A NOVEL APPLICATION OF THE TERMINAL SEQUENCING AND SPACING SYSTEM TO CONVERGING RUNWAY OPERATIONS IN A SIMULATED NEXTGEN ENVIRONMENT

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Abstract

In 2013, the Airspace Operations Laboratory at NASA Ames Research Center conducted a human-in-the-loop simulation that examined the feasibility of applying a number of Next Generation Air Transportation System (NextGen) solutions to complex arrival operations in and around the New York metroplex. The delivery of arrivals to Newark Liberty International Airport (EWR) was the focus of this simulation, which involved extending the Terminal Sequencing and Spacing (TSS) scheduling capability to precisely schedule arrivals to intersecting runways 22 Left and 11.

An important enabler for the concept was the availability of a dependent runway scheduler that was able to coordinate arrival times between aircraft landing on intersecting runways. At the time of the study, there was no functionality within the TSS scheduler to automatically create the dependent runway schedules. Instead, a Traffic Management Coordinator (TMC) manually created a de-conflicted schedule, which allowed for the concept to be tested as well as provided valuable insight into the tool requirements for a dependent runway scheduler.

Throughout the course of preparations for the simulation, the individual serving as the TMC developed a number of strategies and procedures for manually adjusting the Scheduled Time of Arrival (STA) of the EWR arrivals in order to ensure that adequate spacing was provided between runway 22L and 11 arrival pairs. This paper describes the strategies and procedures that were developed and details how they were successfully applied during the simulation. Results will also be presented that shed additional light on exactly how the schedules were manipulated and their impact on delivery performance and safety. Ideas for additional TSS enhancements and next steps, based on participant feedback, will also be presented.

Introduction

Within the National Airspace System (NAS), there are a number of areas in which air traffic operations pose significant challenges to operators and stakeholders. However, few areas, if any, rival the operational complexity and influence of the New York metropolitan area. The complexity of the airspace combined with the consistent demand for access and frequent weather events results in inefficiencies and a disproportionate amount of delay [1]. The effects of these delays, however, are not confined to the region, but are felt throughout the NAS.

As part of NASA's earlier NextGen Future Environments research effort, the airspace in and around the New York area was selected as the environment in which to test the application of certain NextGen technologies and procedures. The goal was to understand the efficacy and feasibility of such an approach in a very complex, highly constrained environment.

HITL Simulation

A human-in-the-loop simulation was conducted at NASA Ames Research Center in the Airspace Operations Laboratory that examined high density arrival operations to Newark Liberty International Airport (EWR) in clear weather operations. Of particular interest was how the application of NextGen tools and procedures could aid in arrival operations involving a converging runway configuration with a physical intersection such as the runway 22 Left (22L) and runway 11 configuration used at EWR today (Figure 1).

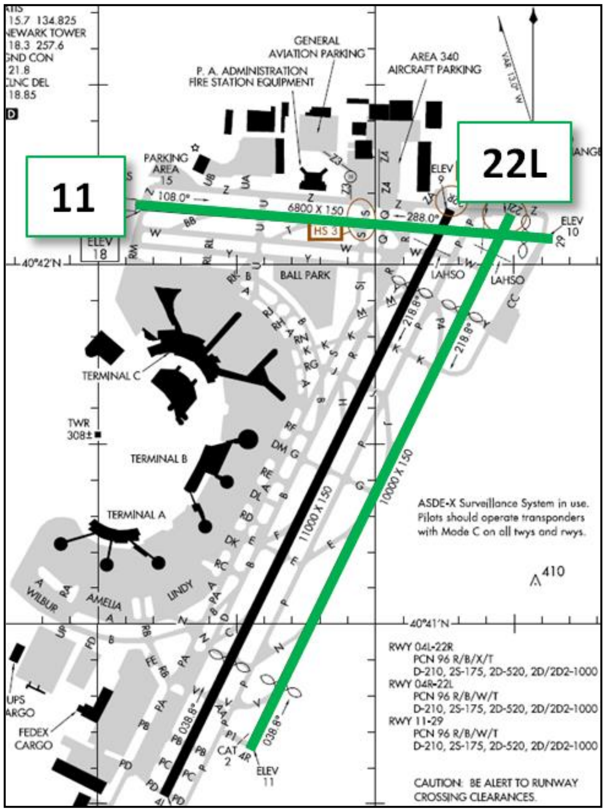

Figure 1. Chart of EWR with converging runways 22L and 11 highlighted in green

Terminal Sequencing and Spacing System

A key enabler for testing high density arrival operations in the 22L-11 configuration at EWR was the use of the Terminal Sequencing and Spacing (TSS) system [2]. The TSS system is a suite of technologies that provides scheduling and controller support for enhanced precision of delivery to the runway. The scheduling component within TSS is the Traffic Management Advisor (TMA) [3], which is a scheduling tool used to develop an arrival sequence and Scheduled Times of Arrival (STA) assignments with de-conflicted merge points to aircraft landing on either independent runways or to parallel, dependent runways. Controller-Managed Spacing (CMS) tools, as part of TSS, provide decision support to controllers in sequencing, spacing, and schedule conformance in the TRACON [4]. Despite the enhancements that TSS provides, scheduling to converging runways within TMA is currently not supported. Through this simulation, TMA was adapted for application in a new operational context in which de-conflicted arrival scheduling to converging runways was successfully achieved through manual intervention.

Experiment Design

The experiment design of the simulation included a Baseline and Future Environment condition (FE2). A full description of the simulation with comprehensive results can be found in [5]. Common to both conditions were Area Navigation (RNAV) arrival procedures designed to provide Optimum Profile Descent (OPD) trajectories, which allowed for more efficient delivery of arrivals to the runway with greater predictability and reduced control instructions. Figure 2 presents the arrival routings to EWR that were used and adapted into TMA for scheduling.

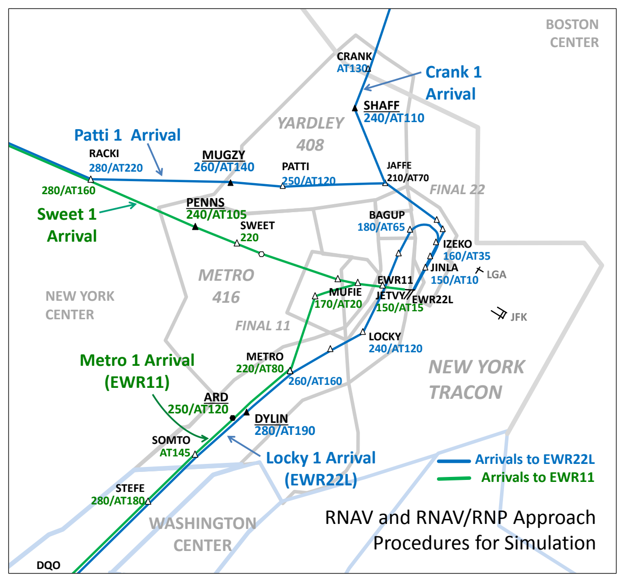

Figure 2. Arrival procedures to EWR

In the Baseline condition, TRACON controllers attempted to deliver aircraft to the runway via the defined OPD procedures with minimal intervention and without the requirement to adhere to a schedule. Although a TRACON Runway Coordinator position worked to provide the controllers with a manageable sequence, it was often necessary for the arrivals to runway 11 to be vectored off of their lateral trajectory in order to ensure a safe delivery sequence with the predominant flow of 22L arrivals to the converging runways. To aid in this task, the final controller for runway 11 was provided with the Converging Runway Display Aid (CRDA) to visualize the position of runway 22L arrivals relative to the runway 11 arrivals in order to ensure adequate separation at the runway threshold [6]. Overall, the Baseline condition served as a point of comparison to highlight differences in performance, safety, efficiency, and throughput.

In the FE2 condition, TSS support was provided in the form of scheduling and decision support tools. TRACON controllers were provided with timelines integrated with their displays, which provided better awareness of the arrival sequence and the associated schedule conformance. Additionally, slot markers were displayed for each aircraft that enabled the TRACON controllers to conform to the STA more precisely. The final controller for runway 11 continued to have the CRDA displayed for additional support. Enhancements to the TMA scheduler were also provided that enabled schedule adjustments in support of converging runway operations to be performed manually by a Traffic Management Coordinator (TMC) position – referred to hereafter as the arrival planner.

Arrival Planner Position and Problem Description

The simulation focused on an arrival problem that involved a runway configuration consisting of converging runways 22L and 11. Because TMA is currently unable to develop a de-conflicted schedule for such a configuration, the decision was made to emulate such functionality through the actions of an arrival planner that created dependent schedules (i.e., de-conflicted runway threshold times) for the 22L and 11 arrivals by manually adjusting the STAs of specific aircraft using the TMA timeline. It should be noted that ideally this functionality would be incorporated into TMA at some point such that de-conflicted intersecting runway scheduling would be performed without the need for manual adjustments.

The role of the arrival planner position in this simulation was multi-faceted. This individual served as a schedule monitor, cross-facility coordinator, in addition to schedule de-confliction. Although each role was important and deserving of further detail, this paper will focus on the arrival planner's role and actions as they pertain particularly to using TMA to de-conflict arrivals landing on converging runways. To understand how TMA was used in this context, however, it is first important to understand the nature of the problem that the arrival planner was tasked to solve.

Converging Runway Configuration

The primary concern with converging runway operations is that two aircraft will be present on the same runway simultaneously. Therefore, it is important to ensure that an arrival on one runway is clear of the runway intersection in advance of the next arrival on the other runway. From Figure 1, it can be seen that the geometry of the runway 22L-11 configuration is such that the intersection is near the threshold of 22L and at the far end of runway 11. This difference meant that arrivals to 22L cleared the intersection quickly while the time necessary for an arrival to 11 to reach and clear the intersection was greater. The greater time requirement also meant that there was greater uncertainty associated with the timing and ability for runway 11 arrivals to reach the intersection and clear the runway in the event of a "go-around." As a result, when considering the sequence of arrivals to both runways in terms of how to pair the aircraft, 22L arrivals were always assigned as the lead aircraft and runway 11 arrivals as the following aircraft. Based on this pairing assignment, the guideline used for ensuring adequate spacing at the runway was for the 22L arrival to be clear of the intersection by the time the runway 11 arrival reached its threshold (see Figure 3).

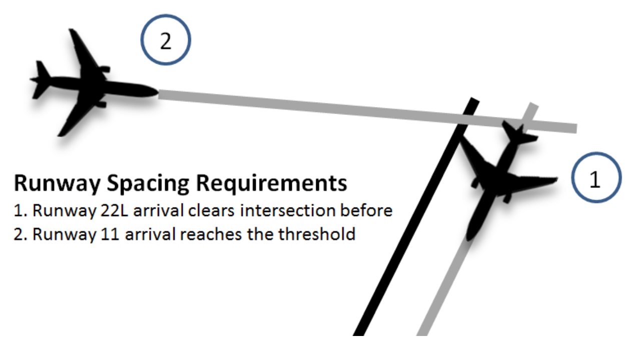

Figure 3. Requirements for adequate spacing at the runway for arrivals to runways 22L and 11

Arrival Traffic

The arrival scenarios developed for the simulation involved a mix of jet traffic from various directions scheduled over one of five meter fixes to the runways. Traffic to 22L was the predominant arrival flow and, after accounting for standard wake vortex spacing and a 0.3 nautical mile (NM) spacing buffer, resulted in a fairly tight TMA schedule with consistent and sustained demand. Runway 11 is used as an overflow runway in today's operations. Accordingly, the arrival flow to 11 was at a reduced rate with seven NM in-trail-spacing. However, the rate was still much higher than what is observed today. The in-trail spacing requirements for 22L arrivals were such that the schedule for 22L was created without need for extra spacing to accommodate arrivals to 11.

To aid the TRACON controllers in delivering arrivals to the schedule, slot markers were provided as a visual representation of an aircraft's STA (Figure 4). The slot markers allowed the controllers to quickly see where a given aircraft was relative to its STA and better estimate the actions required to bring it into conformance if necessary. The position of the slot markers was directly tied to the aircraft's STA, and, as a result, was affected by the arrival planner's adjustments to the schedule.

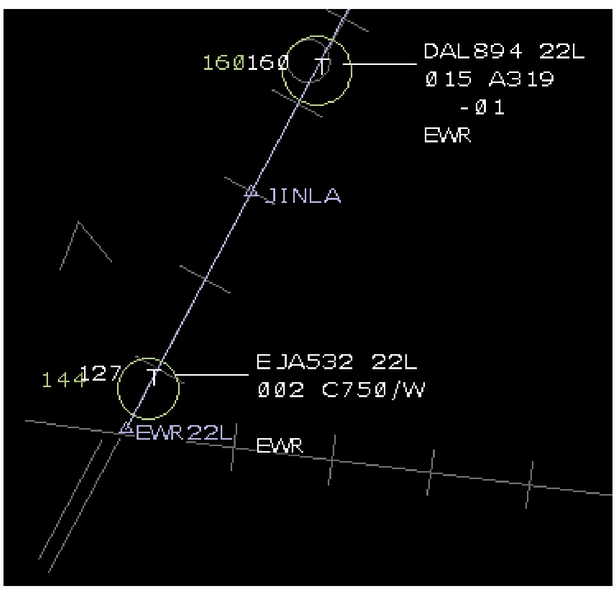

Figure 4. Example of slot markers on a TRACON controller's display

Arrival Planner Considerations and Strategies

In the absence of TMA functionality for dependent runway scheduling to converging runways, the task of the arrival planner was to essentially create a dependent schedule for the two runways by ensuring that the STA for runway 11 arrivals was de-conflicted with the 22L arrivals in accordance with the requirement for the runway 11 arrival to reach the threshold only after the 22L arrival had cleared the intersection. The arrival planner was able to perform this task by manually interacting with the TMA timelines and adjusting the STAs of the arrivals to runway 11 so that they were appropriately paired with the 22L lead with proper spacing. What follows is an explanation of the considerations that the arrival planner needed to account for in performing this task as well as the strategies used.

Converging Runway Schedule De-confliction

In order to facilitate the emulation of dependent scheduling to converging runways, the arrival planner was given a combined runway timeline in addition to the timelines for the individual runways as shown in Figure 5. This combined timeline combined the STAs for both runways on one side and their associated estimated time of arrival (ETA) on the other. By combining the two timelines into one, the arrival planner was able to see the scheduled and estimated order of arrivals to each runway relative to one another, which subsequently better enabled the identification and pairing of the appropriate arrivals.

To create a dependent, de-conflicted schedule in TMA for the 22L-11 configuration, the arrival planner first needed to identify eligible pairs for the two runways. Eligible pairings were decided upon according to the position of a 22L arrival's STA relative to a runway 11 arrival's STA on the combined runway timeline. Typically, the runway 22L arrival with its STA closest to the runway 11 arrival's STA was selected as the lead.

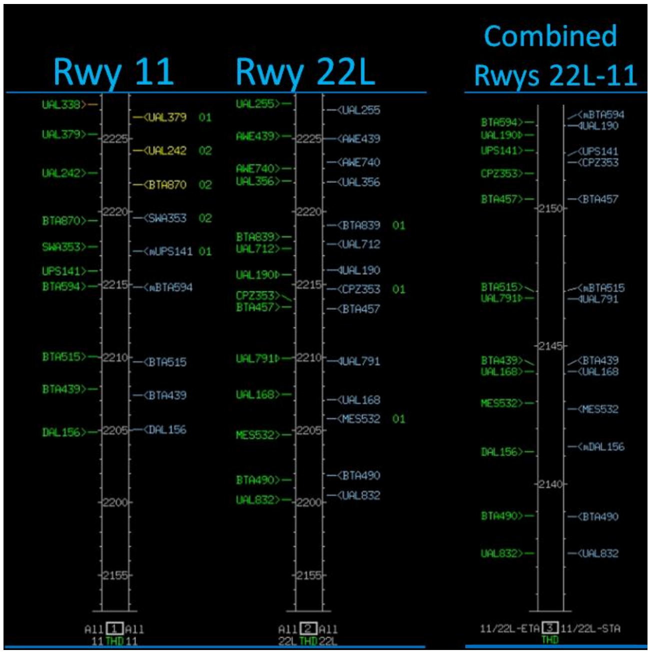

Figure 5. TMA Timelines used by the arrival planner

Once a pair was identified, the next step was for the arrival planner to adjust the 11 arrival's STA behind the 22L arrival's STA to ensure that the arrival pair was de-conflicted at the runway while providing proper spacing with subsequent arrivals. In performing schedule adjustments, three primary considerations were incorporated into the arrival planner's strategy:

- Timing and Location: When/where to adjust the schedule
- Coordination: Requirements for communication between arrival planner and facilities
- Inter-arrival spacing: The optimal spacing of a runway 11 arrival relative to its 22L lead and the next 22L arrival (i.e., the "sweet spot")

Timing and Location

With respect to when and where to begin adjusting the TMA schedule, the arrival planner learned that it was best to begin adjustments as soon as possible before entering the TRACON airspace. This meant that as soon as both aircraft in a given pair had frozen STAs and stable ETAs, the arrival planner was able to begin making adjustments. The freeze horizons were configured such that the STAs for 22L arrivals were frozen before the 11 arrivals. Therefore, the arrival planner waited for the 11 arrival's ETA to stabilize and have its STA frozen, then proceeded to make the STA adjustment relative to its 22L lead.

Coordination

Prior to the actual STA adjustment on the TMA timeline, some level of coordination between the arrival planner and the supervisors from the simulated en route and TRACON facilities took place. In the context of runway de-confliction, coordination simply involved notification of the arrival planner's intent for making a schedule adjustment on particular aircraft. This was done in order to ensure that controllers owning the affected aircraft could anticipate the schedule adjustment and subsequent delay re-calculation and work accordingly.

Inter-arrival spacing

To create a de-conflicted, dependent schedule, the arrival planner worked to interleave runway 11 arrivals between successive 22L arrivals by manually adjusting the STAs of runway 11 arrivals on the combined TMA timeline. The arrival planner developed a strategy for performing this function by using the position or angle of the runway 11 arrival's STA leader line on the timeline, relative to its 22L lead, as a visual cue that translated to desired spacing at the runway. After exploring the effects of various angles, the arrival planner found that the ideal angle for ensuring a de-conflicted runway schedule was approximately 30 degrees. Figure 6 presents a basic sequence that the arrival planner followed in adjusting the schedule to achieve the desired runway spacing.

While effective during the simulation, the general method of runway de-confliction using visual cues is subject to potential complications and inconsistencies. For example, changes to the scale of the combined timeline would result in changes to the angles of the STA leader lines. Consequently, the adjustment angle used previously would no longer be effective. In order to eventually move toward a more algorithm-based approach to converging runway scheduling in TMA, an analysis of scheduling data was performed that examined how the manual adjustments by the arrival planner translated to differences in STA between converging arrivals.

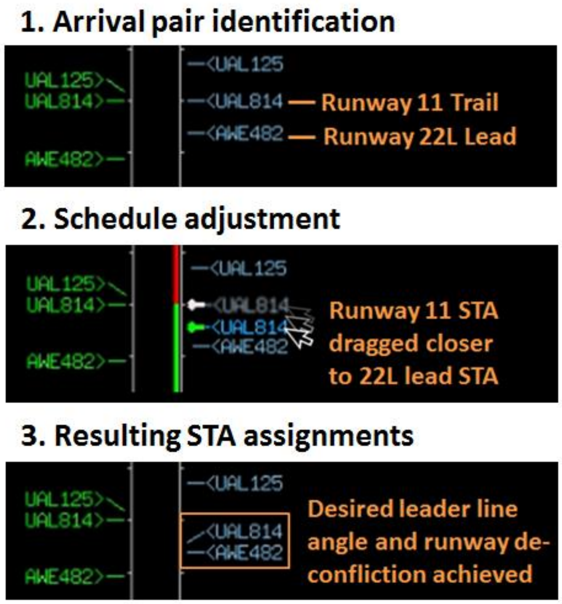

Figure 6. Sequence of STA adjustment performed by arrival planner

Quantitative Data from Arrival Planner's Strategies and Actions

STA adjustment strategy

A total of 89 runway 22L-11 arrival pairs were examined in this analysis. In terms of how the arrival planner performed STA adjustments, Figure 7 presents the degree measurements of the runway 11 STA leader lines as translated from TMA screen recordings and superimposed on a protractor. From this presentation it can be seen that although there was some variance, the highest concentration of leader line angles was within the 25 to 30 degree range, confirming the reported strategy of the arrival planner. Figure 8 represents the translation of the angles into time in the form of a histogram with each bin containing the frequency of occurrences for adjustments that resulted in that particular bin's STA difference. The difference between the STAs was simply derived by subtracting the lead 22L arrival's STA from the trailing 11 arrival's adjusted STA. From these results it can be seen that the schedule adjustments of the arrival planner most often resulted in between a 14- and 18- second difference between the 22L and 11 arrivals' STAs.

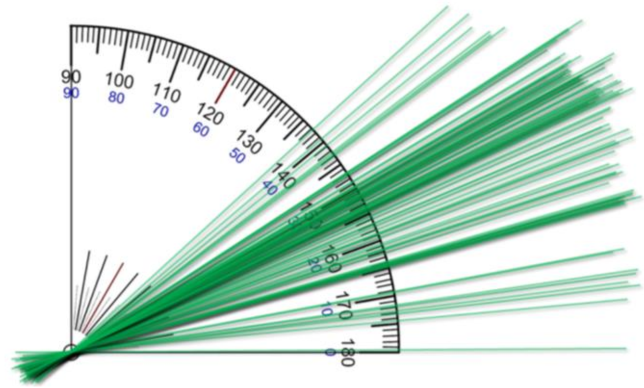

Figure 7. Angle measurements of runway 11 STA adjustments made by the planner

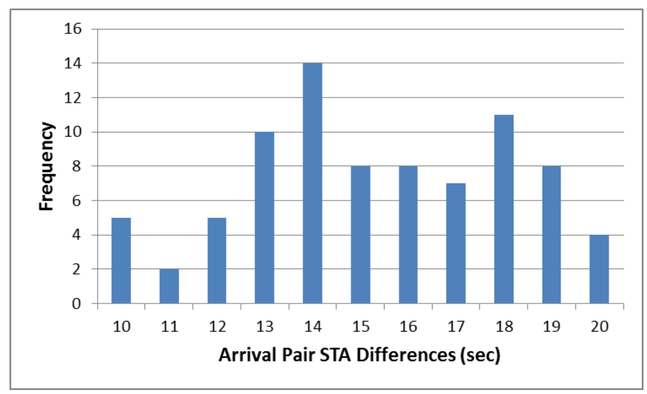

Figure 8. Histogram of arrival pair STA differences following adjustments

Given the results for the STA time differences, it was necessary to see how those values translated to arrival spacing at the runway. Earlier it was mentioned that the STAs for arrivals were represented on the TRACON controllers' displays as slot markers (see Figure 4). The slot markers were used as a visual reference for the controller to more easily assess the schedule conformance of an arrival by comparing the position of the aircraft relative to its slot marker. An important dimension to the arrival planner's adjustments, therefore, was that the resulting STA differences needed to account for some measure of variation in aircraft position. This basically meant that the adjustment of the 11 arrival's STA needed to provide enough buffer so that the aircraft could be at the leading edge of its slot marker and the 22L could be at the trailing edge of its slot marker and still allow for the 22L to clear the intersection before the 11 reached the threshold.

A review of screen recordings from the Final controller for runway 11 was conducted on a number of arrival sequences to determine the effectiveness of different STA offset values at providing adequate spacing at the converging runways. From this review it was found that the 13- and 14-second STA differences were adequate, but left little room for imprecision. Fifteen seconds and greater appeared to provide enough buffer. Figure 9 presents an example of an arrival pair that was given the predominant 14-second STA offset where it can be seen that the runway 11 arrival could have been at the leading edge of its slot marker and would have allowed for the 22L arrival to be at the trailing edge of its slot marker and have tight yet adequate separation through the runway intersection. It should be noted that the arrival planner was careful to avoid scheduling the trailing runway 11 arrival too far off of its lead for fear of not providing enough separation between it and the next 22L arrival. Such a situation could result in a cascade effect where all subsequent arrivals need to be pushed back.

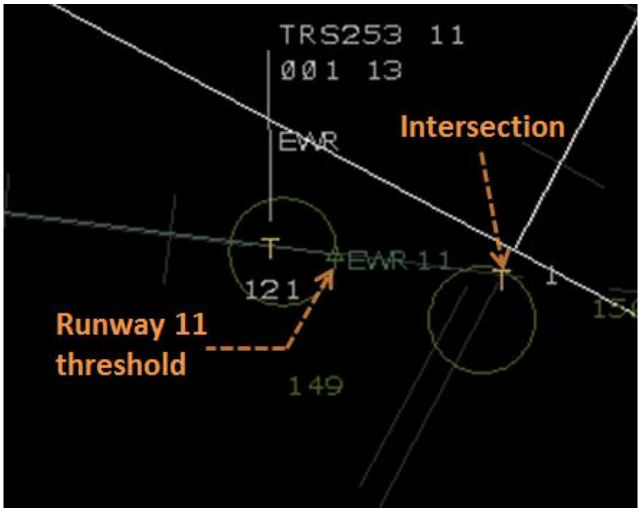

Figure 9. Example of a 14-second STA difference with resulting slot marker location and arrival pair spacing at the runway

Reduced Vectoring

The Baseline condition lacked the enhancements of slot markers and planner-invoked STA adjustments available in FE2. As a result, the final controller for runway 11 was required to anticipate the sequence and spacing of the 22L arrivals in order to safely deliver the runway 11 arrivals between the 22L arrivals. Through coordination, the CRDA, and expertise, the runway 11 final controller was able to deliver arrivals better than one might expect given the nature of the task. However, the means to do so required a great deal of vectoring as shown in the top panel of Figure 10. The plotted trajectories within the bounds of the orange box show the vectoring that was required in order to fit the runway 11 between the runway 22L arrivals. In contrast, the bottom panel of Figure 10 shows that there was no need for vectoring in the FE2 condition due to the work of the arrival planner in adjusting the schedule to integrate the runway 11 arrivals with the runway 22L arrivals.

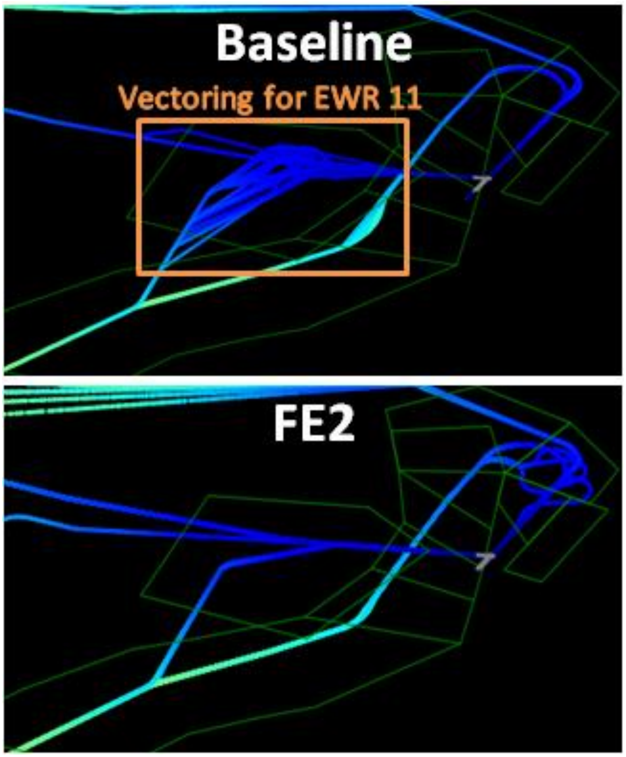

Figure 10. Comparison of arrival trajectories between Baseline (top) and FE2 (bottom)

Delivery to Threshold

Following the examination of arrival trajectories and the differences in required vectoring, the next step in understanding the impact of manual converging runway scheduling was to see how well the runway 11 arrivals were delivered to the runway relative to their leads on 22L. The focus of this part

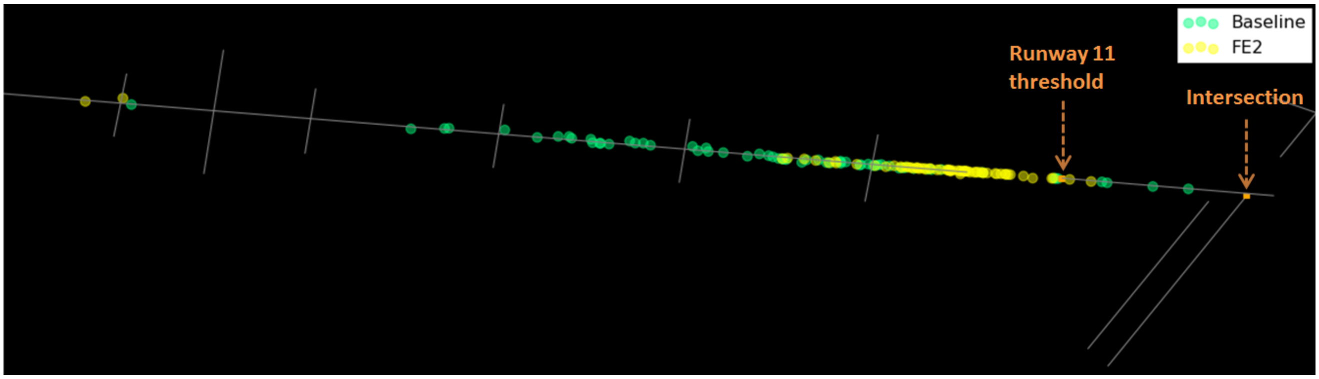

Figure 11. Location of runway 11 arrivals at time of runway 22L lead clearing the intersection

of the analysis was to determine the location of the runway 11 arrivals at the time that their respective 22L leads were just clear of the runway intersection. Figure 11 presents the results of this analysis where it can be seen that the location for the runway 11 arrivals in the Baseline condition (plotted in green) are much more widely spread compared to those in FE2 (plotted in yellow), which are more tightly packed within one mile of the threshold. Figure 12 presents histograms for the distribution of distances per condition with confirmation of this spread: the distribution in FE2 (bottom) is much more tightly clustered around one nautical mile of the threshold whereas the Baseline results (top) are much flatter, widely distributed, and skewed to the right.

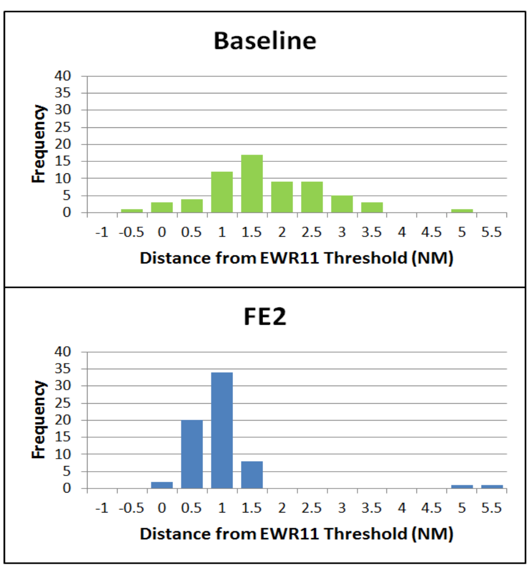

Figure 12. Histogram of distances to runway 11 threshold at time of 22L lead clearing intersection

Results from this analysis speak to the effectiveness and benefit of the arrival planner's schedule adjustments in that the runway 11 arrivals were able to be delivered more predictably and uniformly. In doing so, the landing rate was increased significantly and was accomplished without the need for vectoring or excessive control instructions on the part of the final controller. The planner adjustments also enabled safer arrival operations due to the greater predictability of runway 11 arrivals and the fact that they were able to maintain their trajectories down to the runway.

"Go-around" Violations

The evidence for a higher level of safety enabled by the arrival planner's schedule adjustments can be found in the number of "go-around" violations that occurred in each condition. In today's air traffic operations, a "go-around" can be a very costly event, often with follow-on effects that persist well after. In this simulation, a "go-around" violation was said to have occurred if the runway 11 arrival reached the threshold prior to the runway 22L arrival clearing the intersection or the next 22L arrival was less than 1.5 nautical miles away. In the Baseline condition, a total of 17 such "go-around" violations occurred, which translated to 26% of arrivals resulting in a "go-around." In contrast, there were only three violations in the FE2 condition, which translated to 5% of arrivals. Upon further examination, the three "go-around" cases observed in the FE2 condition were more like edge cases in that they occurred at the upper and lower bounds of the distance criteria. Figure 13 presents a histogram of runway 22L arrival distances to the intersection when the runway 11 arrival had reached the threshold. As noted, the distances in the FE2 condition were just at the edges to be considered a "go-around," whereas the majority of cases in the Baseline condition were squarely within the violation distances.

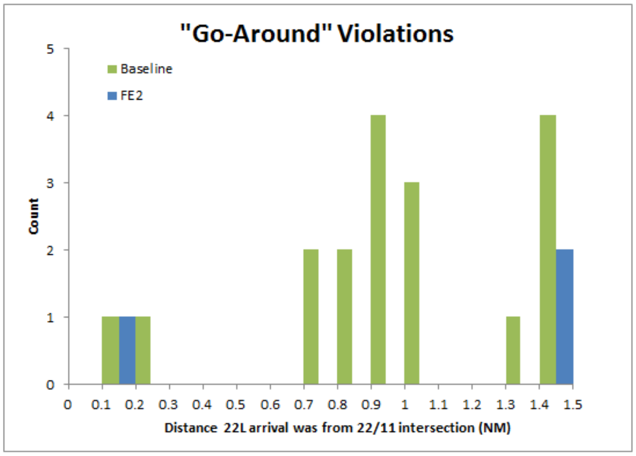

Figure 13. Go-around violation distances for Baseline (green) and FE2 (blue) conditions

Summary

A novel application of TMA to converging runway operations was tested in a human-in-the-loop simulation. An arrival planner developed strategies for creating a de-conflicted converging runway schedule that involved manually adjusting runway 11 arrival STAs relative to 22L arrival STAs on the TMA timeline. This approach resulted in arrival operations that reduced the need for vectoring runway 11 arrivals onto final, enabled more predictable and uniform delivery, and resulted in fewer "go-around" violations.

Improvements to EWR operations, at least in the 22L-11 configuration, hinges on having a dependent runway scheduler for converging runways. In this simulation, a human operator was able to manually create this schedule. However, it would be preferable that the scheduler itself had this functionality because otherwise, it requires a highly skilled arrival planner to be on position to do a fairly manual, intensive job for the concept to work. In order to define the tool requirements for dependent scheduling functionality, this paper described 1) the best heuristic strategies that our arrival planner participant developed and 2) converted those strategies into time-based constraints that can be then implemented in the scheduling tool.

Next Steps

After the simulation was completed, the individual that served as the arrival planner provided feedback on issues in TMA that would benefit from change. Perhaps the primary issue identified was the inability of TMA to assign an STA through a non-manual reschedule that resulted in any amount of negative delay. The arrival planner reported that approximately 60-70% of manual schedule adjustments performed involved moving an arrival's STA forward in time resulting in small but negative delay. The amount of delay created was considered well within reason for the TRACON to be able to absorb without difficulty. Alternatively, attempts to reschedule to an earlier slot often resulted in an aircraft's STA getting shifted essentially to the back of the line, incurring significant positive delay and requiring extra steps to resolve. The ability for TMA to reschedule forward in time would have streamlined the arrival planner's task and enable greater levels of coordination and earlier responses to pending problems.

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