = [6.1, 6.4, 6.0] for overflights and [C2, C3, C4] = [6.1 6.3, 6.1] for arrivals. During the debriefing, most pilots expressed high confidence in AFR operations during en route flight, but some had reservations about implementing AFR during descent. Reliability of the AOP (for the version used during the experiment) and traffic congestion near the meter fix were cited as concerns.

Ames Flight Deck Results

Separation Violations

There were no LOS incidents for the Ames subject-piloted AFR aircraft. There were 139 conflicts resolved. Of these, 122 were detected prior to four minutes to conflict. Figure 8 shows 17 late alerts (less than four minutes to LOS). Consistent with the increased traffic load, the majority (11 late conflicts) occurred in the C4 condition. All 17 were due to an aircraft executing a maneuver which brought about the late alert. However, a maneuver by an Ames subject-piloted AFR aircraft was responsible for these late conflicts (concept violations) in only four instances. Furthermore, in

three of the four cases, a flaw occurred in the conflict resolution software (indicating to the pilot that the maneuver was conflict free, when it was not). The reason for the remaining apparent procedural error remains to be determined.
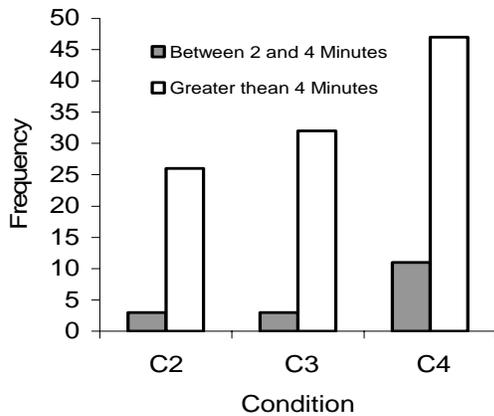

Figure 8. Number of Conflicts Detected vs. Time to LOS and Condition

Figure 9 shows a total of two conflicts with late resolutions (under two minutes to LOS), with one of them due to a software flaw in which the conflict detection did not function properly. The other instance was associated with the aforementioned incident where the pilot maneuvered into a conflict at some point between two and four minutes to LOS, with the result being that the pilot was not able to resolve the conflict until there was less than two minutes until the projected LOS.
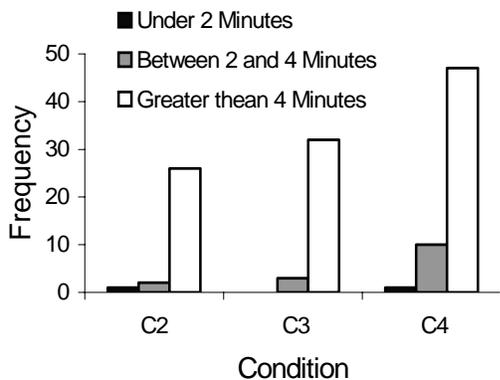
Figure 9. Number of Conflicts Resolved vs. Time to LOS and Condition

Figure 10 shows the amount of time needed to resolve burdened conflicts. While not an integral part of the concept, the Ames AFR pilots were asked

to resolve all burdened conflicts within two minutes (120 sec) of receiving a conflict alert. Figure 10 shows that this criterion was met approximately 89% of the time.
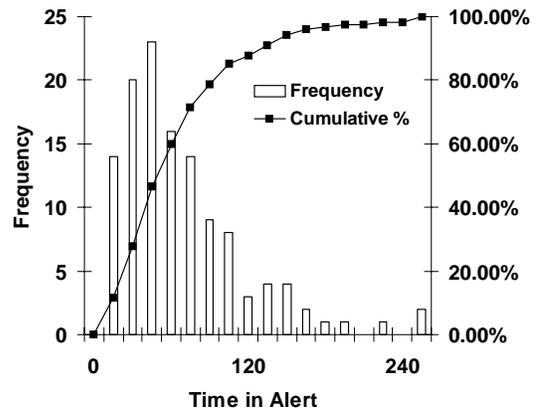

Figure 10. Distribution of Times Required to Resolve Burdened Conflict Alerts

Finally, Figure 11 shows the number of times the ownship and intruder resolved the conflict as a function of burdening [14]. While the IFR aircraft almost never resolved a conflict (it was never burdened), it is noteworthy that almost 1/3 of the non-burdened aircraft resolved the conflicts in AFR-AFR conflicts.
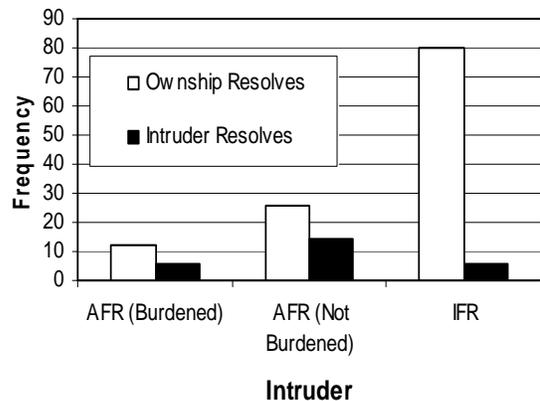

Figure 11. Number of Conflict Resolutions for Ownship and Intruder as a Function of Burdening

Conformance

Figure 12 shows Ames subject-pilot AFR meter fix conformance. There was no significant difference in objectively measured performance as a function of any of the conditions. Therefore, it does not appear that mixed operations, nor increased en route traffic

load had any effect on the ability of the arriving flights to meet the meter fix constraints. Among the AFR flights, one failed to meet the speed constraint, and one failed to meet the altitude constraint, but all met the RTA constraint.
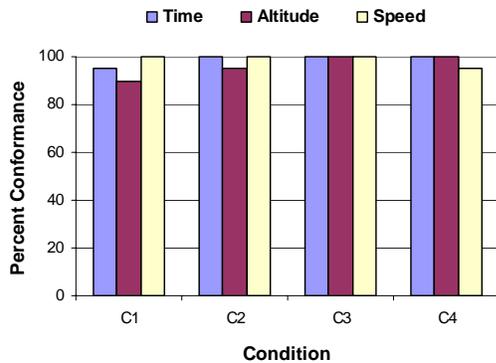

Figure 12. Ames Subject Pilot Meter Fix Conformance

Subjective Assessments
The subjective assessment of pilot workload was measured following each run using the Modified Cooper Harper (MCH) workload scale. The MCH allows for ratings between 1 (Very easy/workload insignificant) and 10 (Impossible/task abandoned, unable to apply sufficient effort). Pilot responses across all simulation trials ranged from 1 to 6. However, approximately 98 percent of responses ranged from 1 to 3. In order to receive a rating between 1 and 3, it must be possible to complete the task and workload must be perceived as tolerable and satisfactory. Ratings from 4 to 6 suggest that task workload is high but not high enough to impact performance on the primary task.

Figure 13 shows the average workload ratings of arrivals and overflights in each condition (±1 SD). Not surprisingly, workload ratings were higher for the arrival flights than for overflights in all conditions. Pilots also responded unanimously with the lowest possible workload rating (1) for the managed overflight runs (C1). In addition, Figure 13 shows an increase in perceived workload from all managed (C1) to mixed (C2-C4) operations for both flight types, but workload remained acceptably low.

At the completion of the simulation, pilots were asked to make preference comparisons between the AFR conditions (C2–C4) and the IFR condition (C1) on four different dimensions: overall safety, overall workload, ease of time conformance, and overall situation awareness.
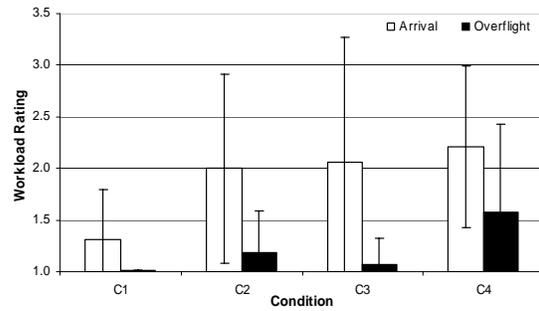

Figure 13. MCH Workload Ratings as a Function of Flight Phase and Condition

Pilot preferences for each question were analyzed using the Analytic Hierarchy Process (AHP) statistical technique [15], wherein the preference data for each question is transformed into a percentage and averaged for all pilots to produce numerical ranking scores. Pilots on average preferred the AFR conditions in terms of overall safety, ease of meeting the RTA/STA, and overall SA. Pilots preferred the IFR condition in terms of overall workload. The average ranking scores are presented in Figure 14.
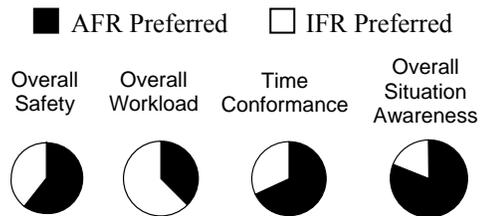

Figure 14. Ames Subject Pilot Rankings

Ground-Side and Controller Results
This section provides overall data for aircraft controlled by subject pilots (Ames and Langley) and those managed by subject controllers. Pseudo aircraft data are not included.

Separation Violations
Overall separation violations are shown in Figure 15. Although the number of violations increased gradually from C1–C4, it is difficult to generalize the results from this number because each violation resulted from a unique circumstance. Previous sections on the air side results summarized the circumstances that led to IFR-AFR and AFR-AFR violations. Six of the seven IFR-IFR separation violations were linked to a pseudo pilot error in

executing its clearance or a pseudo controller breaking procedures by handing off an aircraft in conflict to a subject controller. The absence of subject controller-caused separation violations suggests that the increasing traffic levels of AFR aircraft did not negatively impact their ability to separate IFR aircraft.
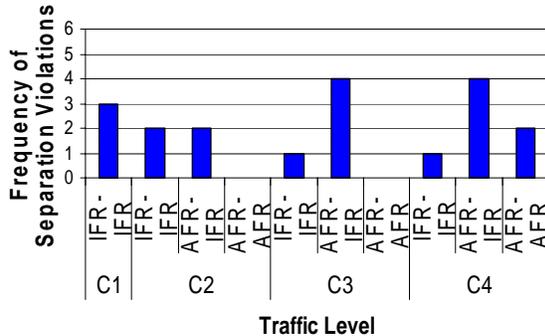

Figure 15. Overall Separation Violations

Conformance

Figure 16 provides the total number of time, altitude, and speed non-conformance events for arriving aircraft. The small difference in time deviations in C1 and C2 (6 and 2, respectively) suggest that mixed traffic had little effect on time conformance. Likewise, time deviation differences in C2, C3 and C4 (2, 4, 1, respectively) show no trend in the number of deviations as overflight traffic increased. Chi square tests revealed that none of these differences were significant.
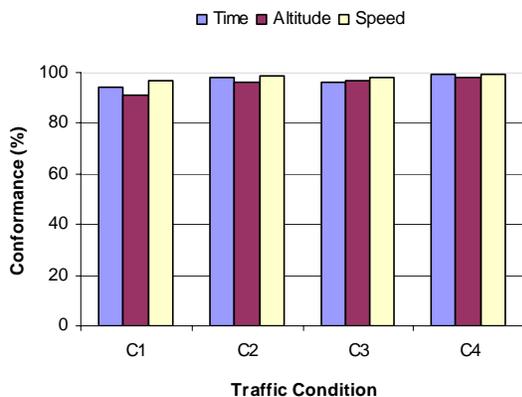

Figure 16. Overall Meter Fix Conformance

IFR aircraft were equally likely to conform to the crossing restrictions regardless of whether or not autonomous aircraft were in the arrival flow. These results suggest that mixed operations did not hinder traffic flow management of arrival flights.

The additional AFR traffic in C3 and C4 were all overflights, therefore the impact of scalability on arrival conformance was expected to be minimal if interactions between arrivals and AFR overflights were negligible. The results revealed that arrival conformance was not significantly affected by the scaled overflight traffic. Time, speed, and altitude restrictions were met with regularity across conditions, suggesting that controllers and AFR pilots were able to handle any extra maneuvering caused by AFR overflights.

Controller Workload Assessment

Controller workload is one of the key metrics to examine the potential benefits of En Route Free Maneuvering. It is presumed that controller workload is a key limiting factor to the number of aircraft that can safely be managed for a given sector. One hypothesis for this study is that offloading the separation responsibilities to AFR aircraft has the potential to increase the overall aircraft count beyond what controllers could manage if all flights were IFR.

Subjective workload assessments were collected from controllers using the Air Traffic Workload Input Technique [16]. Controllers were asked to rate their workload using Workload Assessment Keyboards on a scale of 1 to 7, at 5-minute intervals throughout each simulation run.

Figure 17 presents the average workload rating for each of the four controllers in each experimental condition ($\pm$ 1 standard deviation). The small number of data points (4) in each condition prevents us from determining if the differences between conditions are significant. However, a visual inspection of the graph indicates that for each controller, workload ratings were the highest in C1. The higher average workload in C1, as compared to C2, suggests that the presence of AFR flights did not negatively impact perceived workload.

The ratings in C2, C3 and C4 reflect the influence of increasing traffic through the addition of AFR overflights. It was expected that no appreciable difference would exist in the Bowie sector because no overflights were present in that sector. Workload ratings in C2, C3, and C4 for the Amarillo and Ardmore controllers showed a slight increase. However, all average workload ratings were under four, indicating that increased workload was quite modest. This observation is particularly interesting because the volumes of traffic presented in C3 and C4 were considered not to be manageable under all-managed operations. For example, total aircraft count in C4 was approximately double the count in C1 and C2, and yet the workload was lower in C4

than C1. This finding supports the hypothesis that controllers can handle much larger volumes of traffic than in current day operations if additional traffic consists mostly of AFR flights. However, the lack of workload differences does not suggest that the increase in overflights did not adversely impact controllers, as there were a number of safety issues and concerns, which will be described in the next section.
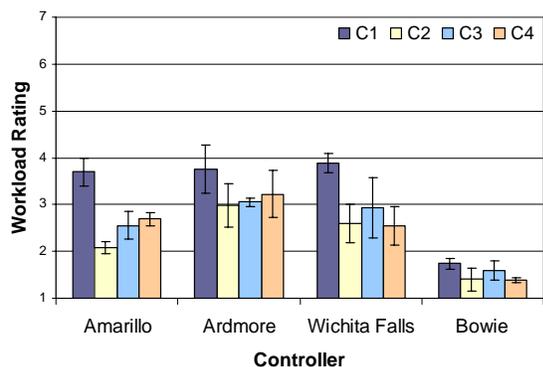

Figure 17. Average Controller Workload Ratings

Controller Safety Assessment

The controller participants were asked to make pairwise preference comparisons between all possible pairs of simulation conditions with respect to overall safety. These comparisons were analyzed using AHP to determine a ranking for each condition. Figure 18 summarizes the safety rank scores of condition by each controller position. The data show that ranking the four conditions from most to least safe, the controllers consistently ranked the all managed condition (C1) as the safest and the L3-mixed condition (C4) as the least safe.
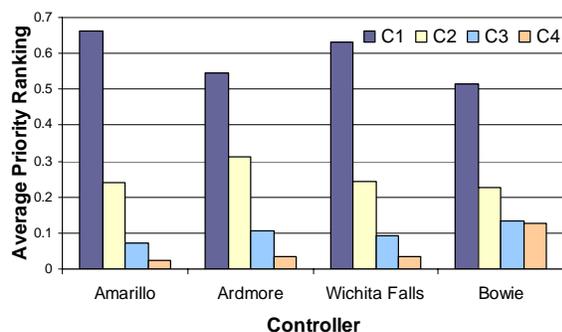

Figure 18. Average Controller Safety Assessment

The most common concern raised pertained to AFR-IFR conflicts. Although conflicts and separation violations between AFR and IFR aircraft changed little across traffic levels for the subject pilots, these events increased dramatically for pseudo pilots under condition C4. As discussed previously, controllers were notified of AFR-IFR near-term conflicts within 3 minutes of predicted separation loss.

In general, controllers felt that AFR-IFR conflicts posed a safety problem because 1) AFR aircraft did not always resolve conflicts in a timely manner, 2) it was not always apparent that the AFR aircraft was taking action, and 3) it was not always clear what the AFR aircraft would do.

Although controllers had been briefed that resolution of AFR-IFR conflicts was not their responsibility at any time, they often felt compelled to act when presented with a short-term conflict that had not been resolved. This mindset left controllers short-handed, due to the lack of available maneuver intentions from the AFR aircraft and the need to suddenly become involved in a situation to which they had previously paid little attention.

These issues highlight the importance of clear and unambiguous procedures for both pilots and controllers when handling short-term AFR-IFR conflicts. If resolution responsibility is to be shared between the pilot and controller under these situations, then some level of air and ground system compatibility is required. Alternatively, if responsibility is to remain solely with the AFR pilot, then the decision to alert the controller to these conflicts should be re-visited.

Additional issues raised by controllers include the need for procedures that handle failures of AFR conflict management capabilities. Controllers also had some concern about their ability to maneuver IFR aircraft in the presence of additional AFR aircraft. Scripted conflict analysis suggests that AFR aircraft did not affect a controller's ability to separate IFR traffic.

Conclusions

The DAG-TM concept element of free maneuvering has great potential to increase en route and transition airspace capacity, provided that safety concerns raised by controllers can be addressed. This large scale, high fidelity experiment with pilots and controllers has indicated that many autonomous aircraft can be added to a moderately high number of managed aircraft in the same airspace without increasing controller workload, while maintaining flight crew workload at acceptable levels. Comparable controller workload benefits associated with some level of aircraft self-separation have also been reported by NLR and Eurocontrol [17-18]. In this study, controller workload appeared to correlate

primarily to the number of managed aircraft, whereas the number of autonomous aircraft in the airspace had far less impact. Mixed operations provided equivalently efficient arrival flows as managed operations, suggesting that time-based traffic management constraints are an effective way to coordinate managed and autonomous flights from mixed into managed airspace.

The experiment has also demonstrated that a well-integrated and compatible set of advanced air/ground automation and well-defined procedures will be required to enable the capacity gains without compromising safety. Separation losses, close calls, and late and false alerts encountered, especially between managed and autonomous aircraft, prompted controllers to rate mixed operations much less safe than managed operations. In most of the safety compromising instances, controllers were aware of an upcoming problem but unable to determine the flight crew's intention based on the data linked information or via a voice inquiry. Inadequate air/ground system and procedural compatibility concerning short-term managed/autonomous conflicts resulted in uncoordinated maneuvers and potential safety hazards. Pseudo pilot ability to effectively maneuver increased numbers of pseudo aircraft at higher traffic levels may also have played a role. Controllers' safety concerns increased with the number of autonomous aircraft in the airspace.

Many pilots were able to maintain safe separation at all times and meet their traffic flow constraints precisely. In general, pilots did not share controllers' safety concerns regarding autonomous operations and reported that they felt comfortable managing separation and air traffic constraints with appropriate airborne automation and information on the other traffic in the airspace. Pilots and controllers reported that the all managed condition simulating advanced trajectory-based operations with data link was safe and would be greatly preferable to current day operations.

Distributing roles and responsibilities between pilots and controllers has the potential to greatly increase airspace capacity. In order to realize these benefits, the following key areas will be considered for follow-on research:

- Harmonization of trajectory specifications and processing among all air and ground system components.
- Further investigation of the value of strategic conflict resolutions that avoid short-term conflicts.

- Development of compatible conflict detection and resolution algorithms between air and ground systems when short-term conflicts appear between AFR and IFR aircraft.
- Definition of clear procedures for autonomous/managed aircraft interactions and for transitions from autonomous to managed status and vice versa.
- Investigation of system failures in the operational environment.

Results of this and follow-on studies, as well as efforts to gain operational experience with key enabling air and ground technologies will help enable progression toward eventual concept implementation.

Acknowledgments

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DAG-TM, free flight, capacity, separation assurance, air/ground

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