Performance of an Automated System for Control of Traffic in Terminal Airspace

Tasos Nikoleris[1]
University of California at Santa Cruz, Moffett Field, CA, 94035

Heinz Erzberger[2]
University of California at Santa Cruz, Moffett Field, CA, 94035

Russell A. Paielli[3]
NASA Ames Research Center, Moffett Field, CA, 94035

and

Yung-Cheng Chu[4]
University of California at Santa Cruz, Moffett Field, CA, 94035

This paper examines the performance of a system that performs automated conflict resolution and arrival scheduling for aircraft in the terminal airspace around major airports. Such a system has the potential to perform separation assurance and arrival sequencing tasks that are currently handled manually by human controllers. The performance of the system is tested against several simulated traffic scenarios that are characterized by the rate at which air traffic is metered into the terminal airspace. For each traffic scenario, the levels of performance that are examined include: number of conflicts predicted to occur, types of resolution maneuver used to resolve predicted conflicts, and the amount of delay for all flights. The simulation results indicate that the percentage of arrivals that required a maneuver that changes the flight's horizontal route ranged between 11% and 15% in all traffic scenarios. That finding has certain implications if this automated system were to be implemented simply as a decision support tool. It is also found that arrival delay due to purely wake vortex separation requirements on final approach constituted only between 29% and 35% of total arrival delay, while the remaining major portion of it is mainly due to delay back propagation effects.

I. Introduction

Researchers at NASA Ames have been developing a software system called Terminal AutoResolver (TAR) that performs automated conflict detection and resolution for all flights in the Terminal Radar Approach Control (TRACON) airspace around major airports.[1-2] In addition to conflict detection and resolution, TAR also ensures that an efficient flow of traffic is maintained by use of its arrival scheduling algorithms. The main difference between TAR and other automation systems that have been developed[3-6] is that TAR is not intended primarily as a decision support tool for air traffic controllers. Instead, TAR checks for conflicts throughout the entire trajectory of a flight and generates maneuvers that resolve a conflict, if needed. Thus, TAR is being designed to eventually perform all functions of an air traffic controller – ensuring a safe, orderly, and expeditious flow of traffic – with a high degree of automation. With the expected future growth of air traffic, higher levels of automation in air traffic management are likely to be needed to handle a denser and more diverse mix of air traffic. In such a future environment, the role of

---

[1] Associate Research Scientist, University Affiliated Research Center, Mail Stop 210-8, AIAA Member.
[2] Senior Scientist for Air Traffic, Aviation Systems Division, Mail Stop 210-10, AIAA Fellow.
[3] Aerospace Engineer, Aviation Systems Division, Mail Stop 210-10, AIAA Associate Fellow.
[4] Senior Software Engineer, University Affiliated Research Center, Mail Stop 210-10.

controllers would change from handling routine separation assurance and arrival sequencing tasks to handling exceptional traffic situations or accommodating special pilot requests.

TAR is also designed to be connected with air traffic simulation software. It can, therefore, be used to perform analyses that examine the efficiency of an automated system for air traffic control in the TRACON. In this study, the primary metric of interest is level of delay in the TRACON as a function of the rate at which traffic is allowed to enter it. That will indicate how efficient TAR is in managing traffic as the density of traffic in the TRACON increases. In addition to delay, a second metric of interest is the percentage of arrival flights that remain on their preferred horizontal path to the runway. With emerging technologies such as Performance Based Navigation, there is high interest from both the airlines and air traffic control authorities to enable appropriately equipped aircraft to use their Flight Management System to fly an optimized profile descent through the terminal area without being vectored off their preferred route.

This paper describes the performance of TAR under several traffic scenarios in the terminal airspace. Since TAR is currently adapted for the Dallas-Fort Worth TRACON airspace as the development testing environment, TAR is employed to handle several daily traffic scenarios that are characterized by the rate at which traffic is metered into the DFW TRACON airspace. For each traffic scenario, the metrics of performance that are examined include: the amount of delay for all flights, the number of conflicts predicted, and the types of resolution maneuvers used to resolve conflicts. In this way, the analysis examines the relationship between volume of traffic that is allowed inside the TRACON and the effectiveness of an automated system for deconfliction of traffic in terms of delay and number of conflicts.

The contribution of this research lies in providing preliminary estimates of the efficiency of an automated system for air traffic control, such as TAR, which aims to achieve zero violations of minimum separation requirements throughout the entire trajectory of every aircraft flying in the terminal airspace, assuming aircraft execute their assigned trajectories as planned. Although the design of TAR is not yet fully complete, the results presented in this paper attempt to answer the question of how efficient an automated air traffic control system can be for various levels of traffic density.

Section II of the paper provides an overview of TAR's algorithm for conflict resolution and arrival management, while Section III describes the methodology used for generating traffic scenarios. The results of simulation runs with traffic to and from Dallas-Fort Worth International airport are presented in Section IV. Finally, Section V summarizes the key results of this paper and outlines work that will be performed in the future.

II. Overview of Algorithm

The algorithm for conflict resolution and arrival scheduling in TAR is outlined in the flow chart shown in Fig. 1. Aircraft-related information is an input, with data for type of aircraft, destination airport, aircraft's current state of motion, as well as wind speed and terminal airspace configuration information. Employing this data, a trajectory synthesizer module computes each flight's predicted four-dimensional trajectory inside the TRACON, with time being the fourth dimension. For every pair of aircraft the conflict probe in TAR checks for loss of separation conflicts. For these conflicts, the 3 nmi and 1000 ft. separation requirement is enforced. In addition to separation conflicts, each arrival aircraft is checked for spacing conflicts on final approach against every eligible aircraft in the arrival stream.

A spacing conflict arises when two aircraft are predicted to cross the final approach fix (FAF) with separation less than a minimum time interval, which itself depends on the wake vortex separation rules between the two aircraft. At the time when a flight's remaining time to fly to the FAF first becomes less than a specified minimum time, referred to as the freeze time interval, the aircraft is assigned a scheduled time of arrival (STA) at the FAF. The STA for the flight would be set equal to its unconstrained arrival time if this does not cause a sequencing conflict with a previously scheduled flight or a loss of separation with any other flight. Otherwise, TAR will employ its scheduling algorithm, referred to as Arrival Manager, to assign an STA to the flight that is currently being scheduled. The additional flying time measured relative to unconstrained arrival time is the spacing delay.

A special situation arises when two aircraft have been assigned to land on independent parallel runways. When both aircraft are established on their final approach path, on a 'staggered' approach to the runways, they are exempted from the 3 nmi and 1000 ft. separation requirement. However, if both flights are turning to final approach but not yet established on it, that constitutes a separation conflict. As a result, if TAR attempts to schedule a flight at its FAF but detects a conflict while the aircraft is turning on its final approach, it will add additional delay to avoid this conflict. That constitutes a special category of conflicts, which is termed as 'staggered' conflict, and it is responsible for a significant portion of arrival delays, as it discussed later in Section IV.

For new arrivals that have just crossed the freeze horizon, the sequence order is generally determined by the first-come-first-served (FCFS) rule, but with some exceptions. Thus, deviations from FCFS, termed as position shifts, are allowed if the flights currently being scheduled can be assigned a landing slot between previously scheduled flights without requiring these flights to be rescheduled. The Arrival Manager also has the capability to reassign flights to a different runway at airports with more that one active landing runway. Normally, new aircraft entering the TRACON have a runway pre-assigned to them, but occasionally a reassignment can significantly reduce delays. The algorithm for runway reassignment, as well as the delay reductions obtained from it, are described in detail in [1].
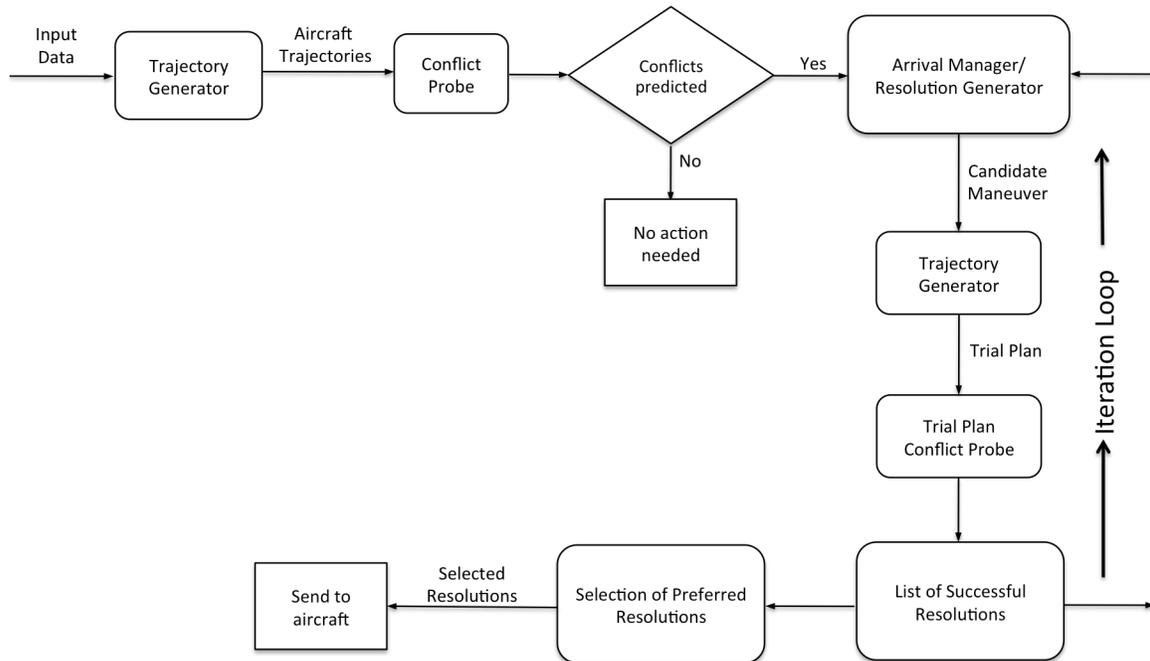
Figure 1. Functional diagram of TAR.

TAR uses a trial planning process as the basic algorithm for resolving combined spacing and separation conflicts. For each spacing or separation conflict, the Resolution Generator module, in coordination with the Arrival Manager module, proposes different maneuvers to resolve it. For arrivals, these include speed control, horizontal maneuvers, and altitude changes, with preference given to speed control. For a thorough description of the maneuvers that Resolution Generator employs to resolve conflicts, the reader is referred to [1]. Each candidate maneuver is sent to the trajectory synthesizer module, which creates a full four-dimensional trajectory of the aircraft from its current position to the runway. This four-dimensional trajectory that implements the candidate solution is referred to as trial plan. Next, each trial plan is sent to the Conflict Probe to determine whether it has resolved the original conflict without introducing new conflicts, referred to as secondary conflicts. The Conflict Probe checks the trial plan trajectory in small time steps against all other trajectories for loss of separation. If the trial plan trajectory is found to be free of all problems, it is retained. If not, TAR loops back to the Arrival Manager/ Resolution Generator, which generates another trial maneuver, as indicated in Fig. 1. Since trial planning can yield more than one successful resolution, the Resolution Generator includes an algorithm to select the most suitable trial plan as the solution to be implemented. Preference is typically given to the trial plan with either lowest delay or with speed control as its resolution method.

The above process is repeated for all flights in the TRACON airspace at a rate determined by the surveillance sensor update rate, which typically has an update cycle of 4-5 seconds. Four-dimensional trajectories are recomputed at each update using the most recent sensor inputs. In the current version of TAR, it is assumed that the trajectories generated by the external trajectory synthesizer are flown with a high level of accuracy, essentially without errors. Future work will account for trajectory prediction and execution uncertainties.

American Institute of Aeronautics and Astronautics

III. Methodology

The objective of this study is to evaluate the effectiveness of TAR in handling air traffic inside the TRACON under several traffic scenarios. The latter are defined by the rate at which arrival traffic is metered into the TRACON airspace. In this study, air traffic to and from the Dallas/Fort Worth metropolitan area was considered. Arrival and departure data for the two major airports in the area, the Dallas/Forth Worth International Airport (DFW) and the Dallas Love Field (DAL) Airport, were used for the analysis. Fig. 2 shows the Dallas/Fort Worth TRACON area, the runway systems of DFW and DAL (not to scale) as well as the standard arrival (green) and departure (blue) routes to and from these airports.

The analysis in this study consists of three major steps: first, a traffic scenario is generated; second, flight trajectories for the traffic scenario are generated using a fast-time simulation environment, and TAR is employed to detect and resolve conflicts; third, delay statistics are derived based on the simulated trajectories. A more detailed discussion of these steps follows.

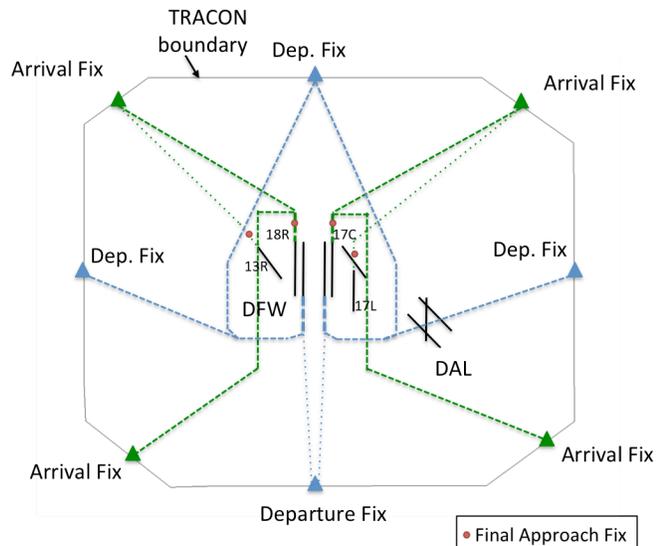### A. Step 1: Traffic scenarios generated

In this step, TAR's resolution generator module was deactivated, and only TAR's scheduling algorithm was used to generate scheduled times of arrival for each flight. As a result, no conflict resolution maneuver was generated by TAR in this step.

Flight plans for arrival and departure flights to and from the two major airports of the area, DFW and DAL, were used as input in the analysis. The flight plan data used include a 24-hour period that begins at 00:00 Coordinated Universal Time (UTC) on 4/25/2012. The data included 900 arrivals and 915 departures at DFW and 229 arrivals and 245 departures at DAL, totaling 2289 flights. This level represents an average day of traffic for DFW and DAL.

Estimated times of arrival (ETAs) at the TRACON's arrival fixes (see Fig. 2) and the final approach fixes were derived for each aircraft from their flight plan. Next, the TAR scheduling algorithm uses those ETAs to generate scheduled times of arrival (STA) for each flight at TRACON arrival fix and final approach fix. The STAs at these airspace fixes are generated based on two constraints: a) minimum required spacing between consecutive arrivals, and b) the maximum amount of delay that an arrival aircraft is scheduled to absorb inside the TRACON. By assigning STAs to each flight, the level of air traffic congestion inside the TRACON is prevented from growing without bound. It is emphasized, though, that at this step trajectories are not checked for loss of separation. This step in the methodology serves as a preparatory task to generate STAs at the TRACON arrival fix between consecutive arrivals that are spaced in a manner that safeguards from excessive delays inside terminal airspace.

Figure 2. Diagram of DFW TRACON. Runway lines not on scale.

Scenarios are characterized by the maximum amount of delay that an arrival flight is scheduled to absorb inside the TRACON in order to meet its STA at the runway final approach fix. As explained previously in Section II, spacing delay is defined as the difference between an aircraft's unconstrained arrival time at the runway's final approach fix and its STA at the final approach fix. In each traffic scenario, spacing delay up to a predefined upper limit, d_{max}, is scheduled to be absorbed inside the TRACON. The remaining amount of delay will be absorbed upstream, in the Air Route Traffic Control Centers ('Centers') that surround the DFW TRACON. Different traffic scenarios are characterized by the level of d_{max}.

In this study, the set of values used in the analysis is $d_{max} = \{30, 60, 90\}$ seconds. That is consistent with the level of delay accepted in operational decision support tools such as the Traffic Management Advisor[4] (TMA) or the Terminal Sequencing and Spacing[3] (TSS) tool. As d_{max} is set to lower levels, traffic flow inside the TRACON is expected to be smoother: a larger proportion of spacing conflicts will be resolved only with speed reductions, thus

avoiding horizontal maneuvers that change the planned horizontal route of an aircraft inside the TRACON. As a result of lower delay inside the TRACON, fuel burn is also expected to be lower. At the same time, since higher amounts of delay will have to be absorbed in the adjacent Center, the opposite conditions are expected to arise there.

B. Step 2: Simulations with TAR

The STAs at arrival entry fixes that were generated by the scheduling algorithm are used as input to a simulation of a day of operations at the DFW TRACON. Aircraft were programmed to enter the terminal airspace at prescribed STAs generated by the scheduling algorithm. Once aircraft were inside terminal airspace, TAR with its resolution generator module enabled was employed to detect and resolve any type of conflict between flights.

A fast-time simulation environment called the Airspace Concept Evaluation System (ACES) was employed to test the Terminal AutoResolver performance in spacing and deconfliction of traffic. ACES is a gate-to-gate simulation of air traffic at airport, regional, and national levels, developed by NASA.[7] ACES generates flight trajectories using aircraft models derived from the Base of Aircraft Data[8] (BADA) and traffic data consisting of departure times and actual flight plans obtained from Airline Situation Display to Industry (ASDI) files. These trajectories are then fed into TAR for conflict prediction and resolution of spacing and separation conflicts.

The south flow runway configuration was assumed for operations (see Fig. 2). For this flow configuration landings at DFW take place simultaneously and independently on runways 18R, 17C, 13R and 17L, and take-offs on runway 18L and 17R. At DAL aircraft were landing on runway 13L and taking off from runway 13R. Also, since an important goal of TAR is to provide an environment that allows aircraft to fly more efficient trajectories in the terminal area, the simulation did not follow all the operational procedures that are enforced in current operations within the DFW TRACON. As a result, relaxation of such procedural constraints produced a greater number of simulated conflicts than what would be expected in actual operations.

C. Step 3: Post processing of results

Three simulation runs were performed, each corresponding to a traffic scenario that was generated with a different level of d_{max}, the maximum planned delay for each flight in the TRACON. For each simulation run several performance metrics were computed, two of which are defined as follows:

1. Arrival Spacing Delay

This is delay due to wake vortex separation requirement on final approach as computed by the TAR scheduling algorithm in Step 1 above. In other words, it is the difference between a flight's STA and ETA at the final approach fix, and it cannot exceed d_{max} for any flight.

2. Arrival Delay

This is the total time by which an arrival is delayed in the TRACON, computed as the difference between the flight's actual time of arrival and its ETA at the final approach fix. It includes Arrival Spacing Delay. Essentially, it represents delay of arrival flights in simulations with TAR's resolution generator module enabled, as described in Step 2 above.

Once aircraft enter DFW TRACON they are subject to both spacing and separation conflict resolution maneuvers by TAR. Even if an aircraft has already been prescribed an STA for crossing of the final approach fix, that STA can be further delayed by TAR in order for the aircraft to avoid conflict with another flight. In such a case the resulting arrival spacing delay will be higher than that planned by the scheduling algorithm in Step 1, and possibly exceed d_{max}. Moreover, an arrival might be predicted to be involved in a separation conflict with another flight, either an arrival or a departure. In that case, the flight might receive a resolution maneuver by TAR that will add delay to its STA at the final approach fix.

IV. Simulation Results

Three simulation runs were performed, each corresponding to a different level of maximum scheduled delay to be absorbed by a flight, namely 30, 60, or 90 seconds.

Table 1 provides traffic volume statistics for the two airports in the study. At DFW, 900 arrivals and 915 departures were handled, while at DAL 249 arrival and 245 departure flights took place. Since DFW handles nearly four times more traffic than DAL, results will be presented only for DFW airport for the remainder of the paper. It is clarified, though, that TAR did handle air traffic arriving to or departing from DAL in the simulations. And, furthermore, results for DAL were similar to those for DFW.

Table 1. Simulated traffic volume

	DFW	DAL
Total number of arrivals	900	249
Total number of departures	915	245

In Table 2, delay statistics for DFW are presented. The first row includes results for Arrival Spacing Delay and the second row results for Arrival Delay, both defined in section III.C previously. Every column in the table represents a different simulated traffic scenario, which is characterized by the level of maximum scheduled delay per flight d_{max}.

To begin with, both metrics of delay increase from $d_{max} = 30s$ to $d_{max} = 60s$: Arrival Spacing Delay increases by 64%, while Arrival Delay increases by 26%. This is an expected finding since scheduling more delay to be absorbed inside the TRACON, as controlled by doubling d_{max}, should increase total delay for all flights. However, the delay difference between scenarios with $d_{max} = 60s$ and $d_{max} = 90s$ is very small, where delay essentially remains constant. An explanation for this result is that the 5 nmi separation rule at the arrival fixes of the TRACON (see Fig. 2) became the traffic bottleneck for the scenario of $d_{max} = 90s$. In other words, although more delay could have been planned to be absorbed in the TRACON with $d_{max} = 90s$, the scheduling algorithm never utilized the upper bound of 90s because flights had to enter the TRACON with at least 5 nmi separation at the arrival fixes, which prevented delay from increasing to levels higher than in the scenario of $d_{max} = 60s$.

Table 2. Delay statistics

	$d_{max} = 30s$	$d_{max} = 60s$	$d_{max} = 90s$
Total Arrival Spacing Delay (hh:mm)	0:59	1:37	1:37
Total Arrival Delay with full conflict resolution (hh:mm)	4:05	5:09	5:15

Next, Arrival Spacing Delay is compared against Arrival Delay. Regardless of the level of d_{max}, Arrival Delay is substantially higher than Arrival Spacing Delay. Specifically, Arrival Delay is 4.2 times higher when $d_{max} = 30s$, 3.2 times higher when $d_{max} = 60s$, and also 3.2 times higher when $d_{max} = 90s$. The difference between Arrival Spacing Delay and Arrival Delay, as explained in section III.C, is that the former is computed when TAR's conflict resolution module is switched off and only delay due to wake vortex separation requirements is considered.

Examination of simulation trajectories uncovered two primary reasons that can explain this large discrepancy between arrival spacing delay calculated from a scheduler and arrival delay occurred in simulation runs with TAR enabled. First, in many cases resolution of a spacing conflict created a separation conflict with a third flight that TAR's Arrival Manager treated as non-maneuverable, either because it was an arrival with a frozen STA or a departure that had already received another resolution maneuver. Resolution of those additional conflicts would typically cause additional delay, which would result in larger than minimum required separations along the final approach path. These larger than minimum time separations not only increase delay on the particular flight that was being scheduled, but they also propagate backwards to upstream traffic in the same arrival stream.
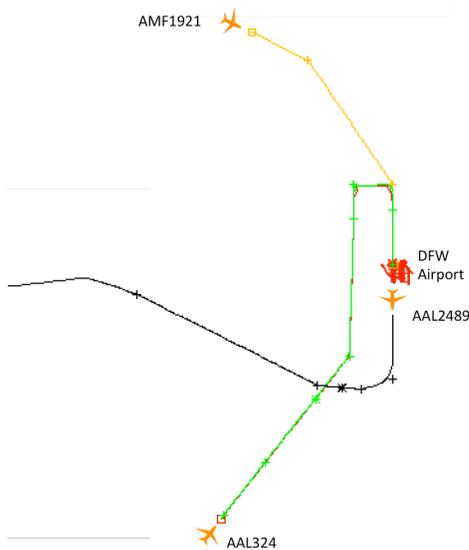
Figure 3a. Example of spacing secondary conflict.
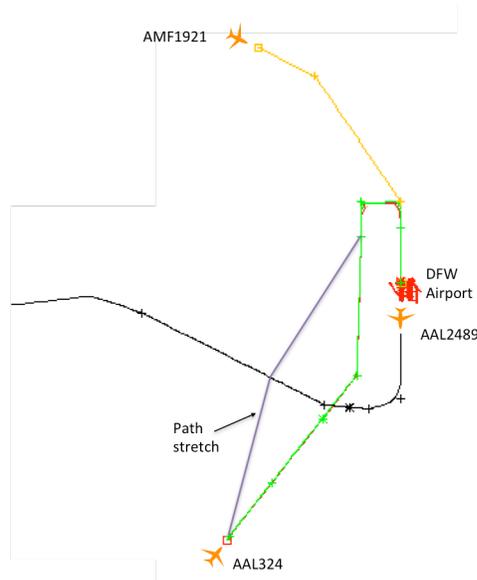
Figure 3b. Example of spacing conflict resolution.

This situation is illustrated in Fig. 3a. Flight AAL324 is being scheduled behind the already scheduled AMF1921. Arrival Manager estimated that in order for the minimum required separation on final approach between the two flights to be attained AAL324 must be delayed by 10 seconds, which is the Arrival Spacing Delay for this flight. Doing this, however, will cause flight AAL324 to be in conflict with departure flight AAL2489. After unsuccessful attempts to find a conflict-free trajectory through maneuvering departure AAL2489, TAR found a conflict-free trajectory by assigning a path-stretch combined with speed reduction maneuver to AAL324 as shown in Fig. 3b. This maneuver, though, resulted in an additional 30s of delay to AAL324, yielding a total 40s of Arrival Delay to this flight.

An example of a staggered conflict is illustrated in Fig. 4. In this situation, flight EGF2723 is being scheduled behind the already scheduled AAL1856 flight, which is going to the same runway 18R at DFW. The Arrival Manager estimated that in order for the minimum required separation on final approach between the two flights to be attained EGF2723 must be delayed by 18 seconds, which is the Arrival Spacing Delay for this flight. TAR initially attempted to absorb this delay by reducing EGF2723's speed. Doing this, however, caused EGF2723 to be in conflict with flight TCF6014 shortly prior to both flights turning on their final approach path and forming a staggered approach for landing on the two parallel runways 18R and 17C, respectively. Since TCF6014 already had a frozen STA to the final approach fix, the Arrival Manager treated it as a non-maneuverable flight and did not attempt any resolution maneuver on it. Consequently, TAR had to continue trying different maneuvers on EGF2723 in order to find a trajectory that satisfies the minimum in-
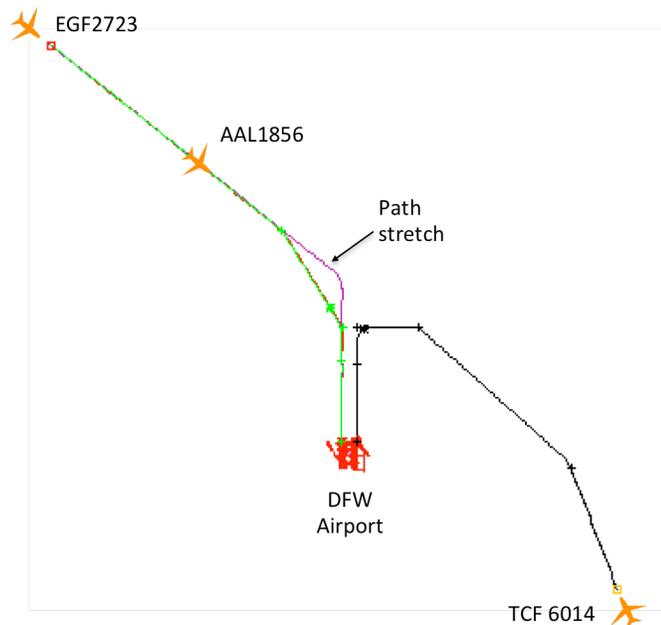
Figure 4. Example of conflict during 'staggered' approach and resolution through path stretch.

trail spacing requirement on final approach with AAL1856 and is free of conflict with TCF6014. Eventually, TAR found a conflict-free trajectory by assigning an extension of final approach combined with speed reduction maneuver to EGF2723 as shown in Fig. 4. This maneuver, though, resulted in an additional 40s of delay to EGF2723, yielding a total 58s of Arrival Delay to this flight.

Another such example is illustrated in Fig 5. Flight EGF2946 was being scheduled for landing on runway 17C behind flight EGF3414. Arrival Manager had determined that no delay was needed for EGF2946 to meet minimum in-trail separation requirement on final approach with EGF3414. However, TAR detected a separation conflict between EGF2946 and another flight, EGF3280, which was going to land on parallel runway 18R and it was going to be on a staggered approach with EGF2946. The conflict was predicted to occur while both aircraft were turning onto final approach for landing on parallel runways 17C and 18R. To avoid this conflict, TAR delayed flight EGF2946 by 40s by issuing a speed reduction maneuver to the aircraft. In real-world practice, air traffic controllers sometimes address this problem by ensuring that flights are separated more than 1000 feet vertically as they turn onto their final approach path. To achieve that, they will most likely extend the downwind leg of EGF2946 in order for its turn to approach path to the runway to occur later than EGF3280. But regardless of the type of maneuver, speed reduction by TAR and extension of the downwind leg in actual practice, delay had to be issued in order to avoid the
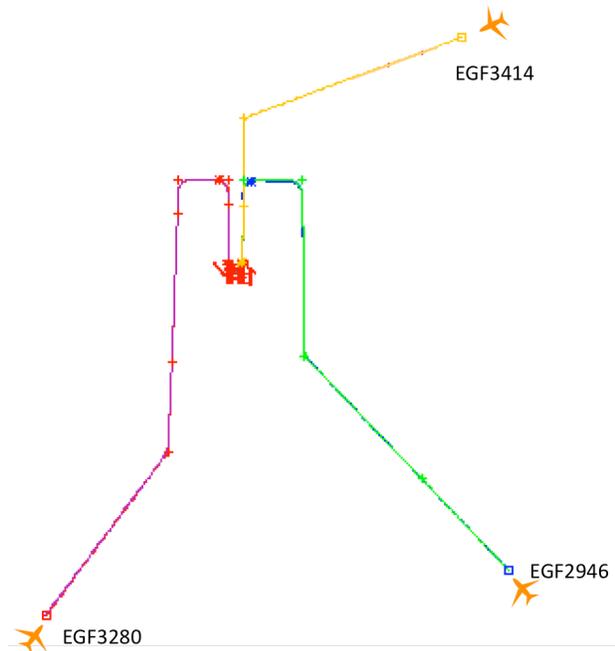
Figure 5. Example of conflict during 'staggered' approach.

separation conflict with the flight landing on the parallel independent runway. This type of conflict, and subsequent delay, could not have been predicted by the scheduling algorithm because the scheduling algorithm considers only one runway at a time when it assigns STAs to landing traffic. As a result, Arrival Delay includes delay due to not only scheduling of aircraft at the FAF, but also due to secondary conflicts that arise as part of the scheduling process.
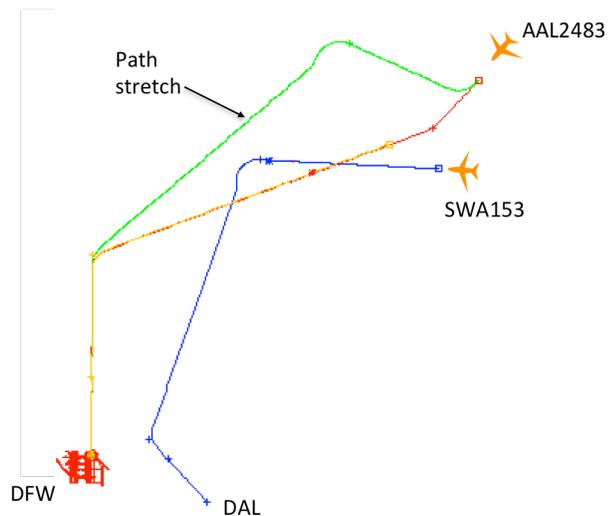
A second factor that contributes to the discrepancy between Arrival Delay and Arrival Spacing Delay is when the additional delay from avoiding secondary conflicts propagates upstream because there are no gaps in the arrival stream. In that case the delay effect is amplified since it causes more than one flight to be scheduled later than their estimated time of arrival at the FAF. This is illustrated in Fig. 6, which continues the discussion on the previous example. In this Figure, a timeline of arrivals on runway 17C is illustrated. The upper horizontal line shows the Estimated Time of Arrival (ETA) at runway 17C of each flight, while the lower one corresponds to the Scheduled Time of Arrival (STA) for landing issued by the Arrival Manager. To start with, it can be seen that the difference between EGF3414's STA at the runway and EGF2946's ETA is above three minutes, which is higher than the minimum required 84s. However, due to the situation described previously in Fig. 5, EGF2946 receives 40s of delay to avoid a separation conflict with EGF3280 as it turns to final approach. Next, flight OPT852 requires 106s of separation between the aircraft in front of it, which is flight EGF2946. The difference in ETAs between in two flights is 75s. Had EGF2946 not been assigned delay due to the secondary separation conflict, OPT852 would need only 31s of delay to meet the required separation with EGF2946. Instead, OPT852 needs $106 - 75 + 40 = 71$ s of delay to maintain minimum required separation with EGF2946, an additional 40s from the initial estimate of 31s. Using a similar method, it is calculated that EGF2731 needs 54s of delay to meet its required 97s separation with OPT852, instead of 14s initially. Therefore, one can calculate that the predicted conflict between EGF2946 and EGF3280, see Fig. 5, as both aircraft turn to final approach caused delay that propagated backwards and resulted in $3x40 = 120$ s of delay. That amount of delay was not predicted by the initial scheduling algorithm, but it was encountered by the Arrival Manager during the simulation.

American Institute of Aeronautics and Astronautics
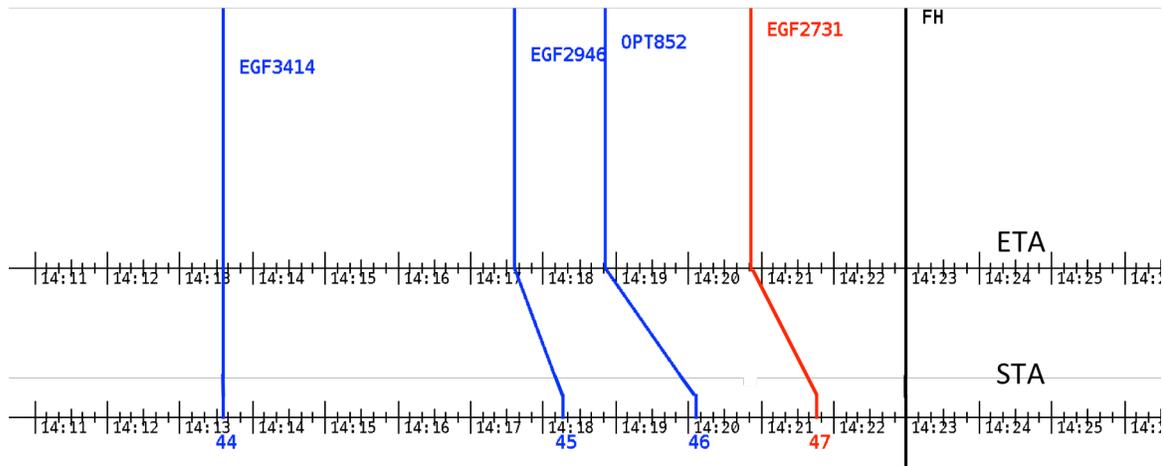
Figure 6. Snapshot of arrival timeline on runway 17C.

The above discussion provided examples of how secondary conflicts encountered during the arrival scheduling process can increase the scheduling delay of arrivals and propagate backwards adding delay to upcoming arrivals. It is due to these phenomena that Arrival Spacing Delay appears significantly lower than Arrival Delay.

Apart from spacing conflicts that occur on final approach, arrivals might be involved in general separation conflicts with other aircraft. Fig. 7 provides an example where two arrivals going to different airports are involved in a separation conflict with each other. In particular, flight AAL2483 going to DFW is involved in a separation conflict with flight SWA153 that is going to DAL airport. Since SWA153 had already crossed the freeze horizon and had been assigned an STA for arrival, TAR attempted to maneuver only AAL2483. A path-stretch maneuver was found, shown in the Figure, which cleared the conflict and resulted in 54s of Arrival Delay for AAL2483.

Table 3 presents statistics on the type of maneuver used to resolve the conflicts encountered in the various traffic scenarios. The number of arrivals that were maneuvered in order to resolve a conflict was split into those that were assigned a speed maneuver only and to those that were assigned a maneuver that was

Figure 7. Example of separation conflict between two arrivals and path stretch resolution.

a combination of speed and route-change maneuver. The latter includes path-stretch maneuvers, extensions of final approach, extensions of downwind leg, and in general any maneuver that changes the horizontal path. This metric is of particular interest since it shows what percentage of aircraft can adhere to Required Navigation Performance (RNP) approaches, without having to change their horizontal path to the runway.

Table 3. Resolution maneuver statistics for arrivals

	$d_{max} = 30$s	$d_{max} = 60$s	$d_{max} = 90$s
Number of arrivals	900	900	900
Number of arrivals maneuvered	298	338	343
Number of speed resolutions (arrivals)	196	214	209
Percentage of arrivals with speed resolutions	22%	24%	23%
Number of route-change resolutions (arrivals)	102	124	134
Percentage of arrivals with route-change resolutions	11%	14%	15%

Of all arrivals, the percentage of those receiving a speed control maneuver ranged between 22% and 24%, while the percentage of arrivals that required a route-change ranged between 11% and 15%. The high percentage of route-change resolutions is due to the fact that many conflicts, including spacing conflicts on final approach, cannot be resolved with speed reduction only. Examples of this situation were provided in Figs. 3,4, and 6. The results imply that even if the rate of arrivals in the TRACON is metered, for example with d_{max} of 30s, numerous conflicts still arise that cannot be resolved with only speed reduction but require a change of horizontal route.

A similar analysis was performed in a study involving the Terminal Sequencing and Spacing system[3], a controller's decision support tool for arrival management. Comparing the results from that study, however, cannot be performed in a direct way. The main reasons are that the simulation experiment described in [3] did not include any departure traffic and it considered traffic into only one major airport, namely Phoenix Sky Harbor International Airport (PHX), whereas in this study arrival and departure traffic to both DFW and DAL airports was considered. As a result, simulations in this present study represent more complex traffic patterns than in [3], and therefore a direct comparison of conflict resolution results between the two studies is not possible.

V. Concluding Remarks

This paper examined the effectiveness of an automated system for air traffic control in TRACON airspace under several traffic scenarios. Using the Dallas-Fort Worth TRACON airspace as the testing environment, the Terminal AutoResolver (TAR) was used to handle several daily traffic scenarios that are characterized by the rate at which air traffic is metered into the TRACON airspace. For each traffic scenario, two main metrics of performance are examined: the amount of delay, and the types of resolution maneuver used to resolve conflicts.

In all traffic scenarios an initial estimate of delay due to wake-vortex separation requirements on final approach is computed by the TAR scheduling algorithm. This is called Arrival Spacing Delay. Next, simulation runs are conducted and it is found that the actual delay incurred by all arrivals is at least two times higher. This discrepancy is primarily attributed to two types of separation conflicts that cannot be predicted a-priori by the scheduling algorithm: conflicts with other traffic and conflicts with other flights while they turn onto the final approach path of a parallel independent runway.

It is also found that of all conflicts combined, including separation and spacing on final approach, the percentage of arrivals that required a route-change resolution ranged between 11% and 15% in all three scenarios of traffic. These results suggest that an automated system for air traffic control should be able to resolve conflicts by issuing maneuvers that change the horizontal path of an aircraft, thereby causing it to deviate from its preferred route to the runway. It would require those aircraft to modify their RNP routes in TRACON airspace, adding to pilot workload.

Finally, the long term objective of the research is to create and validate a system design that provides the basis for an autonomous air traffic control system where routine controller tasks can safely be delegated to the autonomous agent and controllers can instead focus on handling special problems that require a human's unique problem solving skills.

Acknowledgments

References

[1]Erzberger, H., Nikoleris, T., Paielli, R., and Chu, Y-C. "Algorithms for control of arrival and departure traffic in terminal airspace", Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering, published online before print, doi: 10.1177/0954410016629499, 2016

[2]Nikoleris, T., Erzberger, H., Paielli, R., Chu, Y-C. "Autonomous system for air traffic control in terminal airspace", AIAA ATIO Conference, paper # 2014-2861; doi: 10.2514/6.2014-2861; 2014.

[3]Thipphavong, J., Jung, J., Swenson, H., Martin, L., Lin, M., and Nguyen, J., "Evaluation of the terminal sequencing and spacing system for performance-based navigation arrivals," *32nd IEEE/AIAA Digital Avionics Systems Conference* (DASC), 2013.

[4]Swenson, H. N., Hoang T., Engelland S., Vincent D., Sanders T., Sanford B., and Heere K., "Design and Operational Evaluation of the Traffic Management Advisor at the Fort Worth Air Route Traffic Control Center," *First USA/Europe Air Traffic Management Research and Development Seminar*, Online Proceedings, 1997.

[5]Davis, T. J., Krzeczowski, K. J., and Bergh, C., "The Final Approach Spacing Tool," IFAC Thirteenth Symposium on Automatic Control in Aerospace, Palo Alto, CA, Sep. 1994.

[6]McNally, D., Sheth, K., Gong, C., Sahlman, S, Hinton, S., Lee, C., Sterenchuk, M., and Shih, F-T, "Dynamic Weather Routes: two years of operational testing at American Airlines," *Eleventh USA/Europe Air Traffic Management Research and Development Seminar* (ATM2015).

[7]George, S., Satapathy, G., Manikonda, V., Palopo, K., Meyn, L., Lauderdale, T. A., Downs, M., Refai, M., and Dupee, R., "Build 8 of the Airspace Concept Evaluation System," AIAA Modeling and Simulation Technologies Conference, No. AIAA-2011-6373, Portland, OR, 2011.

[8]"User Manual for the Base of Aircraft Data (BADA) Revision 3.9," Eec note no. 11/08, Eurocontrol Experimental Centre, November 2008.