DECISION SUPPORT TOOLS FOR CLIMBING DEPARTURE AIRCRAFT THROUGH ARRIVAL AIRSPACE

Eric Chevalley, San Jose State University / NASA Ames Research Center, Moffett Field, CA
Bonny Parke, Paul Lee, Faisal Omar, Hyo-Sang Yoo, Joshua Kraut, Daphne Rein-Weston, Nancy Bienert, Kari Gonter, San Jose State University / NASA Ames Research Center, Moffett Field, CA

Everett Palmer, NASA Ames Research Center, Moffett Field, CA

Abstract

In 2013, Chevalley, et al., presented a concept of shared airspace where departures fly across arrival flows, provided gaps are available in these flows. They explored solutions for separating departures temporally from arrival traffic. Arrival controllers were responsible for deciding whether to climb departures through gaps, based on the departure aircrafts' trajectory and on the estimated flying time across the arrival flow. It was found that aircraft climb efficiency increased with more accurate departure time from the runway. Although in this earlier simulation, workload, coordination, and safety were judged by controllers as acceptable, it appeared that controllers would need improved tools to support this procedure.

In the current follow-up study, decision support tools were developed to help controllers decide whether it was safe to climb aircraft through gaps in the arrival flow. In all three tool conditions, controllers could refer to a timeline to show how close in time the departures were predicted to be to the arrivals. In two of the conditions, controller could either see tie-points on videomaps, or could use a conflict probe to assess the separation of arrivals and departures dynamically.

The tools were tested in a Human-In-The-Loop simulation. The efficiency and safety of 144 departures from the San Jose airport (SJC) climbing across the arrival airspace of the Oakland and San Francisco arrival flows were assessed. The simulation replicated the airspace and the manipulation of the accuracy of departure release times as reported in Chevalley et al. (2013) but used different aircraft climb profiles.

Results show that again aircraft climb efficiency improved with departure time accuracy. Additional tools, such as the tie-points and the conflict probe, helped controllers make decisions to climb aircraft. In most cases, the tools helped controllers to keep aircraft vertically separated. For example, the tools helped controllers keep aircraft at safe altitudes longer when aircraft departed outside of their scheduled time. However, the tools did not prevent losses of separation. Seven losses of separation took place. Four of those were just below the required separation standards.

This paper presents problems involved in predicting separation, and with controllers using anticipated separation to make decisions. New procedures and more precise tools are needed to limit the use of anticipated separation and to give options to controllers to climb aircraft safely.

Introduction

Today in terminal environments, arrival and departure flows are segregated and assigned to distinct arrival and departure sectors. This spatial segregation avoids interactions by separating flows of traffic procedurally. This results in safe but sometime inefficient routes. Inefficient routes are found in metroplex environments, where interdependent flows of traffic share common waypoints, paths or airspace volumes [1].

As an alternative to altitude separation, temporal lateral separation has been proposed to coordinate the use of common resources [2, 3, 4]. Today, temporal separation is used to manage choke points, such as merging traffic or intersecting runways. To run temporal separation efficiently, precision in timing is required. To this effect, scheduling technology can be used to anticipate high volume of demand as well as conflicting demand.

The Airspace System Project at NASA Ames Research Center develops scheduling and automation technologies for complex operational choke points in metroplex airspace. One objective has been the optimization of scheduling for arrival and departure operations. Modeling studies from NASA Ames have shown that the use of hybrid spatial and temporal separation supports more efficient routes in the metroplex environment [3, 4].

Previous Study

In the Sharing of Airspace Resources (SOAR) concept, Chevalley, et al (2103), used scheduling to coordinate the demand of both arrivals and departures over common waypoints (crossing fixes) in a simulated shared airspace of the San Francisco metroplex terminal area. In that study, 96 SJC departures used a more efficient route that crossed two arrival flows (to Oakland and San Francisco) at crossing fixes, instead of flying a 360 degree turn above the SJC airport and flying well above the arrival flows. The departures were filed on a REDDT1 Standard Instrument Departure route (SID) that flew under both arrival flows at 5,000ft. The arrivals crossed the crossing fixes at 7,000ft (at HEIDE) and 6,000ft (at REDDT) respectively. Both fixes were located less than 5nm away from each another. The arrival controller had control of the departures after takeoff and had the opportunity to lift the altitude restriction to let the departure climb higher provided there was no arrival traffic through the arrival airspace. The shared airspace, the route and the coordination procedure are described in [2].

In the previous study, both arrivals and departures were scheduled. Arrivals were scheduled to the runway. Controllers used the Controller Managed Spacing (CMS) tools developed in the Airspace Operation Laboratory (AOL) to manage time conformance [2, 5]. Departures were scheduled to take off at a time that would allow them to cross an arrival fix inside gaps in an arrival flow. An average nominal flying time to the arrival fix was calculated so that departure time slots could be displayed on a runway timeline. These slots corresponded to gaps in the arrival flow. A tower Traffic Management Unit (TMU) confederate scheduled departures into time slots, following the function and concept of the Departure Flow Management (DFM) tool [6]. A DFM tool allows a tower TMU to assign departures to departure slots on a runway timeline. These slots correspond to time slots available at a departure fix. In DFM, a center TMU manages available slots, as well as approves or rejects slots that the tower TMU picked. In the SOAR study, the slots corresponded to gaps in the crossing fix of the departure and the arrival flows and the approval process was automatic.

In the previous study, ownership of departure aircraft varied between the departure and the arrival sectors; the accuracy of the takeoff time was also manipulated. Half of the aircraft took off on time to fly across inter-arrival gaps with enough lateral spacing from arrivals to be cleared to climb. The other half took off outside of the matching gap. The results showed that the more accurate the departure times were, the earlier controllers were able to climb aircraft across the two arrival flows. The results also showed that controllers gradually vectored departures opportunistically across the first arrival flow to climb aircraft above the second arrival flow. Only in two instances did controllers keep a departure at level altitude under both arrival flows.

Controllers relied on the good climb performance of the departure aircraft to climb above arrivals. They knew that the earlier the aircraft were cleared to climb, the higher the departures would fly above the arrival traffic. For this reason, at times, controllers would vector aircraft away from arrivals in the first arrival flow and then would climb aircraft to fly above the second arrival flow. In most cases, however, controllers kept departures on their route below the first arrival flow but then expedited aircraft to climb above arrivals on the second flow. Because of the close proximity of the two crossing fixes (less than 5nm), such a decision did not guarantee a safe operation.

Current Study

In this study, our goal was twofold: 1) replicate the main results of the first SOAR study, 2) provide controllers with decision support tools to assess separation in shared airspace operations.

We replicated the SOAR concept used in Chevalley, et al. [2], except we modified the departure route and provided decision support tools to controllers. The departure route was modified to have a more direct path to the departure fix and a wider crossing angle (45°) with the arrival routes, as shown in Figure 1. This would allow controllers to use the diverging separation rule between the arrival and the departure aircraft. The new route crosses the SFO arrivals at HEIDE, and then at REDDT, which was moved to the left. In this simulation we did not allow controllers to vector aircraft off the routes, unless it was necessary to avoid a loss of separation. The purpose was to assess the use of new tools for established procedures.

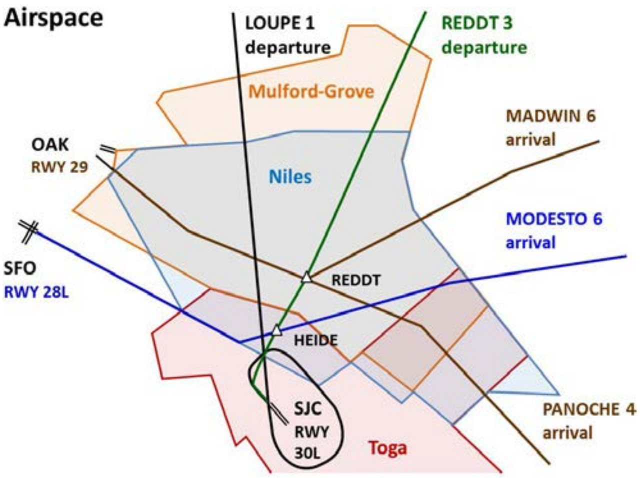

Figure 1. Routes and Sectors in SOAR2

In this simulation, we also varied the aircraft fleet mix and climb performance as well as the departures' takeoff time accuracy (see Method section). Most importantly, we developed tools to support controllers' decisions.

Decision Support Tools

Three decision support tools were used by controllers during this study. The purpose of the tools was to help controllers assess whether there would be adequate lateral separation between arrivals and departures at the crossing fixes, thus helping them to decide when to climb departures to a higher altitude.

Timelines

The first tool was a timeline for each crossing fix, HEIDE and REDDT, as shown in Figure 2. Timelines are part of the scheduling tools developed in Multi-Aircraft Control System (MACS) software [5] used for the simulation. The timeline displayed a flight plan Estimated Time of Arrival (ETA), as well as a nominal ETA of aircraft at the fix. These two times depict a relative position of an aircraft to a fix and are computed by MACS. The Flight Plan ETA is the predicted time the aircraft will reach the fix given the trajectory it is flying, its altitude, speed constraints, and forecast winds. The Nominal ETA is a time the aircraft would need to cross in order to meet the Scheduled Time of Arrival (STA) at a downstream fix, given the trajectory the aircraft is on.

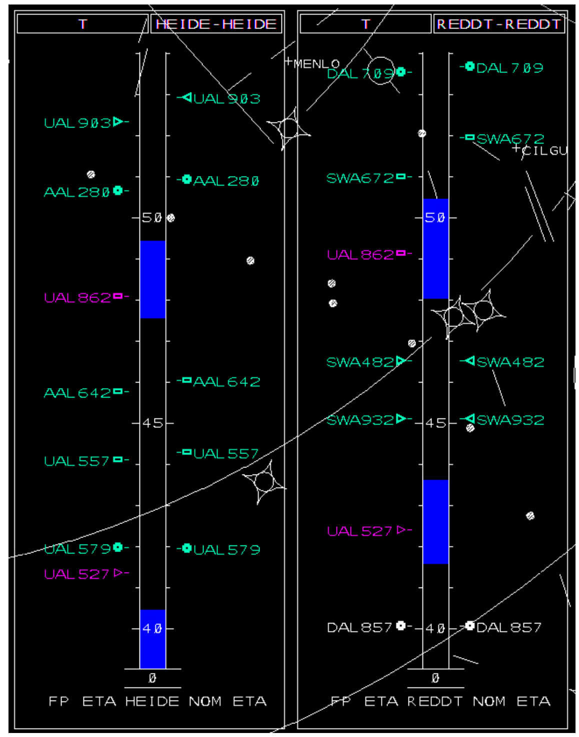

Figure 2. Timelines at Crossing Fixes

In this study, both arrival and departures had a scheduled time at the runways (OAK, SFO for arrivals and SJC for departures). The difference between an arrival ETA and its nominal ETA indicated how early or late the arrival was. It corresponded to the slot marker controllers used to control the time conformance of the aircraft when using the CMS tools. No nominal ETA was displayed on the crossing fix for departures. However, the nominal flying time was used to compute the time at the crossing fix onto the runway timeline at SJC.

The arrivals' ETAs and nominal ETAs were displayed in green, and the departures' ETAs in magenta. The timelines also displayed the time slots, or gaps (in blue), that the departures were expected to cross. For example, Figure 2 shows that United 527, a departure, is expected to cross HEIDE approximately 30 seconds before United 579, an arrival. The same United departure is expected to cross REDDT 2.5min after Delta 957 and 2.5min before Southwest 932, both arrivals.

Tie-boxes

In addition to timelines, we developed a static tool that featured tie-points on a videomap, called tie-boxes. Videomaps are used on TRACON sector radar scopes to provide background information to controllers. They typically display landmarks, such as sector boundaries, obstacles, route crossings, localizers, etc. We used the videomap provided currently in Norcal TRACON and added HEIDE and REDDT crossing fixes, as well as Tie-boxes (See Figure 3).

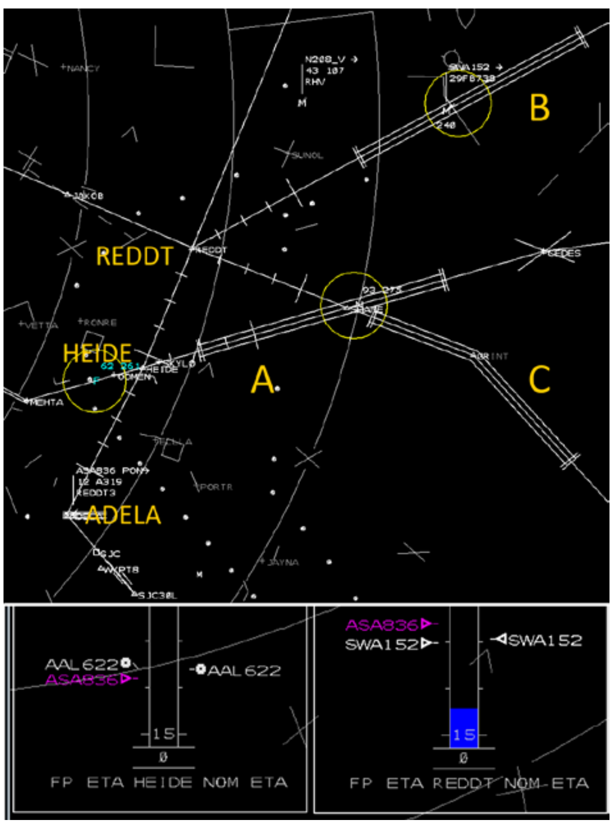

Figure 3. Videomap with Tie-boxes

The tie-boxes (A, B, & C) show the portion of the route where arrivals would be less than 4nm from the departures at HEIDE and at REDDT, when the departure is flying by ADELA (the reference point). The front of a tie-box shows when the arrival would pass the crossing fix 4nm in front of the departure. The end of the tie-box refers to when the departure passes the crossing fix at least 4nm in front of the arrival. The locations of the tie-boxes were based on average flying times of arrivals and departures.

The procedure for the controllers was to check to see whether there were any arrival aircraft inside the tie-boxes when a departure flew by ADELA. If there were, then the controllers were advised to keep aircraft at a level altitude. In the example in Figure 3, a departure is at ADELA, and 2 arrivals are inside 2 tie-boxes on the arrival routes to HEIDE and REDDT. On the timelines, both pairs of aircraft are estimated to cross the fixes less than 30sec away from each other.

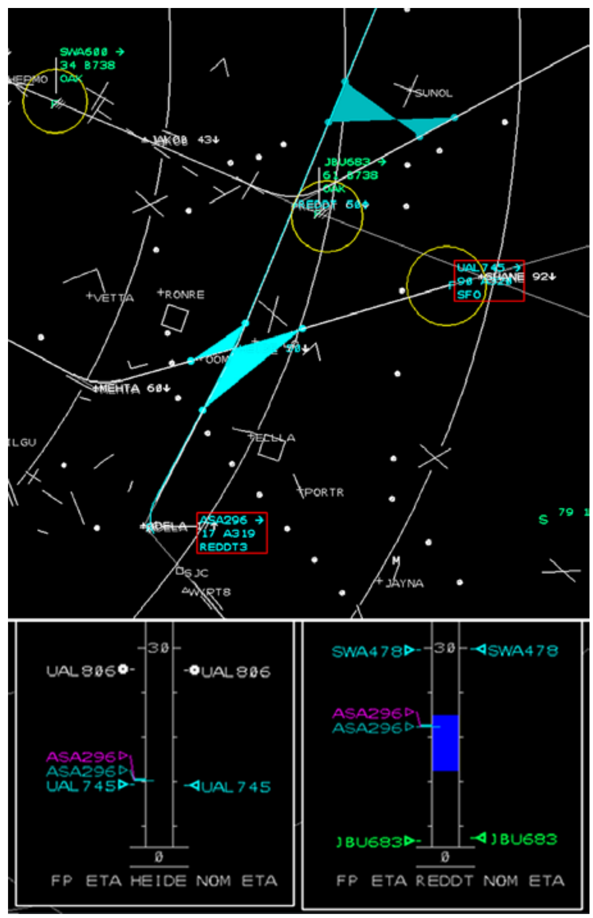

Figure 4. Conflict Probe Tool

Conflict Probe

The conflict probe is a dynamic tool based on far-term conflict detection automation for en-route controllers developed by the Airspace Operations Laboratory [7]. We adapted a semi-automatic version, where controllers could use the conflict probe to see any potential conflict for any given aircraft at any point. The tool indicated all other aircraft that were predicted to get closer than 4nm and/or 1,700ft from each other, based on their flight plan trajectory. The conflicting call signs would then be indicated with a red frame. We used the trial-planning trajectory function of the conflict probe tool; this function displayed the predicted tie-points along the route of any conflicting trajectories, as shown in Figure 4.

In Figure 4, Alaska 296, a departure, is predicted to loose 4nm or 1,700ft separation with United 745, an arrival. The webbing of the tie-points shows that the loss would happen before and after HEIDE. Another tie is predicted to take place with an arrival when the departure has passed REDDT. In this case, the controllers could use the diverging separation rule and ignore that conflict.

Controllers can apply the diverging separation rule to aircraft that are on crossing headings with an angular difference of at least 15 degrees. Aircraft on converging courses need to maintain standard separation (3nm and 1,000ft in TRACON airspace), but as soon as one aircraft has crossed directly in front of the other, they are said to be diverging and the standard separation can be discontinued (Section 5-5-7 in FAA Order 7110.65V [8]).

The conflict probe did not make any distinction between converging or diverging headings.

Method

We ran the study in a high fidelity Human-in-the-Loop simulation at the AOL using MACS software [9].

Participants

Seven retired controllers, with an average of 26 years of experience in TRACON airspace, staffed seven sectors. They had been retired for an average of 5 years. The three most recently retired controllers rotated through Niles, Mulford and Sunol arrival sectors. Three other controllers staffed the Toga sector (SJC departures), Richmond sector (SFO, OAK and SJC departures) and a Final sector (both SFO and OAK final approaches). The seventh controller conditioned arrival traffic in a ghost airspace that surrounded the test sectors. One researcher was a confederate and acted as a local controller at SJC Tower. Six pseudo-pilots supported the operations. Each pseudo-pilot was responsible for flying multiple aircraft within one sector. All pilots were students from the Aviation Department at San Jose State University.

Experimental Design

One hundred and forty-four departures were tested in a 3x3x2x(x4x2) full factorial experimental design of 18 runs. Each of the following parameters was fully crossed: tool (timeline only vs. timeline + tie-boxes vs. timeline + conflict probe), three controllers, two coordination conditions (point-out vs. pre-arranged), takeoff time accuracy (four positions related to the departure slots) repeated in each run, and two gaps (REDDT only vs. REDDT & HEIDE), repeated in each run.

Tools

Three tools were designed to help controllers assess separation of arrival and departure aircraft at the crossing fixes. Each tool was used in a third of the runs and crossed with all other conditions. The tools were used in the following manner:

1. **Timeline**: Controllers had a timeline for each crossing fix on their scope.

2. **Tie-boxes**: Controllers had tie-boxes displayed on their scope, in addition to the timelines for the crossing fixes.

3. **Conflict probe**: Controllers could use the conflict probe to assess potential conflicts, in addition to the timelines for the crossing fixes.

The controllers were requested to use the tools to help assess the position of the aircraft. We hypothesized that the conflict probe would provide more accurate support to controllers than the tie-boxes and timelines. Tie-boxes and timelines, in turn, would provide better support than timelines alone.

Controllers

Three experienced TRACON controllers rotated through the following arrival sectors throughout the simulation:

1. **Mulford**: This sector controls two Oakland arrivals flows and surrounding traffic. The Mulford controller made the decision to climb the departures through the arrival flows. Mulford coordinated departures with Niles.

2. **Niles**: This sector controls the Modesto arrivals to San Francisco, and is above the Mulford sector.

3. **Sunol**: This sector controls both the Oakland and San Francisco arrival flows, and hands off control of arrivals to Mulford and Niles, respectively.

Our intent was to assess whether the rotating controllers would use the tools differently.

Coordination

Mulford had to coordinate with Niles to have the authorization to climb aircraft in Niles' airspace, which is on top of Mulford's airspace. Two types of coordination were tested. Controllers either followed a point-out or a pre-arranged coordination procedure. This aspect of the study is presented in Parke, et al. [10] in this conference.

Takeoff Time Accuracy

We replicated the manipulation of the departure accuracy of our first SOAR study [2]. The purpose for this manipulation was to release departures at predicted times from arrivals at REDDT and test its impact on controllers' decisions. To that effect, a tower confederate scheduled the departure release times using a departure runway timeline that displayed relative gaps in the arrival flow. These gaps were back-propagated from the crossing fix to the runway timeline based on an average nominal time the departures needed to fly to the crossing fix. The gaps displayed on the runway timeline represented the time slots the departures would need to depart inside to fly within the gaps.

All 144 departures were initially scheduled to depart inside departure slots. However, an offset error was manipulated to make half of the departures actually take off outside the slot, as shown in Figure 5. Eight REDDT3 departures took off in each run. Four departures took off inside the slot (accurate) and 4 outside the slot (inaccurate). The manipulation resulted in 4 relative time differences between departures and arrivals at the crossing fix: 150sec and 120sec apart (accurate) or 60sec and 30sec apart (inaccurate). Also, 4 departures took off at the front end of the slot and flew behind arrivals at the crossing fix, and 4 took off at the back end of the slots and flew in front of arrivals. The order of the 8 positions was counterbalanced so that each run had a different order and an equal distribution of each position for each run.

The length of the slots was determined by a buffer we used before and after arrival STAs, as shown in Figure 5. A buffer of 90 seconds was set, so that if a departure took off inside the gap/slot it would fly across the arrival flow with adequate lateral separation. Both arrivals and departure were estimated to fly between 220 and 240 knots, so 90seconds would provide a 5.5-6nm range of lateral separation when either aircraft would reach the crossing fix.

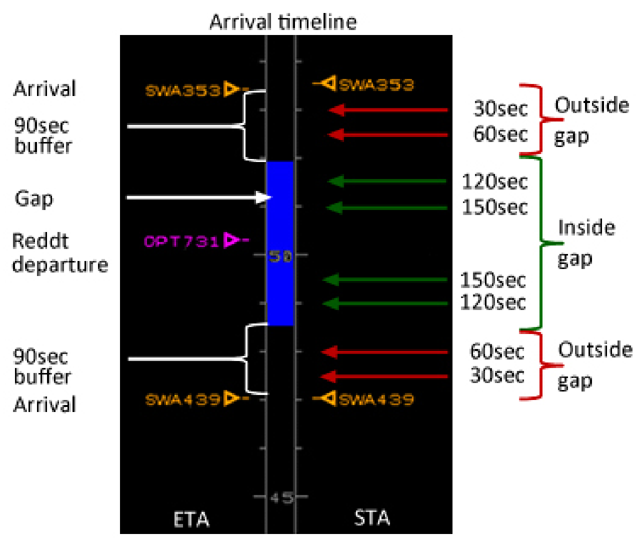

Figure 5. Takeoff Time Accuracy

Gaps in the Arrival Flow

A minimum of 10 gaps were built in the arrival traffic to Oakland in each scenario. When the gaps in the Oakland arrival flows reached REDDT, half of the time, another gap would also exist at HEIDE on the San Francisco arrival flow. The two gap conditions thus were: gap at REDDT, and gaps at both HEIDE and REDDT.

The spacing in the arrival flows were set to be 5 minutes wide, providing 2-minute gaps after deduction of the buffer spacing. The gaps were distributed across the arrival flows for each scenario.

Traffic Scenarios

Three traffic scenarios were derived from actual traffic data. All had similar attributes and variability. Each scenario was used 6 times. Callsigns were changed in each scenario. A total of 18 scenarios were developed.

Arrival traffic landed on RWY28L at SFO and on RWY 29 at OAK. Some overflight and Visual Flight Rules (VFR) traffic were included for realism. The arrival traffic rate met the maximum landing capacity at SFO and was increased at OAK compared to today's traffic. Gaps in the Modesto arrival flow occurred every time a GOLDN6 arrival from the North merged with the MODESTO flow downstream of HEIDE.

Departures departed from RWY30L at SJC. Some departures flew the LOUPE1, some the SJC9 and all others flew the REDDT3 Standard Instrument Departure routes. There were a total of 12 departures per run. Eight flew the REDDT3 route.

Apparatus

MACS software was used to emulate Standard Terminal Automation Replacement System (STARS) displays shown on large-format monitors similar to those used in current TRACON facilities. Keyboards like those used in the field helped to further replicate the look and feel typical of these facilities. MACS provides a high fidelity environment to prototype scheduling tools, to simulate the air traffic and to collect data [7].

Operational Procedure

We replicated procedures used by Chevalley et al [2]. We assumed that pilots would be able to change their departure route 10-15minutes before takeoff and would agree to fly the REDDT3, a SID 32nm shorter route than the LOUPE1 SID.

In all runs, the Mulford controller had control of the REDDT3 departures right after takeoff. Other departures were controlled by Toga, the departure sector. Once Mulford had control of the aircraft, they had to decide whether to clear the departure to climb to a higher altitude through the Niles airspace or if it needed to level off at 5,000ft and fly below the arrival flows at HEIDE and REDDT. If traffic appeared to permit a climb, Mulford could clear the aircraft to 11,000ft, the ceiling altitude of Niles sector, and could hand-off the datablock to Quake, a higher altitude departure sector. Coordination between Mulford and Niles controllers was handled either by point-out or by Pre-Arranged Coordination Procedure (see Parke, et al. [10] for details).

Controllers were dispersed across 2 control rooms in such a way that neighboring sectors would be in separate rooms. This was done to force controllers to use voice or the automated communication system (point-outs), and not use face-to-face coordination.

Experimental Procedure

We tested our tools and procedures in MACS with the participants several times prior to the study. The study itself took place over five days. On the first day, we briefed controllers about their tasks and about the operational procedures. Controllers then trained during practice runs using training scenarios different from those used during the actual data collection. During the next four days, controllers participated in 18 data collection runs. After each run, controllers completed an online survey. At the end of the study, controllers answered questions on a post-sim survey about workload, coordination, acceptability, feasibility and safety of the operation. We concluded the study with a debrief discussion with all participants.

Results

Post-run analyses revealed that some of the offsets of the takeoff times in the takeoff accuracy categories did not conform to the desired value. A new categorization of the departures offsets was therefore performed. This resulted in an unequal number of departures in each condition: 28 departures in the 150sec condition, 41 departures in the 120sec, 35 departures in the 60sec and 31 departures in the 30sec. Nine departures were removed from the sample because they did not fit in any of the 4 categories. The total sample was 135 departures.

The following analyses assess the controllers' decisions to clear departures to climb to 11,000ft. Such decisions needed to assume that the departure was clear of arrivals and could climb through the arrival airspace. Analyses also assess whether the tools helped the controllers make safe decisions.

Decisions to Climb Aircraft to a Higher Altitude

The decisions to climb departures were influenced by whether there were gaps present at REDDT only or at both REDDT and HEIDE, as well as how far departures were expected to be from arrivals while crossing the arrival flows. These two parameters are shown in the box plots in Figure 6. The boxplots show the distribution of the distances flown when departures were cleared to climb to 11,000ft. It shows the median and the first and the third quartiles of the distribution. The whiskers show the 2nd and 98th percentiles.

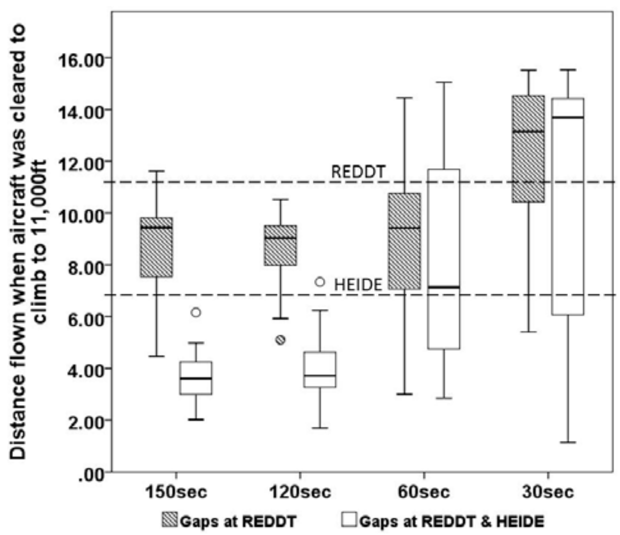

Figure 6. Decision by Gaps and Accuracy

The boxplots indicate that when gaps were present at REDDT only, most of the time controllers cleared departures before REDDT, except when aircraft were predicted to be 30sec away from arrivals at REDDT. Then controllers most often cleared departures after REDDT. The "Total" column in Table 1 shows that overall, controllers most frequently cleared departures to climb before REDDT (51%), compared to before HEIDE (35%), and after REDDT (14%). In regards to the takeoff accuracy categories, controllers cleared aircraft most frequently before REDDT except when departures were predicted to be 30sec away from arrivals. Then, controllers most often climbed aircraft after REDDT (46%), χ^2 (63) = 16.1, p = .013.

Table 1. Decisions with Gaps at REDDT

Dep. climbed	Predicted distances with arrivals: 150sec	120sec	60sec	30sec	Total
Before HEIDE	4 (36%)	8 (40%)	7 (37%)	3[a] (23%)	22 (35%)
Before REDDT	7 (64%)	12 (60%)	9[b] (47%)	4 (31%)	32 (51%)
After REDDT	0 (0%)	0 (0%)	3 (16%)	6 (46%)	9 (14%)
Total	11	20	19	13	63

a. Loss of separation: Separation of 2.2nm laterally with less than 1,000ft vertically

b. Loss of separation: Separation between 2.8 and 2.99nm of laterally with less than 1,000ft vertically

In Figure 6, when gaps were present both at REDDT and HEIDE, the takeoff accuracy categories seemed to have a stronger effect. Controllers cleared aircraft much earlier, before HEIDE, in the conditions where departures were 150sec and 120sec away from arrivals at REDDT. They cleared increasingly later in the 60sec and 30sec categories. The decisions varied somewhat more when departures were 60sec away from arrivals, with the majority of departures cleared near HEIDE. The decisions varied even more when aircraft were 30sec away from arrivals, with a majority cleared after REDDT. Table 2 shows that decisions were indeed made earlier when gaps were present both at HEIDE and REDDT. Controllers cleared aircraft most often (74%) of the time before they reached HEIDE. This was true for all takeoff accuracy categories, except one (30sec). When departures were expected to be 30sec away from the arrivals, controllers most often climbed aircraft after REDDT (59%), χ^2 (72) = 34.8, $p < .001$.

An analysis of variance with gaps and takeoff accuracy as factors indicates an interaction effect as well as main effects that support the direction of the above observations (interaction $F(3,127) = 3.5$, p = .017, gap effect $F(1,127)$ = 28.1, p =.000, and takeoff accuracy, $F(3,127) = 21.4$, p .000).

Table 2. Decisions with Gaps at REDDT and HEIDE

Dep. climbed	Predicted distances with arrivals 150sec	120sec	60sec	30sec	Total
Before HEIDE	17 (94%)	21 (100%)	10[a] (63%)	5[a] (29%)	54 (74%)
Before REDDT	1 (6%)	0 (0%)	3 (19%)	2 (12%)	5 (8%)
After REDDT	0 (0%)	0 (0%)	3 (19%)	10 (59%)	13 (18%)
Total	18	21	16	17	72

a. 3 losses of separation between 1.9 and 2.9nm laterally with less than 1,000ft vertically

The wide distribution of the 30sec category over the various locations is due to the fact that 5/17 (29%) of the time controllers cleared departures to climb before HEIDE and 10/17 of the time (59%) after REDDT. The distribution of the scores when gaps were only at REDDT is narrower, because controllers overall cleared departures most often before (31%) or after REDDT (46%). Nevertheless controllers cleared aircraft before HEIDE 3/13 (23%) of the time. This suggests that controllers waited until the Modesto arrival was on a divergent heading to clear the departures. When the departure was expected to be tied with the arrival at REDDT, controllers cleared the aircraft to have altitude separation with arrivals at REDDT. This strategy worked most of the time, but failed some of the time. Out of 8 instances, 2 losses of separations occurred because aircraft did not climb as quickly as other aircraft.

Relative Positions of Departures with Arrivals

The decision to climb departures was influenced by the predicted relative position of the departure to the arrival aircraft when at REDDT. The departure aircraft would pass the crossing fix either behind or in front of an arrival aircraft.

Table 3 shows cases with departures expected to be either 60sec or 30sec away from arrivals. When gaps were present at REDDT only and when departures were crossing REDDT behind arrivals, controllers had to wait to clear aircraft to climb after HEIDE (before REDDT) most of the times (11/17). When departures were in front of arrivals, controllers cleared departures before HEIDE (6/15) as often as they did after REDDT (7/15). When gaps were present both at HEIDE and REDDT, nearly half of the times, controllers cleared aircraft to climb before HEIDE (5/9 when the departure was behind the arrival, and 11/24 when the departure was in front of the arrival) rather than before REDDT or after REDDT, regardless of the aircraft position. In this situation, controllers expected the departure to climb above the arrival aircraft.

Table 3. Decisions, Aircraft Position and Gaps

	REDDT		HEIDE & REDDT	
Climb	Dep. Behind	Dep. Front	Dep. Behind	Dep. Front
Before HEIDE	4[b, b]	6[a]	5[b]	11[a, c, c]
Before REDDT	11	2	1	3
After REDDT	2	7	3	10
Total	17	15	9	24

Losses of separation (with less than 1,000ft):
a. Between 1.9 and 2.3nm
b. Between 2.8 and 2.99nm
c. Between 3 and 3.4nm (near loss)

Anticipated Separation

Why did controllers clear departures so frequently before REDDT when both aircraft were expected to be tied at REDDT? The first explanation is that controllers applied the diverging separation rule. This rule allowed controllers to clear departures to climb once the arrivals had passed REDDT in front of the departures. Once minimum separation rules no longer applied, controllers could then climb departures before REDDT. These were safe operations.

The second explanation is that controllers anticipated altitude separation. The controllers cleared departures to climb before HEIDE, when departures were tied laterally at REDDT (well before divergence could take place). This happened whether departures were slightly in front or behind arrivals at REDDT. This data suggests that controllers expected that the departures would have enough time to climb above the arrivals to have vertical separation by the time they lost lateral separation. These decisions are not safe. Separation was lost or nearly lost 7 times when controllers cleared departures before HEIDE when aircraft were laterally tied with arrivals (see notes a, b and c in Table 3).

Controllers anticipated separation and often cleared departures to climb before aircraft were diverging with arrivals. In many cases the arrivals were far enough from REDDT to not be a factor (when they were 150sec and 120sec away from each other). But in other case, separation was lost.

How close did aircraft come to each other? The plot depicted in Figure 7 shows the relative positions of the arrival aircraft *when the departures crossed REDDT (horizontal axis)* and the departures *when they were cleared to climb to 11,000 ft (vertical axis)*. Each value represents the distance to REDDT for both the arrival and the departure. The axes show both negative and positive values. The negative numbers show nautical miles before REDDT, and the positive numbers value show nautical miles past REDDT. There are four quadrants in Figure 7. The two quadrants on the right side indicate arrivals that had not reached REDDT yet. The two quadrants on the left side indicate arrivals that passed REDDT. The two quadrants at the bottom indicate the departures that were cleared to climb before REDDT (HEIDE and ADELA are also indicated by dotted lines). The two quadrants at the top indicate departures that climbed after REDDT. The grayed-out area indicates when arrivals and departures were on a diverging course (both when departures climbed after REDDT regardless of where the arrivals were, and also when departures climbed once arrivals passed REDDT). The figure also depicts losses or near losses of separation. The red circles indicate that separation came to less than 2.8nm laterally and 1,000ft vertically. The orange triangles indicate separation that was briefly lost and was between 2.8 and 2.99nm laterally and 1,000ft vertically. The blue squares indicate separation that came close to the minimum, between 3 and 3.4nm laterally and 1,000ftvertically.

The upper right quadrant shows departures that climbed *after* they crossed REDDT. The arrivals were all within 4nm before REDDT when the departures crossed REDDT. These are case when controllers waited for the departures to cross REDDT, and become divergent. These were safe operations. In this quadrant, the most frequent decisions were made in the conditions with the conflict probe (8) and tie-boxes (7) and to a much lesser extent with timelines only (2).

The upper left quadrant depicts a similar situation as the upper right quadrant. The departures climbed soon after they passed REDDT, which was after the arrivals had passed REDDT as well. These decisions were most often made in the conditions with the tie-boxes (2) and conflict probe (1).

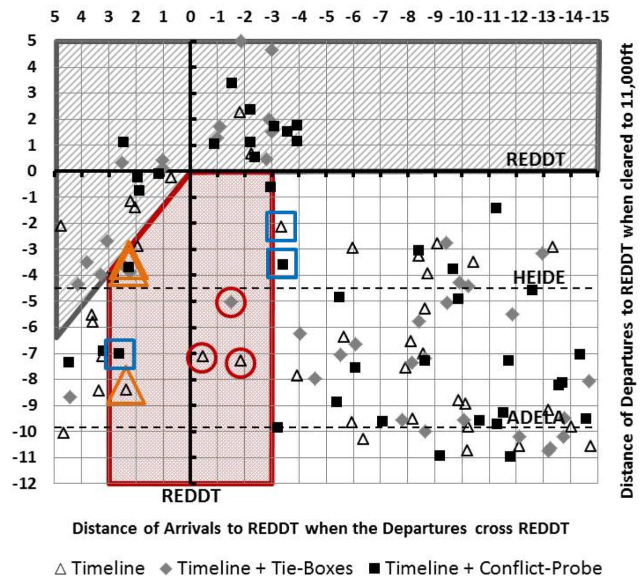

Figure 7. Arrivals' Distance to REDDT

The bottom left quadrant shows departures that climbed *before* REDDT and where the arrivals were *after* REDDT when the departure crossed REDDT. These are the cases where departures passed behind arrivals at REDDT. In this quadrant, two behaviors can be detected: 1) the controllers had to wait until both aircraft had diverging courses (gray lined area). These were safe operations. 2) Controllers anticipated separation to climb aircraft. In this situation, the largest differential values between the distance of the departure to REDDT and the value of arrival past REDDT produce the best outcome. For instance, one aircraft was cleared to climb 10nm before REDDT and the arrival had already passed REDDT by 4.5nm when the departure crossed the fix. In this quadrant the further past REDDT the arrivals were, the greater the separation. When the arrivals were less than 3nm past REDDT when the departures crossed REDDT, it meant that departures had to wait for diverging courses to be climbed (gray lined area). All cases that fell outside that area were operational errors (red lined area). Of all the 6 cases depicted, 3 came between 2.8 and 2.99nm of lateral separation (triangles), and 1 came to 3.3nm of lateral separation. These are cases where controllers anticipated separation by "betting on the come[1]". In this quadrant, decisions to climb with diverging courses (gray lined area) were made 4 times in the tie-boxes condition, 4 times in the timelines condition only and 3 times in the conflict probe condition. Decisions made while aircraft were converging were made most often while using timelines only (7), then conflict probe (4), and then tie-boxes (2).

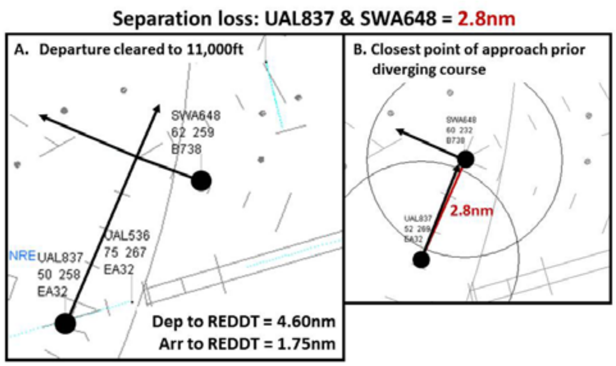

Figure 8. Departure Behind Arrival

Figure 8 shows an example of a 2.8nm separation loss when the departure passed REDDT behind the arrival aircraft. This is a case where controllers expected to have separation by the time aircraft was on a diverging course. In this example, the departure had been stopped at 5000ft (SID procedure). The controller cleared the departure to climb to 11,000ft when it was 4.6nm and the arrival was 1.75nm away from REDDT (A). Both aircraft came to 2.8nm at the closest point of approach just before their course became divergent (B). By the time the departure reached REDDT, the arrival was 2.2nm past REDDT.

The bottom right quadrant in Figure 7 shows departures that climbed *before* they crossed REDDT and the arrivals were *before* REDDT when the departure crossed REDDT. These are the cases where both departures and arrivals are on a converging course and when departures passed in front of the arrivals. Arrivals located less than 3nm laterally and less than 1,000ft vertically meant a loss of separation (red lined area). Arrivals located further than 3nm meant that controllers estimated that the relative distance between departure and arrival would be sufficient to maintain separation. In this quadrant, 3 losses or near losses occurred while controllers were using timelines only, one loss occurred in the tie-boxes condition and 1 near-loss in the conflict probe condition. Controllers made decisions with aircraft on converging courses more often with the timelines only (26), then with the conflict probe (24) followed the tie-boxes (22). In this quadrant, departures that were climbed early and ended up near 3nm of arrivals should be considered operational errors. The symbols of these aircraft appear on the lower left side of the quadrant. On the upper right portion of the quadrant, decisions seem to be safer. That was when departures were cleared to climb while the arrivals were still far enough from the departures at REDDT.

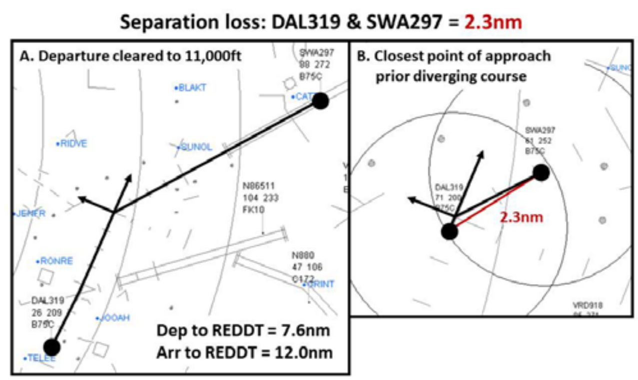

Figure 9. Departure in Front of Arrival

Figure 9 shows an example of separation loss when the departure passed REDDT in front of the arrival. The controller cleared the departure to climb to 11,000ft before HEIDE before it reached 5,000ft, expecting the departure to have enough vertical separation when the two aircraft would lose lateral separation. At the time of clearance, the departure was 12nm and the arrival was 7.6nm away from REDDT. Lateral separation came down to 2.3nm before the aircraft was separated by at least 1,000ft of vertical clearance.

[1] The expression to "bet on the come" is derived from a gambling expression and means you don't have what you want or need, now at the moment; but, you are betting or hoping you will have what you want or need when the time comes.

Both examples of separation loss involved anticipated separation. In the first example, the controller misjudged how early the departure could be climbed. In the second example, the two aircraft were on a converging course and either vertical or lateral separation could be maintained. Separation was dependent on the aircraft performance. If the departure was a slow climber, then aircraft could lose minimum separation vertically.

Tool Conformance

Table 4 shows where controllers climbed aircraft in each of the tool conditions (TL = Timelines, TB = Tie-boxes and CP = Conflict probe). Overall, more than half the time (57%), controllers cleared departures to climb before HEIDE, a fourth of the time (26%) after HEIDE but before REDDT, and only one sixth of the time (17%) after REDDT. Controllers cleared departures to climb before HEIDE more frequently when they had timelines only (65%) than when they also had one of the other tools (52% for both tools). Controllers cleared departures equally across the three tool conditions after HEIDE but before REDDT: timelines 29%, timelines and tie-boxes 21%, and timeline and conflict probe 27%. Finally, controllers cleared aircraft after REDDT only 3% of the time in the timeline condition, as opposed to 25% and 21% of the time in the other two conditions.

Table 4. Decision to Climb and Tools

Climb	TL	TL & TB	TL & CP	Total
Before HEIDE	31 (65%)	25 (52%)	25 (52%)	82 (57%)
Before REDDT	14 (29%)	12 (25%)	13 (27%)	38 (26%)
After REDDT	3 (6%)	11 (23%)	10 (21%)	24 (17%)
Total	48 (100%)	48 (100%)	48 (100%)	144 (100%)

The boxplots in Figure 10 show the distance flown by departures when they were cleared to climb as a function of tools and departure accuracy. The pattern depicted by the distribution of the boxplots was supported by an ANOVA. Two main effects of takeoff accuracy and tools were found. Aircraft that were predicted to cross REDDT 150sec and 120sec away from arrivals were cleared to climb earlier than aircraft that were only 60sec and 30sec away ($F(3,122) = 23.8$, $p = .000$). A main effect for tools was also found. Controllers using timelines only climbed departures earlier ($M = 7.0$nm, $SD = 3.6$nm) than in the tie-boxes condition ($M = 8.3$nm, $SD = 4.2$nm) and the conflict probe condition ($M = 8.6$nm, $SD = 4.3$nm) $F(2,122) = 3.8$, $p = .025$. A interaction effect was marginally significant, $F(2,122) = 2.1$, $p = .054$. As shown in the boxplots, controllers in the 30sec condition cleared departures to climb mostly after REDDT when using the tie-boxes and conflict probe as opposed to when using timelines. Controllers also cleared departures later in the 60sec condition when using the conflict probe.

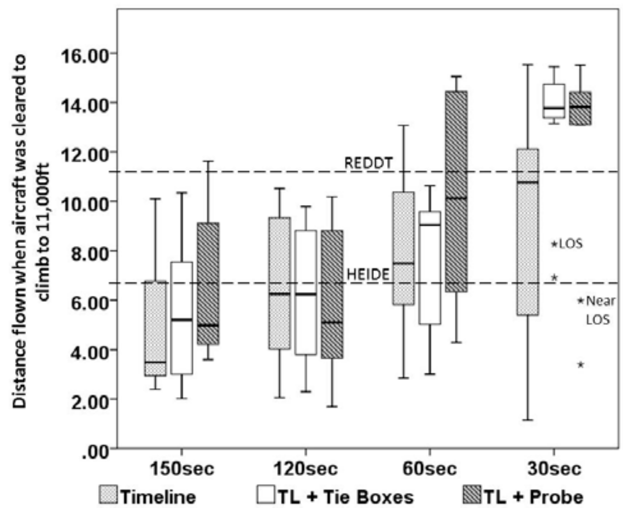

Figure 10. Decision to Climb and Tools

Controllers seemingly overrode the information the tie-boxes and the conflict probe provided. Figure 11 depicts 18 arrivals that were in the REDDT tie-boxes when departures were at ADELA (horizontal axis), and how far from REDDT the departures were when they were cleared to climb (vertical axis). HEIDE and ADELA fixes are indicated on the vertical axis with dotted lines. Two aircraft with loss of separation are also shown. The positions of the arrivals in the tie-boxes were plotted as a percentage, as both tie-boxes for the REDDT crossing fix were not located the same distance from REDDT. 1% percent means that an aircraft was at the front edge of the box, and 99% means that an aircraft was at the very end of the box. If controllers followed the tie-boxes rules, departures should not have been climbed before REDDT anywhere in the space depicted in the graphic. Departures were cleared to climb after REDDT when the arrivals' location in the tie-boxes fell approximately between 20% and 90%, except in the two cases where separation was lost. Departures for which arrivals were located between 0% and 20% in the tie-boxes were cleared to climb 3-4nm miles before REDDT behind arrivals, indicating that controllers applied the divergence rule as soon as the arrivals passed REDDT. The divergence rule was also applied with aircraft at the end of the tie-boxes. On two occasions, arrivals were near the edge of the tie-boxes (90%), and the departures were cleared to climb before HEIDE. These were the cases where controllers hoped that the departures would reach altitude separation by the time they were less than 3nm from REDDT.

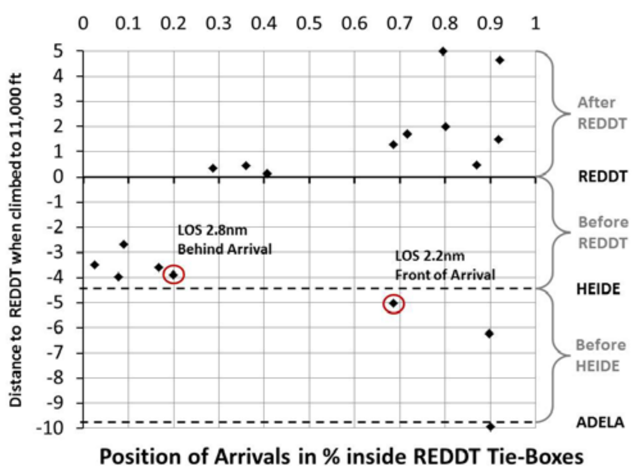

Figure 11. Arrivals in Tie-boxes

Controllers followed the tie-boxes separation rule 74% of time overall. That percentage went down to 58% when departures took off outside their slot and came to 60sec and 30sec away from arrivals. In comparison, controllers conformed to the conflict probe warnings 84% of the time overall and in 73% when departures took off outside their slot. When taking into account the diverging separation rule the controllers followed, the tool conformance for the tie-boxes goes up to 91% (83% for departures taking off outside the slots) and up to 96% (94% for departures taking off outside the slots) for the conflict probe. In three cases the controllers did not conform to the tie-boxes rules nor the conflict probe advisories, did violate the divergence rule and eventually lost separation. In two instances, the controllers used the tie-boxes (2.2 and 2.8nm), and in one instance, the controller used the conflict probe (2.97nm). In the last case, the controller checked for conflict. The prediction of the conflict went on and then off. The controller cleared the departure to climb before course divergence and minimum separation was briefly lost.

Other Results

One controller tended to climb aircraft earlier (M = 6.3nm, SD = 3.3nm) than the two other controllers (M = 8.8nm, SD = 4.1nm, M = 8.9nm, SD = 4.3nm), $F(2,123) = 8.7$, $p = .000$). That controller also lost separation more often (4/48, 92% success) than the two others did (1/48 each, 98% success). That controller also conformed less well to the tie-boxes rules (7/16 times, 44%) than the two other controllers (14/16 times, 88% & 15/16 times, 94%). The three controllers used the conflict probe properly equally well (81%, 81%, 88%).

Controllers responded to 5-point rating scale (1 = lowest to 5 = highest) items in post-run surveys as well as in a post-sim survey. Post-run results show that on average, controllers used the tools nearly half the time they were available to decide to climb departures. There was no difference in mean ratings of use of the timelines, tie-boxes and conflict probe, due to the high variability between raters. Controller 1 reported that he 'always' (score 5) used both the timelines and tie-boxes and used the conflict-probe 'sometimes' (score 2) and 'most of the time' (score 4). Both Controller 2 and 3 rated their use of the tools similarly: either never (1) and 'sometimes' (2). Video recordings of the controllers' activities indicated that all 3 controllers used the conflict-probe for each departure, as required by the procedure. There were no objective measures to verify that controllers looked at the tie-boxes. No difference in mental activity (between 2.3 & 2.5) or time pressure (between 2.1 & 2.2) was found between the 3 tool conditions.

In the post-sim questionnaire, the controllers indicated they preferred the tie-boxes over the timelines and the conflict probe: One controller noted: "*Tie markers were passive and served [their] purpose well.*" Another stated: "*Tie-boxes are nice because they are part of the display on the map.*

They need to be larger if you want them to account for degree divergence better."

One controller liked the conflict probe: "*Conflict probe boxes the aircraft in question and gives you all conflicts at one time--making it better to see and decide who is a problem from all areas of the map*". The two others complained that "*Conflict probe was distracting with lots of lines*" as well as "*Conflict probe is OK, but many times when I wanted to look at a conflict between 2 aircraft, it would display 2, 3, or even 4 conflicts. This created a large amount of unneeded clutter on the scope.*"

Discussion

In this follow-up study of Sharing of Airspace Resources (SOAR), we investigated the use of three decision support tools to help controllers make safe decisions on when to climb departures through gaps in arrival flows.

The tools tested by the controllers were (1) timelines showing the expected times of aircraft at the crossing fixes, (2) tie-boxes showing potential ties between aircraft, and (3) a probe which detected conflicts between aircraft. The tie-boxes were static drawings on a video map. The conflict probe was a dynamic tool that assessed aircraft trajectory.

The tie-boxes and the conflict probe helped controllers better assess separation between arrival and departure aircraft than the timelines alone. The conflict probe was the most reliable since it showed where the conflict would occur, as opposed to the tie-boxes which indicated only potential ties. Most of the time, controllers could detect by themselves when aircraft would be tied at the crossing fixes and could make appropriate decisions. However, it appeared that controllers often took liberties with the tools. Two behaviors stood out: 1) controllers applied the diverging separation rule earlier than the tie-boxes or the conflict probe advised, and 2) controllers cleared the departures to climb early to have vertical clearance by the time they reached the crossing fix. In both cases, controllers anticipated separation. Controllers "bet on the come," and because aircraft climb and speed performance is not reliable, controllers lost separation seven times.

Anticipated separation exists when a controller expects to have minimum separation by the time two aircraft are on diverging course and issues a clearance beforehand based on that expectation. With anticipated separation both the prediction of separation, as well as the uncertainties of aircraft performance become critical factors. It is critical to accurately predict future separation when both aircraft are far apart, but difficult to do so. It is critical to accurately predict the climb performance of the departures, but difficult to do so. It is well-known that aircraft performance is much harder to predict for departure than for arrival aircraft. Arrivals are slowing down and descending to conform to altitude and speed constraints that all aircraft are supposedly able to meet. Departures are accelerating and climbing at different rates and multiple factors influence their climb trajectory. The aircraft's lift and the thrust, for example, are dependent on the pilot, the aircraft type and weight, and the weather.

In shared airspace operations where temporal separation is used to optimize the efficiency of trajectories, decision support tools should help controllers make decisions without compromising the safety of operations or increasing controller workload.

The tie-boxes and conflict probe did not prevent controllers from making mistakes, nor did they offer alternative trajectories. Path options could have limited losses of separation and possibly provided more opportunities to climb departures. In contrast to the previous study, controllers were asked to leave aircraft on its filed route. In that study, controllers could vector aircraft. This gave them more flexibility in crossing departures at other places and in avoiding separation loss with arrival aircraft.

In light of both the previous study and the current study, a better decision support tool is needed to help the controllers separate departures from arrival aircraft. A time-based prediction tool could provide the controller with the assurance that an aircraft could be safely climbed without losing separation. The tool would also need to take into account the different separation rules for departures passing in front of or behind arrivals.

The results and lessons learned from this study have already been incorporated into the development of a Route Crossing Tool, which is described in this conference [11]. This tool is built to predict separation of departures and arrivals at multiple route crossing points along an arrival route. It also supports the diverging separation rule.

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Acknowledgements

We thank the research and development teams in the Airspace Operation Laboratory at NASA Ames for the development of prior decision support tools. Their contributions have been essential to the results of this research. We also thank the NASA Airspace Systems Project for supporting and funding the SOAR project.