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Maximum Capacity Terminal Area Operations in 2022

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Abstract

Today's primary constraint on an airport's runway capacity is the combination of reduced visibility and wake vortex avoidance. Raytheon is developing an innovative approach to future Terminal Area operations based on using existing parallel runways to their full VFR potential as well as expanding capacity by adding closely spaced parallel runways within the boundaries of today's busiest airports. Raytheon's Terminal Area Capacity Enhancing Concept (TACEC) addresses today's wake vortex capacity constraints by landing and departing multiple aircraft on closely spaced parallel approach corridors. This insures each aircraft operates in a region where the wake vortex location is well known, minimizing the need for in trail separation requirements. VFR operation in IFR conditions is a consequence of the fully automated approach and landing used to achieve safe closely spaced parallel operations. Activities have included a study of very closely spaced parallel runway safety issues as well as the potential capacity increase for the National Airspace System.

Introduction

This paper discusses the overall TACEC concept, a Terminal Area approach for implementation 20 years from now. The core ideas around which the concept is built are reviewed and the key technology drivers for implementation are described. Recent focus has been the evaluation of the capacity gains that are possible and preliminary results are presented. The overall increase in airport arrival and departure rates is driven by the safe operation of aircraft in narrow flight corridors. The trade-off between increased arrival rates and the aircraft's ability to precisely maneuver is reviewed in the context of safety and human vs automated systems performance.

TACEC Overview

The need for significantly increasing the National Airspace System (NAS) capacity 20 years into the future is well established. NASA's Virtual Airspace Modeling and Simulation (VAMS) Program is addressing the challenge by developing new approaches to air traffic management as well as the simulation tools to evaluate the concepts. Raytheon is participating in the VAMS program as both a concept developer under a Space Act Agreement and a simulation developer under contract with NASA's ATMSDI Program. In general the various concept developers are addressing different domains, Gate to Gate, Enroute, Terminal and Surface. Raytheon is addressing the combined domains of terminal airspace and airport surface. The inter-relationship between these two domains establishes the true capacity of the airport.

The VAMS program set air traffic growth at 100% over the next twenty years. Dramatic changes in operations are needed to accommodate this growth and the United States' major airports will face the brunt of the change. If the fundamental nature of airline operations remain "hub and spoke" and travel patterns persist, 40% of our major airports will continue to deal with 80% of the traffic. Table 1 shows the projected growth in operations per hour for the busiest airports.

The column "OEP/2010" reflects the current FAA capacity envisioned in the year 2010. OEP is the FAA's Operational Evolution Plan[1] which addresses the near term changes envisioned to handle the growth in air traffic. The OEP subsection "Arrival and Departure Rate" focuses on the same Terminal Area domain that TACEC deals with and hence may be viewed as an early step in the evolutionary operational changes necessary to handle the increase in traffic. Specifically the OEP achieves growth in Terminal capacity by:

1.) Adding new runways
2.) Redesigning airspace and procedure
3.) Enhancing surface movement

The FAA expects an overall capacity growth of 30% as a result of their 10 year improvement program. Of the 30%, most of the gains are the result of building new runways.

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Table 1. Required Operations in 2022

OPS per HR			
AIRPORT	TODAY	OEP/2010	VAMS/2022
ATL	185	237	426
ORD	200	236	460
DFW	261	316	600
LAX	148	185	340
DTW	143	187	329
PHX	101	132	232
MSP	115	152	265
LAS	84	109	193
MIA	124	153	285
DEN	204	251	469
CVG	123	172	283
BOS	118	125	271
STL	104	135	239

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Raytheon's initial study of capacity increasing ideas for the terminal area addressed the following core ideas;

1. Improved surface traffic management.
2. Integration of departure, arrival, and surface management systems
3. Integration of Airline ramp and gate management within the overall Terminal operation.
4. Reducing Runway Occupancy Times or alleviating their impacts.
5. Reducing Wake Vortex separation constraints.
6. Further decreasing longitudinal separation standards by introducing self separation and self merging of arrival streams
7. Precise 4D delivery of aircraft to the runway threshold
8. Multiple dynamic 4D RNAV approach and departure corridors
9. Alleviation of noise and pollution impacts of airport operations via flight path control and more efficient airport surface operations
10. Potential capacity gains through more autonomous aircraft operations in the terminal area
11. Revolutionize the current paradigm of air traffic c*ontrol* to air traffic m*anagement*. Provide the Human Centered capability to safely and efficiently manage air traffic in the Terminal area.
12. Techniques to permit closely spaced parallel runways in all weather conditions.

In general the application of technology, such as highly accurate surveillance through the use of GPS, was envisioned as the primary means to gain the needed capacity increases.

Interim Results

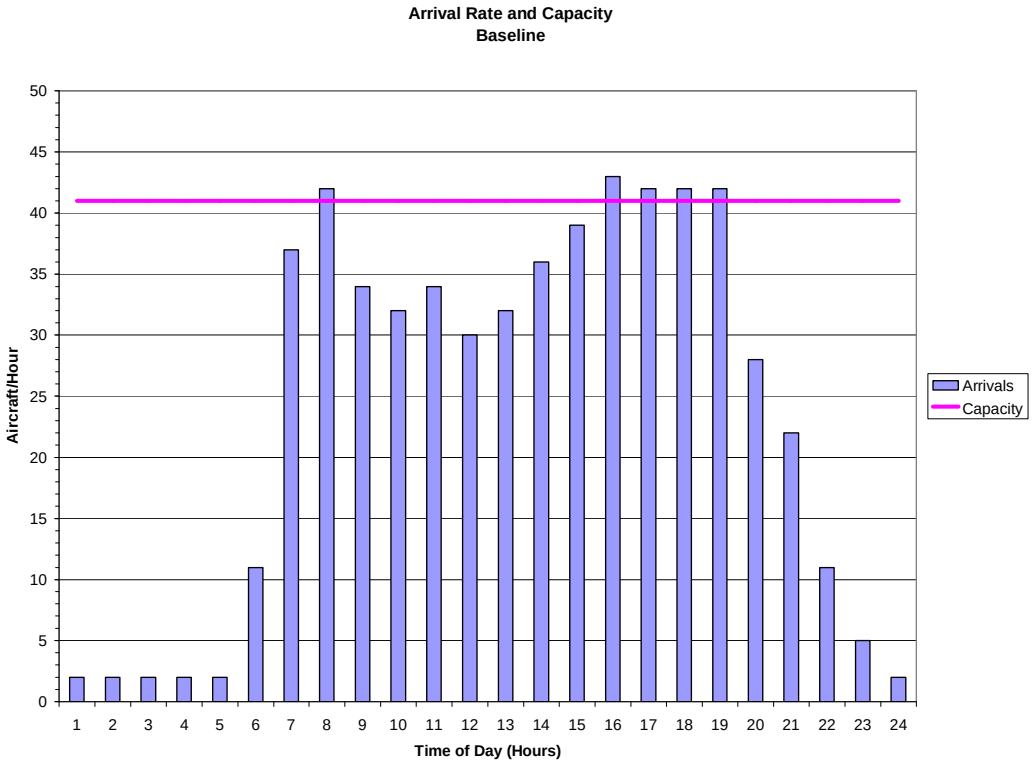
Raytheon conducted a preliminary concept evaluation using a simple queuing model to assess the constraints imposed by terminal airspace volume and airport acceptance rates. The focus of this evaluation was to determine what part of our goal of doubling operations per hour could be accomplished by eliminating inefficiencies in the aircraft's use of terminal airspace.

Our model constrained the airport's landing rates to a level achievable with advanced wake vortex avoidance concepts, namely an in-trail spacing that could approach one minute separations. To approximate our vision of precise 4D trajectory operation within the terminal airspace we allowed increases in the number of aircraft entering the airspace far greater than today's separation standards allow. As the number of aircraft increased we monitored the number of aircraft "on hold". This waiting state is additional time between today's typical terminal airspace flight path and start of a final landing maneuver. This additional holding time was considered a delay, and was deemed unacceptable when it approached normal flight time through the terminal airspace, i.e. the time to traverse through the terminal airspace doubled.

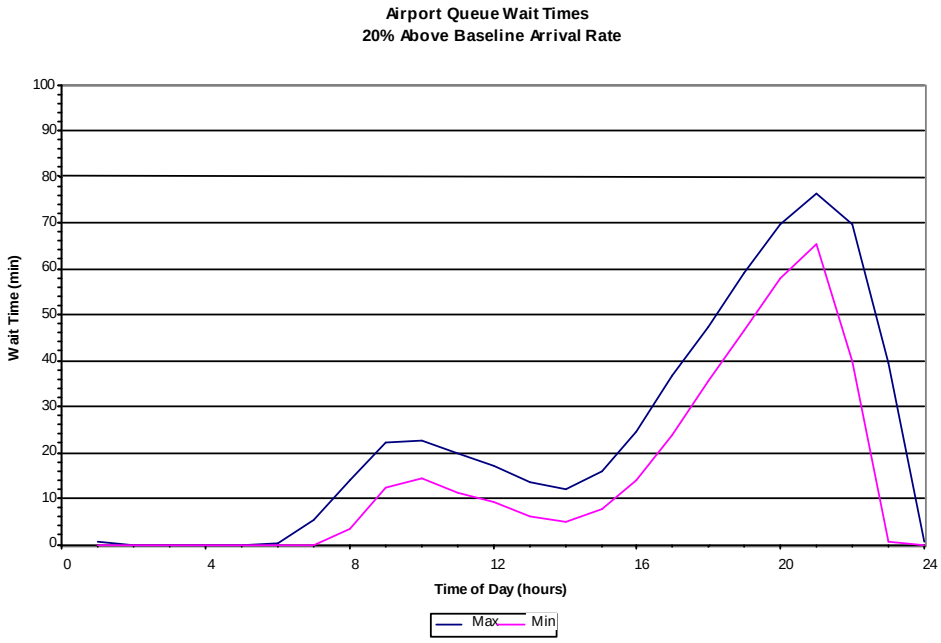
Runs were done for a full day of operation, approximating a typical airport variation in arrivals, shown in Figure 1.

We tracked both the aggregate delay times experienced in the holding queue and the individual aircraft's time in the queue for increasing numbers of arrivals.

As illustrated in Figure 2, for only a 30% increase in traffic, the amount of time spent in the holding queue quickly grew unacceptable, driven by the inability to land the aircraft at the rate they were entering the terminal airspace.



Arrival Rates and Capacity for "Typical" Airport
Figure 1



Aggregate Waiting Time
Figure 2

Based on this simple model it became clear that the fundamental constraint on Terminal operations was landing rate, which is driven by;

1.) Available runways
2.) In trail wake vortex separation requirements for landing on a runway.

Although departures were not modeled, a similar constraint would exist on the departure rate.

Runway occupancy would be the next fundamental constraint if the wake vortex hazard were eliminated. Safe operation on an active runway demands a minimal separation between arrivals, hence time to establish this separation limits the airports arrival rates. Normally this is set by the required in trail separation needed to avoid wake vortex hazards.

Further literature investigations support these conclusions as well. NASA's Terminal Area Productivity program evaluated a similar terminal operational concept for a 30% increase in airport operations (see Reference 2) and various studies of FAST at DFW have indicated a consistent increase in arrival rates of 10-20%.

In general the ability of any terminal area concept to accommodate major capacity growth relies on runway availability. Raytheon has focused our on going concept development on key contributors to providing more usable runways. Real capacity gains require more than just putting more aircraft on the runway threshold. Efficient surface movement and gate availability are required to realize any gains provided by additional runways. Raytheon intends to investigate VAMS Surface Domain concepts currently ongoing to begin a preliminary "blending" activity to gain insight into the key issues.

A summary of core ideas and their contribution to capacity growth is given in Table 2. More parallel runways and efficient surface movement are the key to capacity gains.

Element	Projected Capacity Benefit	Comments
4D Trajectories: Aircraft execution of required trajectories	10-30%	Optimized for current arrival/departure operations (Utilize "FAST" algorithms)
Reduced separation standards	No direct benefit	Necessary to support optimized 4D trajectories
Airborne self separation	No direct benefit	Element of redundancy in fully automated 4D trajectories
Complex finals – curvilinear approaches	Minimal benefit	Primary benefit is noise reduction
Parallel Runways (Multi-aircraft landing)	Linear increase	Fundamental change in terminal operations
Optimized surface movement	Linear increase	Must accommodate multi-aircraft landings

Table 2
Capacity Growth Potential

The Challenge of Additional Runways

To achieve the needed 100% growth in capacity it is clear that additional runways are required. These additions could arise from pouring more concrete or using the existing runways more effectively. Today's operational constraints on using runways for "independent or dependent" operation are delineated in the FAA's operational procedures, FAA 7110.65M. In essence independent operation requires 4500 feet between runways or, if a Parallel Runway Monitoring radar is in use, the separation can be reduced to 3000 feet. Independent runways do not loose significant capacity during IFR conditions

Adding more "independent" runways would require almost 2 square miles of land, impossible for many of the highly used urban airports that will see the bulk of the capacity growth.

The alternative of using existing runways more effectively has been the focus of many FAA studies, "The Airport Capacity Benchmark Report 2001"[3] addresses the top 31 airports in the country. Analysis and assessment of the current arrival and departure rates, as well as projected improvements that arise

from the implementation of the OEP's technology advances are provided. Where applicable, new runway construction benefits are also included in the projected capacity improvements.

There are two rates for each airport – an optimum rate to reflect VMC (clear weather) operations and a reduced rate for IMC (reduced visibility) conditions. This reflects the need to increase separation between aircraft when the controllers are maintaining separation by radar.

It is worth noting that the FAA has projected significant capacity improvements for the addition of new, independent runways. St Louis International's assessment included the addition of a new independent parallel runway, which yielded capacity gains for VMC of 14% while IMC increases of 84%. Providing all weather parallel landings at an airport where poor visibility reduced operations to a single runway significantly improves capacity. Unfortunately most airports cannot provide the 2 square miles needed to construct a new independent runway. A key aspect of the TACEC terminal solution is to maintain VMC like operations during IMC conditions. TACEC has the capability to achieve that same improvement at all the major airports, without demanding large land mass for runway construction.

Wake Vortex Challenge

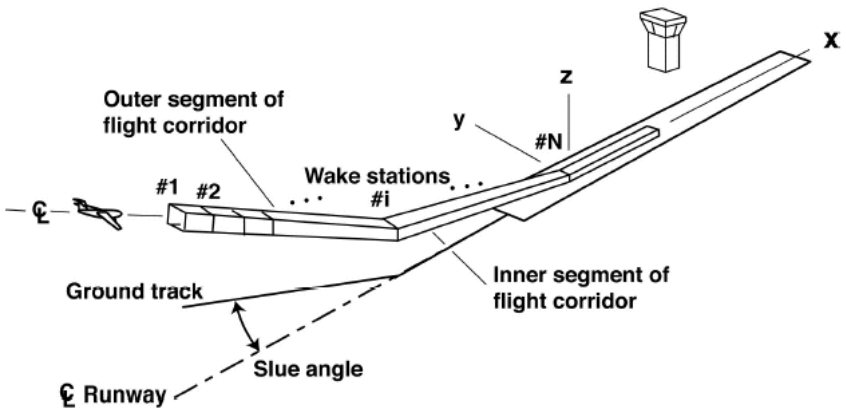
The fundamental limit on the number of aircraft that can land or depart from a runway is their "in trail" spacing, namely how far the following aircraft must stay behind the lead aircraft as they approach the runway threshold. Today's separation standards in Air Traffic Operations and are typically set at 3 miles. the terminal airspace are delineated in FAA7710.65M

However the lift generated vortex wakes generated at the lead aircraft's wing can pose a rolling moment hazard to following aircraft. To avoid this hazard aircraft remain far enough behind a leading aircraft to insure the wake has dissipated and can no longer pose a threat. FAA in trail separation standards are:

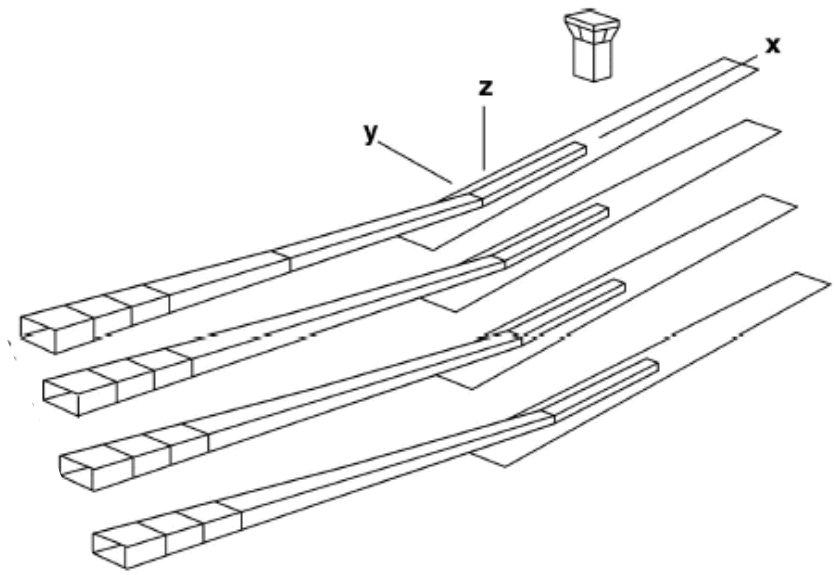
ARRIVAL IMC and low-VMC only Behind Heavy, B757, or other large aircraft Separation Requirements = 4-6 miles	DEPARTURE All times Between Heavy, B757, or other large aircraft Separation Requirements = 4-5 miles or 2 minutes
PARALLEL RUNWAYS IMC and low VMC only Behind Heavy, B757, or other large aircraft Treated as a single runway when runways separated by < 2,500 ft Separation Requirement = 4-6 miles	Intersecting Runways All times When airborne B757 or heavy jet passes intersection Separation Requirement = 4-5 miles or 2 minute wait

To a large extent the separation requirements are designed to accommodate the uncertainty of the wake vortex location. The exact position of the hazardous region is affected by winds, atmospheric conditions, and aircraft configuration. By maintaining a conservative distance between aircraft these uncertainties can be accommodated.

TACEC addresses the wake vortex hazard by taking advantage of the Flight Corridor concept proposed by NASA's Rossow[4]. A Flight Corridor is a defined region in space wherein the hazardous vortex rolling moment can induce no more than 5 degrees of unplanned roll. Typically the corridor would extend from the aircraft's current position to the threshold of it's assigned runway. Flight corridors are dynamic, reflecting the changing nature of vortices. As originally proposed these Flight Corridors would be established by sampling the atmospheric conditions and the aircraft's actual position at different points along the flight path. The vortex generating characteristics of the "leading" aircraft would then be modified with the sampled data over time to establish the breadth and depth of its hazardous region. Flight corridors are established as hazard free regions….hence they need to accommodate not only the wake hazardous region but also the uncertainty of the aircraft's flight path within them.
Figure 3 illustrates a notional Flight Corridor established by sampling data at sequential "wake stations" to get accurate characterization of the regions.



Flight Corridor for Final Approach
Figure 3



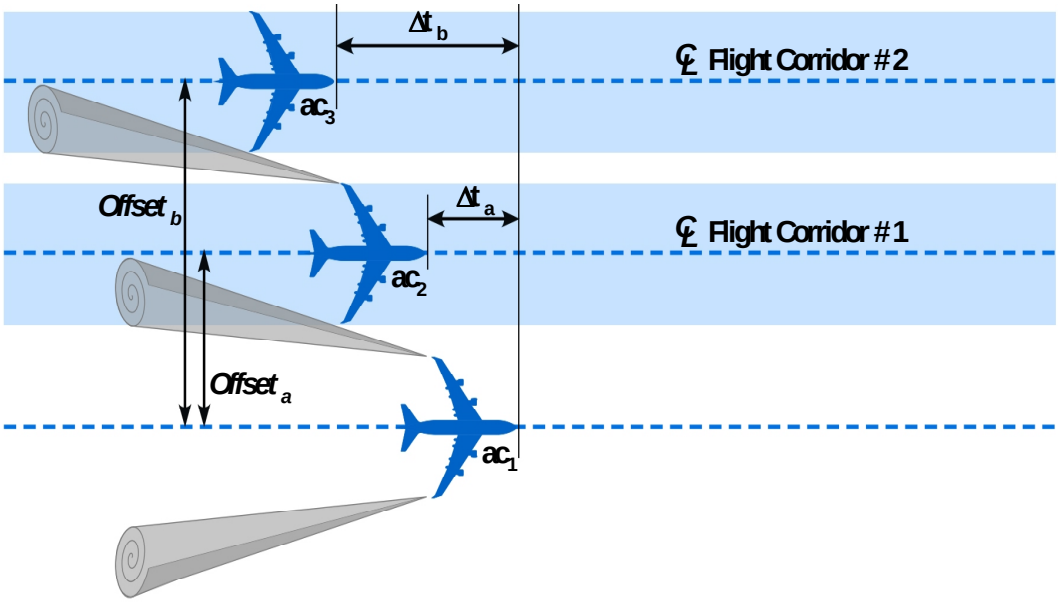
Parallel Flight Corridors
Figure 4

The extension of the single flight corridor concept to multiple parallel corridors is shown in Figure 4. Once again the uncertainty of wind, aircraft location (both leading and following aircraft), and wake decent velocity require real time measurement and computation of the corridors. Despite the "parallel" nature of the corridors, in trail separation is still required to accommodate these uncertainties.

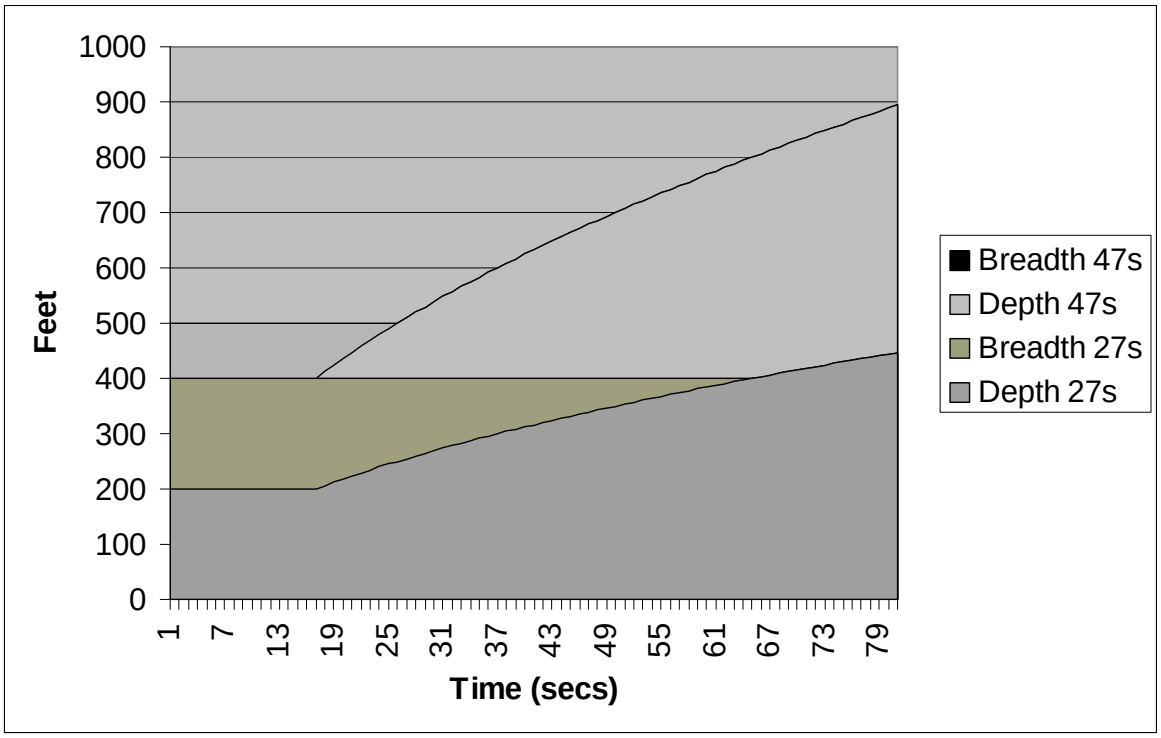
The TACEC approach to wake hazard avoidance reduces the uncertainties that require both measurement and in trail separation. Instead of positioning the following aircraft far enough behind the lead aircraft such that the wake is dissipated, TACEC positions the following aircraft as close as possible to the lead aircraft. This guarantees a wake free region and eliminates the uncertainties introduced by winds, etc. Figure 5 illustrates a multiple aircraft approach where hazard free regions are assured by maintaining longitudinal position offsets and a maximum time (or in trail) separation. The key difference between this concept and current parallel runway implementations is the fact that TACEC minimizes in trail separation (Δt) to reduce wake vortex hazards instead of increasing separation to accommodate uncertainties. This principal can be applied to both arrivals and departures. Each wave of arrivals/departures will continue to be separated in trail to allow the dissipation of hazardous wake vortices generated by the leading group of aircraft.

An obvious consequence of this wake avoidance approach is the ability to use very closely spaced parallel approaches/runways. Eliminating vortex hazards by minimizing the time difference between aircraft requires accurate flight control. It is envisioned that this will be accomplished by using differential GPS landing aids in conjunction with auto-land avionics similar to the CAT3 performance achieved today. This capability will allow all weather operation and has the ability to fly approach paths within meter level accuracy.

The in trail separation between aircraft necessary to insure wake free operation is a function of the time dependent dispersion of the lead aircraft's wake. From Rossow[5] this dispersion is a function of the



TACEC Parallel Approach Concept
Figure 5



Wake Dispersion vs Time
Figure 6

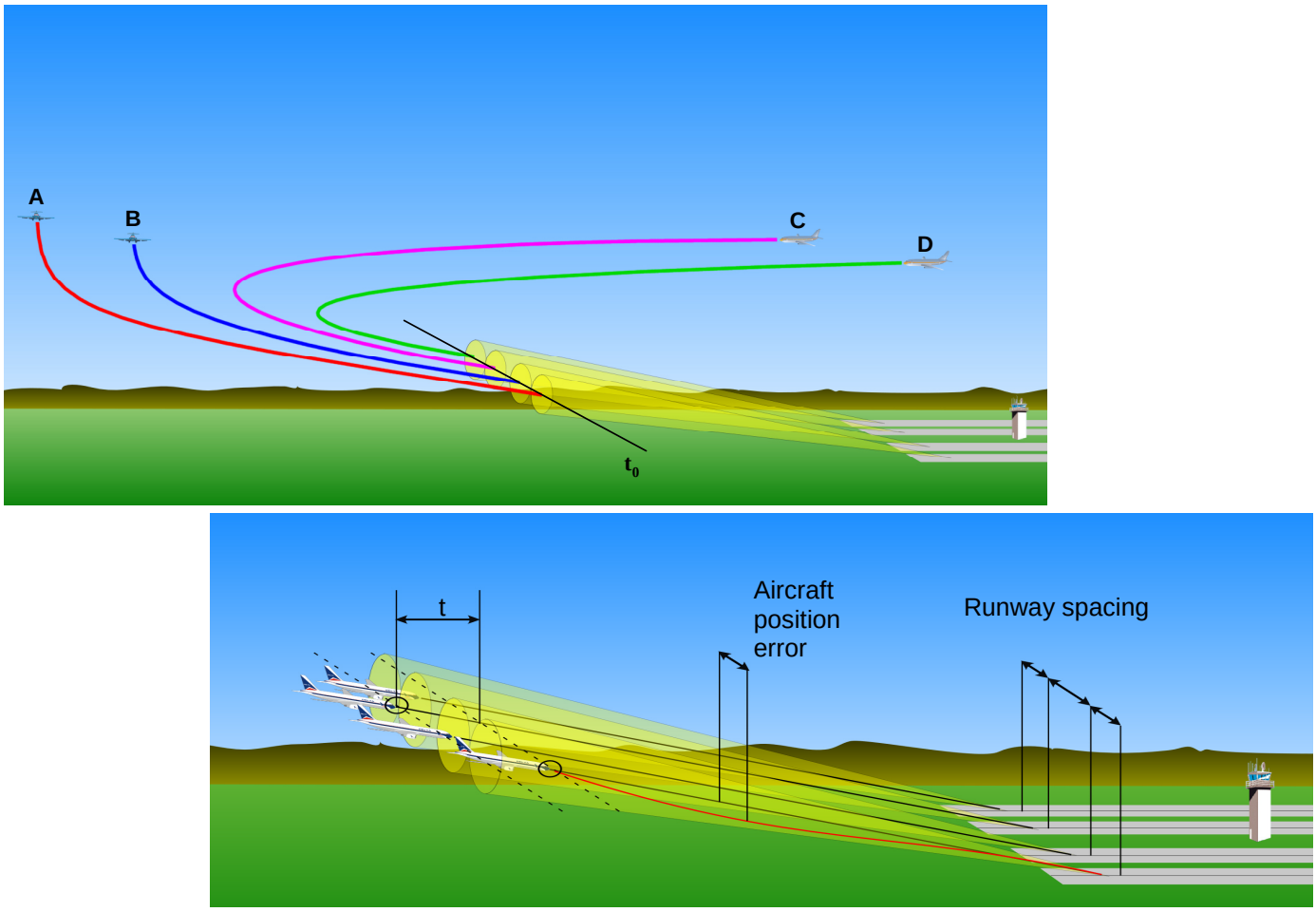
square root of **t.** The actual dimension of the wake vortex hazardous region is a function of the generating and following aircraft's wing span. An approximate analysis of the time characteristics of hazardous wake breadth and depth for a pair of B747's and a B727 following a B747 is shown in Figure 6. In essence an in trail time difference of less than 20 seconds would keep the dispersion to a minimum, but the effects of cross winds over that period need to be considered. Analysis is ongoing to establish a range of time/distance operational characteristics for multiple aircraft approach paths. Safety is a dominate factor and is discussed below. The final dimensions of the wake free region, or Flight Corridor, must include the uncertainty of the aircraft's flight path, which involves flight technical error, position uncertainty, and the operating environment.

Current Concept Development Activities

TACEC can significantly increase the airport's arrival (and departure) rate by "simultaneously" landing multiple aircraft on parallel runways. The current focus of Raytheon's ongoing TACEC development includes the following key tasks:

1.) Capacity improvement – the primary focus for TACEC is capacity enhancement of the NAS. Ongoing analysis is evaluating the potential improvements in arrival and departure rates provided by TACEC. It is the intent to use the NASA VAMS tool kit, and particularly the NAS wide fast time simulation ACES to assess the impact of increased airport capacity on the overall NAS capacity.

The capacity benefits of TACEC revolve around the ability to land/depart multiple aircraft "simultaneously" on closely spaced parallel runways. To assess the potential for achieving this Raytheon is currently analyzing the ability to stage the arrival aircraft upon entering the Terminal airspace as shown in Figure 7. Using actual flight plans extracted from the FAA's recorded ETMS data for a typical full day of operations, we are evaluating the characteristics of arrivals at the key airports. The ability to place multiple aircraft on parallel final approaches with very short time differences between them drives the potential capacity gains.



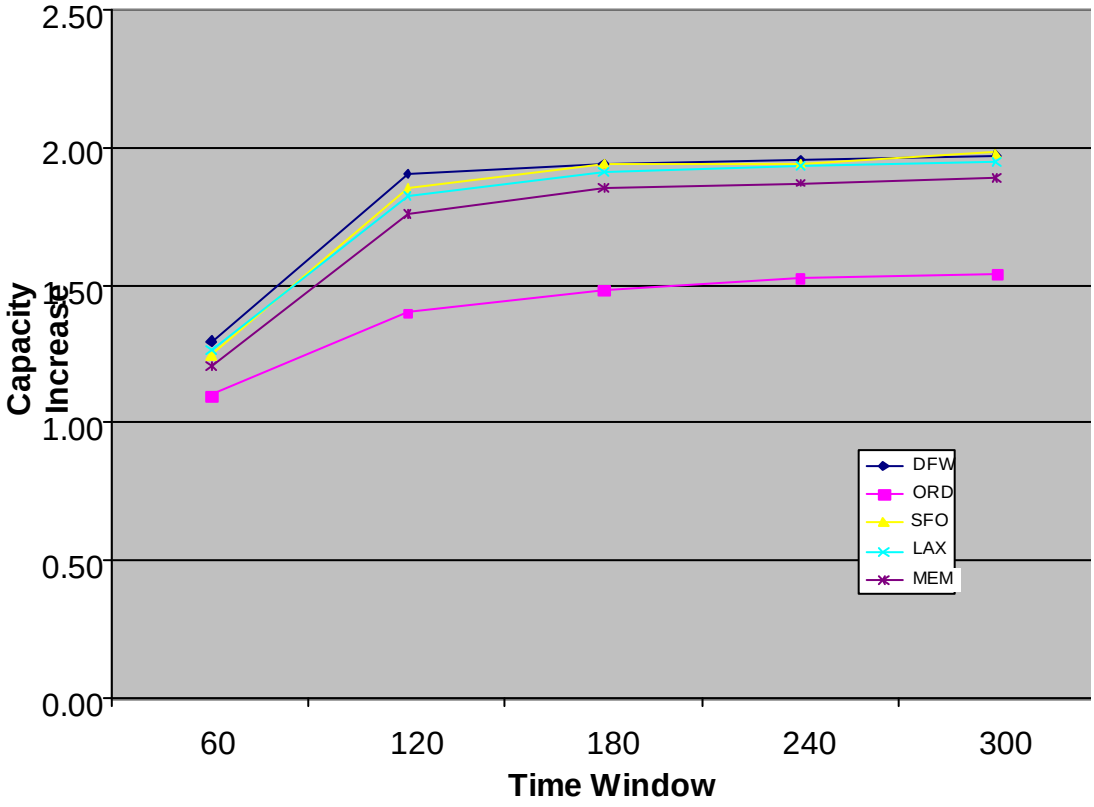
Staging arrivals for Final Approach
Figure 7

The timing of arrivals into the terminal airspace, at what geographical point they enter the airspace, and what type of aircraft all contribute to the ability to stage their entry into final approach corridors. By evaluating a range of arrival times and grouping similar aircraft from reasonably close entry fixes a capacity multiplier can be derived.

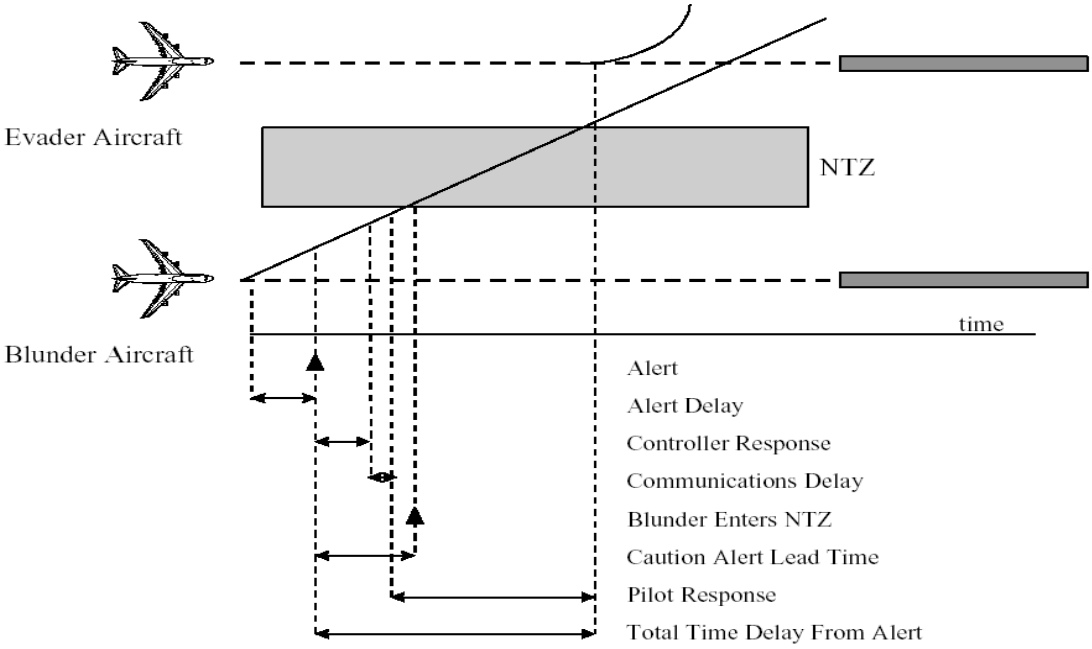
Figure 8 is an example of the analysis results, indicating in this case that a two minute (or more) time difference of arrival is needed to significantly improve capacity. Note that different airports have different benefits, reflecting the mix in arrival characteristics.

Activities will focus on comparing delays between current airport operations and TACEC operation. This will be a primary assessment method for evaluating the concept. We will derive the delay characteristics by comparing the total flight times (Departure Gate to Arrival Gate) using current airport operations with total flight time under TACEC operations.

2.) Safety Analysis – it is expected that highly reliable Differential GPS landing systems will be installed at all airports in 20 years. The use of this extremely accurate landing aid to automatically conduct final approaches will allow implementation of the TACEC wake avoidance approach in all weather conditions. However the possibility of errors remain and hence appropriate design considerations for blunders is necessary. Raytheon is investigating the potential for “blunders” on final approach as the first order safety issue. The potential for aircraft flying parallel approaches to collide if they move into the flight path of its neighbor has always driven the spacing requirements for parallel runways.



Capacity Increase vs Arrival Time Difference
Figure 8



Blunder Events
Figure 9

Blunder and associated events are illustrated in Figure 9. Each event needs to be addressed in the context of TACEC operation using DGPS auto land and the appropriate new roles for the controller and flight crew.

These events in Figure 9 reflect today's operation, where the pilot and controller are the primary actors in resolving blunders. TACEC envisions autonomous control using onboard avionics, both the controller and pilot are monitoring the flight progress. For example today the controller response to an ALERT event shown above is the time/activity that the controller performs in dealing with the visual/aural indication that the aircraft is off course. In TACEC that event is a control signal response to the auto pilot.

Response to blunders may well be automated as well. We are investigating the use of aircraft to aircraft data links to maintain the parallel approaches between multiple aircraft. The links would maintain safe aircraft separation on final approach, however when an aircraft wanders off course for whatever reason , all aircraft would follow the wandering aircraft as opposed to avoiding it.

Summary

Raytheon's advanced Terminal Area concept activities are addressing innovative ideas for significantly increasing airport capacity. Increased capacity fundamentally requires more runways, and maximum utilization of runways (both new and old) requires solutions to the wake vortex hazard. By vortex hazard free flight corridors and minimizing the in trail spacing between aircraft on final approach we envision the ability to safely land multiple aircraft almost simultaneously on closely spaced parallel runways. Significant work is required to analyze the capacity gains achievable, and to assess the NAS wide benefits of airport capacity increases. In addition Raytheon is addressing TACEC's ability to conduct safe, reliable all weather operations.

References

1. Department of Transportation, Federal Aviation Administration, National Airspace System Operational Evolution Plan, December 2002.
2. Lee, D., Kostiuk, P.F., Hemm, R., Wingrove, E., and Shapiro, G. "Estimating the Effects of the Terminal Area Productivity Program, NASA Contractor Report 2011682, April 1997
3. Department of Transportation, Federal Aviaiton Administration, The Airport Capacity Benchmark Report 2001, June 2001.
4. Rossow, Vernon J, Use of Individual Flight Corridors to Avoid Vortex Wakes. AIAA Atmospheric Flight Mechanics Conference, Monterey, CA, 5-8 August 2002.
5. Rossow, Vernon J., "Implementation of Individual Flight Corridor Concept", to be published, AIAA Aviation Technology, Implementation and Operation Conference, Denver, CO, November 2003