ARRIVAL MANAGEMENT WITH REQUIRED NAVIGATION PERFORMANCE AND 3D PATHS

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Abstract

This paper describes an operational concept that enables increased airport and airspace capacity and efficiency through the integration of Flight Management System (FMS) Required Navigation Performance (RNP) capabilities and ground based air traffic management (ATM) automation tools. The concept applies to en route and terminal area operations and uses voice or data link for air/ground communication. This concept is technically feasible for implementation in the 2008-2012 timeframe in a voice environment, assuming that advanced automation tools currently under development are deployed by Air Traffic Service Providers. This near-term step is a key element in the transition to trajectory-based operations in the Next Generation Air Transportation System (NextGen).

The paper describes the operational concept in detail for arrival management, and provides an analysis of several key performance parameters that influence the arrival management process. The concept is applied to arrival operations in Houston airspace. Arrivals into Houston Bush Intercontinental Airport (IAH) are modeled using a fast-time performance modeling approach. The results illustrate the influence of path and speed discretization, wind, trajectory prediction and navigation performance on delivery accuracy and delay in the arrival process.

Introduction and Background

Air traffic management in high-density domestic airspace such as the US and Europe is characterized by a reliance on manual execution of tasks that are based on the limitations of decades-old technology. As traffic continues to grow, both in overall operations counts and in the variety of aircraft performance characteristics, the system operation in its current form will be unable to serve the demand. The complex network of restrictions that have gradually been instituted to manage controller workload have to be replaced by more sophisticated decision support tools that can help optimize the use of system resources.

The development of the ATM system from current operations to an envisioned system such as NextGen is postulated to involve a progression of operational change from today's tactical control by radar to a more performance-based operation, where the initial transition steps rely on airspace and procedure design that is relatively static but trajectory based. This lays the foundation for a fully performance based ATM system using dynamic airspace and trajectory concepts. This operational change process will be supported through a progression of communication, navigation, surveillance (CNS) and ATM automation technology enablers. The concept presented in this paper is a near-term step toward trajectory-based integration between air and ground systems that leverage investment in highly accurate and reliable navigation systems, present on modern aircraft in the form of Area Navigation (RNAV) and RNP capability. Advances in automation support for controllers are assumed, with active 3D path generation for arrivals and en route conflict resolution capability. The concept does not make integrated ATC datalink a firm requirement, but works with the limitations of controller-pilot VHF voice communications. These technology choices are driven by considerations of available airborne technology that is currently underutilized, while working towards matching ground system technology to minimize investment risk and prepare the operation for the introduction of integrated domestic datalink in the mid-term.

Operational Concept

The highly accurate navigation available with RNP is fundamentally based on the aircraft tracking a defined path over the ground in lateral navigation mode (LNAV). Modern FMSs are also equipped with features that enable significant control over the vertical profile, using the vertical navigation mode (VNAV). Aircraft adherence to a 3-dimensional flight profile is best ensured when a complete 3D path ahead of the aircraft can be defined. Research on ATM automation technologies has shown that traffic planning algorithms based on predicting aircraft trajectories 10-20 minutes or more ahead of current time are feasible and can deliver a significant increase in capacity and efficiency in all phases of flight ([1] -[7]). Research is still needed to more clearly define the best method for controlling the 4th dimension, e.g. along-track timing. Based on these considerations, the concept in this paper is centered on using trajectory-based traffic planning technologies, along with LNAV, VNAV and RNP in the aircraft, to take a significant and near-term feasible transition step to future trajectory-based operations. ATM clearances defining complete 3D paths are assumed to be issued by voice, so as not to require domestic datalink equipage for initial implementation, given the uncertainty about the implementation schedule for integrated domestic datalink. Wherever feasible and beneficial, clearances will be issued such that the aircraft can remain in LNAV and VNAV modes on a fully-defined 3D path, to ensure efficiency and predictability. This will generally require advanced automation support for the controller, to ensure that all 3D paths remain properly sequenced and spaced. Some key assumptions made about the system in which this concept will be implemented include

- Implementation time target is 2008-2012
- Separation standards remain at current levels: 5 nm en route, 3 nm in TRACON, and IFR or VFR rules for runway systems depending on visibility
- Center and TRACON airspace and sectorization remains largely unchanged

The concept of using ground automation to fully define efficient conflict-free 3D RNAV paths applies to all phases of flight, as described in [8]. As discussed in [8], the benefits of this concept in US operations are expected to be most significant for airport operations, of which the arrival management problem poses a more significant challenge than departures due to the converging nature of arrival flows. Thus, this paper focuses on arrival management using 3D paths.

Arrival Management

The concept includes the use of an advanced trajectory-based arrival planning system (see ([1] - [5]). Generally, the architecture is based on a two-step arrival planning process, with the first step performed well prior to the aircraft's desired top of descent (TOD) point and aimed at accurately and efficiently delivering aircraft to the terminal area meter fix. The second planning step is performed as the aircraft enters the terminal area airspace, and serves to compensate for timing errors at the meter fix to ensure full utilization of the runway system [1]. The first planning stage (Center planner) will dynamically produce a conflict free arrival plan that includes [2]

- Runway assignments
- Airplane sequences and schedules at runway thresholds and terminal area entry points (meter fixes – MF)
- 3D paths from the airplane's present position to the runway threshold
- Cruise and descent speed schedules, or required time of arrival (RTA) to the meter fix

The lateral definition of the 3D path will be through "Place/Bearing/Distance" phraseology that includes named maneuver start and end points, or through the use of lateral offsets, as discussed in detail in [9].

The vertical definition of the 3D path can be specified by several options, depending on how constrained the arrival airspace is for the given location. The vertical path can be defined either as a geometric path, using 'AT', 'AT OR ABOVE', 'AT OR BELOW' or Flight Path Angle (FPA) features, or as a performance-based path defined through FMS computations in each aircraft. The latter feature will provide the most efficient descent profile for each aircraft, but will result in a significant variation in TOD location for each aircraft, and thus might not be usable in areas where there is frequent traffic crossing the arrival flow.

The second planning stage is performed as aircraft enter terminal area airspace at the meter fix. This plan includes most of the key features of the Center plan, with the Final Approach Fix (FAF) being the key timing target. Lateral path adjustments in the terminal area could be pre-defined as a set of published approach transition procedures that are available in both aircraft and ground system navigation databases [9]. These procedures can include vertical and speed constraints as required, with the most desirable vertical profile being a near-idle descent that provides low noise and fuel burn but offers the ability to tactically adjust speed for timing control. The use of pre-defined procedures to perform path adjustment in the terminal area is attractive as it offers lower controller and pilot workload than Place/Bearing/Distance clearances and enables RNP accuracy and efficient vertical profiles to simultaneously ensure throughput and efficiency.

The arrival sequence of events is illustrated in Figure 1 for a pair of arrivals into a meter fix called DAISETTA. In the figure, the timeline inset is the CTAS Traffic Management Advisor (TMA) display, which shows the Estimated Times of Arrival (ETA) for a set of arrivals on the left, and their corresponding Scheduled Times of Arrival (STA) on the right. The difference between the STA and the ETA show the required delay, in green next to the label in the STA column. A delay of 3 min is shown for EGF586 in this example. This delay can be implemented as any combination of path, descent and/or cruise speed changes, once EGF586 crosses the freeze horizon at point 3. The controller will subsequently issue the path and speed clearance by voice and it will be activated by the pilot upon reception and confirmation.

Figure 1 only depicts Center-based planning and illustrates a descent clearance to the meter fix, but the concept applies all the way to the runway, where a complete 3D arrival path to the runway would be selected to meet appropriate metering constraints in the terminal area and at the runway thresholds. Due to the potentially large distances, times, vertical and speed gradients that exist between the original planning region and terminal area entrance [10], a second planning process for the terminal area alone is most likely necessary. This two-tiered approach to arrival management has been a pillar of NASA arrival management system development [1].

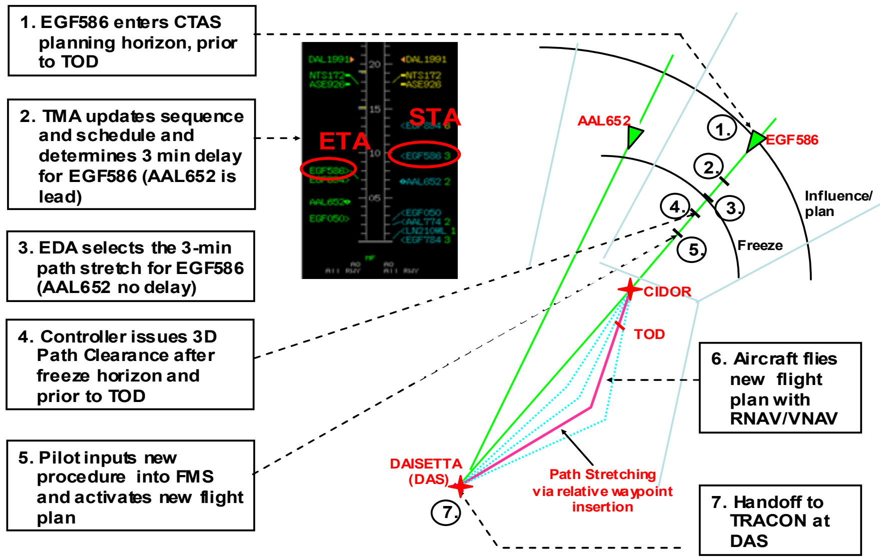

Figure 1. Arrival Management Event Sequence

Aircraft without 3D path-following capability (i.e. LNAV and VNAV modes) will be handled as today, with controller clearances to achieve the computed 3D paths using speed, heading, and altitude. These less frequent operations are not anticipated to reduce meter fix delivery error below 15 s, based on NASA studies [10]-[11].

Analysis Approach

Arrival Management Performance

The arrival management performance aspects studied in this analysis are variability in delivery time at the meter fixes and at the runway, as well as arrival delay. Separation minima are assumed to be the same as today, i.e. 5 nm in Center airspace, 3 nm in the TRACON, and the IFR wake turbulence separation minima on final approach [12]. Variability in delivery time leads to the need to plan for larger separations than the minimum, to reduce the probability of violations. These "spacing buffers" are proportional to the in-trail spacing variability and translate into lower runway throughput and larger delay. Thus an essential performance goal for runway throughput is reduced variability in aircraft delivery time at the runway.

Modeling Approach

Boeing has developed a model of the arrival management process that includes many of the key performance elements of that process. The analysis approach used in this study builds on the Trajectory Analysis and Modeling Environment (TAME), a fast-time trajectory simulator that includes a stochastic lateral navigation performance model [13]. TAME was enhanced to include a traffic demand generator based on the Official Airline Guide (OAG) [14], and the Boeing Multiple Runway Planner (MRP) [15] was integrated into TAME to represent a Center-based arrival planning process.

Figure 2 illustrates the key components of the arrival management model currently implemented in TAME. Figure 3 illustrates the overall 4-meter fix arrival scenario for Houston IAH airport used in this analysis, showing the design of lateral path offsets to absorb delay prior to the meter fixes. The aircraft model in Figure 2 simulates aircraft from the scenario entry points to the arrival runways, and the Trajectory Predictor, Traffic Scheduler and Trajectory Synthesizer are active for aircraft until they cross the freeze horizon illustrated in Figure 1.

TAME does not currently include a model of a separate TRACON traffic planner. The Center planning process performs runway assignment, final approach sequence assignments, TRACON delay assignments and Center delay assignments, such that it does provide a total solution from prior to TOD to the runway. This is adequate for the study reported here, but it is anticipated that a second planning process for the TRACON may be required in TAME to achieve an adequate final approach spacing performance level.

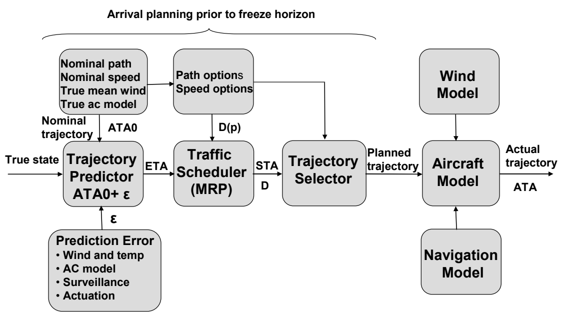

Figure 2. Arrival Management Model in TAME

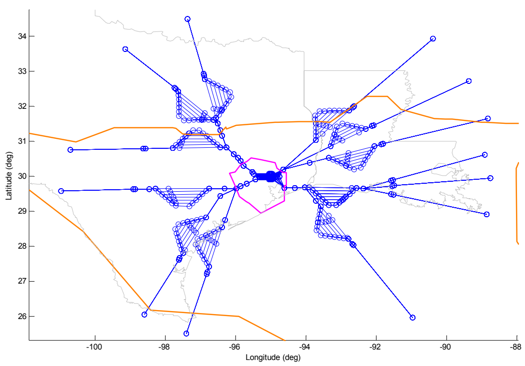

Figure 3. Arrival Paths to Houston IAH with Lateral Path Offsets

Aircraft Model

The Aircraft Model represents the aircraft executing a planned trajectory, subject to disturbances caused by the wind field and with a specified lateral navigation accuracy. Aircraft motion is represented over a spherical earth with five states (latitude, longitude, altitude, airspeed and heading), and integrated in MATLAB using ordinary differential equations solvers such as Adams-Bashforth-Moulton. The wind is modeled as constant mean wind that varies with altitude, and a stochastic component representing wind gusts. Lateral navigation accuracy is modeled as a zero-mean stochastic process. The current model does not include errors in the speed profile, or coupling between vertical and longitudinal motion, but this is planned for future work. The Aircraft Model is described in detail in [13].

Arrival Planning Process

The arrival planning process consists of three key steps, as illustrated in Figure 2, resembling the functional architecture of NASA's CTAS [1]. The Trajectory Predictor uses a model of aircraft performance to predict the estimated time of arrival (ETA) of each aircraft at the meter fix and at the runway. In the current implementation, the same aircraft model is used for trajectory prediction and execution, but the perfect trajectory prediction is degraded to represent several key prediction error factors. As shown in Figure 2, the factors included in the trajectory prediction error are:

1. Wind and temperature prediction errors (difference in predicted and actual mean values)
2. Difference between the aircraft model used by the predictor and the true aircraft model
3. The error in the aircraft state at the time of the prediction (surveillance error).
4. Actuation error, which accounts for delays in delivering and executing clearances.

The estimated time of arrival for each aircraft is computed as the ideal arrival time ATA0, using the true nominal wind and perfect navigation, and ε representing the error sources listed above, so that ETA=ATA0+ε. The variable ε is modeled as a normal random variable whose Gaussian probability distribution is sized by considering the flight test results reported in [16]. Those results indicate an observed variability (one standard deviation) in timing at the MF of 13.9 s, which includes the factors listed above, variability in navigation performance for aircraft flying an FMS path, as well as the variation in wind due to gusts along the trajectory. Gusts and navigation errors are modeled within the Aircraft Model in TAME, so they have to be excluded from ε. Furthermore the reported experimental and residual errors have also been removed. Removing this variability from the total reported variability leads to a value of 7.5 s for the standard deviation of ε to the meter fix. It is very likely that the biases in timing reported in [16] are a product of the experimental conditions on the days of the tests and it was decided to not include them in the sizing of ε. A bias due to the difference between the predicted mean wind and the actual mean wind is however modeled, and that value can be different for each meter fix to reflect that wind predictions in one quadrant of the arrival airspace can be more accurate than in the others.

The Traffic Scheduler in TAME is the Boeing Multiple Runway Planner (MRP) [15], which has been integrated into TAME. The MRP is capable of optimizing arrival sequences and schedules in the presence of a discrete delay field, which is a product of the discrete paths and speeds that are used for delay absorption in TAME. The level of delay discretization is a by-product of a particular arrival procedure design and can have an effect on overall arrival delay as discussed in [17]. The Traffic Scheduler is executed every 2 minutes and includes all aircraft that fall inside the planning horizon and upstream of freeze horizon of all arrival streams. In this study it is assumed that the region where Center delay is taken is 150 nm upstream of each meter fix. Thus arrival clearances have to occur prior to that point. It is assumed that aircraft should be within the scope of the arrival automation some 50 nm earlier, corresponding to event number 1 in Figure 1. This was arrived at by allowing a 10-minute planning region (i.e. the distance between the planning and freeze horizons) and a 2-3 minute clearance delivery period after the freeze horizon and before the 150 nm mark, which should occur after event number 5 in Figure 1.

Achievable delay in the TRACON is determined based on fixed delay paths within the TRACON, where speed and vertical profiles are pre-determined as illustrated in Figure 4. The delay absorption capability in the Center includes the Center arrival paths and path options illustrated in Figure 3 and also lower descent and/or cruise speed combinations. The vertical dimension is not used to meet the schedule and all aircraft have uninterrupted descent profiles from TOD to the meter fix. Arrival traffic is allowed access to all three East-West parallel runways at IAH (26R, 26L and 27).

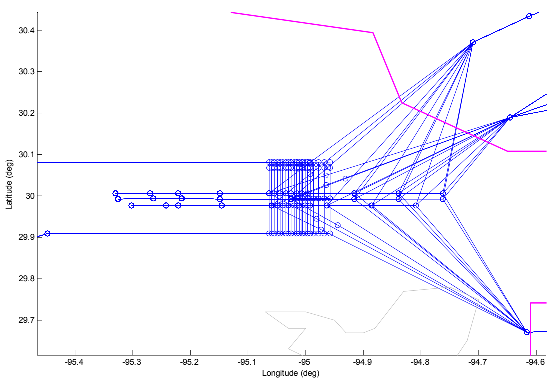

Figure 4. Delay Path Options in the TRACON

The Traffic Scheduler produces an arrival schedule that minimizes delay, subject to minimum in-trail spacing requirements at the runway and at each meter fix [15]. As shown in Figure 2 it uses the available discrete delay values, D(p), that are obtained by evaluating the ideal flying time along all combinations of path and speed options for each arrival. The prediction of flying times along the different paths is also subject to trajectory prediction error, which potentially differs from the ε factor for the nominal path. This incremental effect is not included in the results presented here.

The output of the Traffic Scheduler consists of Scheduled Times of Arrival (STA) for each aircraft in the planning horizon at the runway and at the meter fix. Each STA is either equal to the ETA, if no spacing conflicts are present, or larger than the ETA by the required delay, D. Associated with each D value is a particular path and speed combination, and the Trajectory Selector searches through the set of D values to determine the path and speed combination that implements the required delay.

The selected path and speed are then executed by the Aircraft Model, subject to a wind field that includes mean wind and random gusts, and subject to navigational performance represented by a particular Actual Navigation Performance (ANP) level [13]. The result is the simulated aircraft trajectory, with associated actual times of arrival, ATA, at the meter fix and at the runway.

Scenarios

The arrival scenario used in this study includes arrival path options in the center that are designed using fixed lateral offsets. All center arrival paths are nominally based on the current published Standard Terminal Arrival Routes (STAR) and their transitions into IAH and have been enhanced to include a set of path options for each STAR and transition. Lateral offsets were chosen due to their equal or better delay absorption capability over triangular paths at equivalent offset distances and base leg lengths, and also because the path clearance associated with pre-defined offsets is assumed to be less complex than that required for relative waypoint insertion. For a more in-depth study of the differences between relative triangular paths and offsets the reader is referred to [9].

Figure 3 depicts the arrival paths and path options considered for the four meter fixes to IAH. Delay paths are designed within 150 nm of the meter fix in order to maximize the delay absorption capability but remain within the scope of the assumed arrival planning automation. Operational issues such as Center (ARTCC) boundaries and required center-to-center coordination are not included in this study to simplify the modeling task, but it is acknowledged that for such a scenario to be implementable in Houston, an upstream coordination component is necessary due to the proximity of the Dallas Fort-Worth Center boundary on the north side of the arrival airspace.

In this scenario, with lateral offsets in 5 nm increments up to 30 nm, descent speeds varying from 250 kts to 290 kts CAS (in 5 kts increments) and cruise speed options of Mach 0.70, 0.75 and 0.80 at 34,000 ft, center delays up to 390 s can be achieved by path/speed combinations. Offsets larger than 30 nm in this airspace would likely interfere with the departure corridors used between arrival flows. For larger delays, holding patterns at altitude are placed at the 150 nm mark. A standard hold at cruise altitude with 90 s legs and speed and turn limits as defined in the Airmen's Informational Manual (AIM) [18] provides approximately 500 s of delay, and thus the design includes a hold gap of about 110 s between the longest path/speed combination and a hold. In any design the hold gap should be minimized to the extent possible as it increases overall delay propagation effects [17].

Metrics

The key performance metric of interest for this study is delivery accuracy of aircraft at the meter fixes and at the runway, and the associated inter-arrival spacing distribution of in-trail aircraft pairs. Delivery accuracy is defined as the difference between the actual time of arrival (ATA) and the scheduled time of arrival (STA). High delivery accuracy is desired to ensure the strategic plan is realized to achieve optimum flows into the TRACON and to the runways.

Delivery accuracy as modeled in this study is a product of three processes that are subject to inaccuracy as illustrated in Figure 2. The first is the trajectory prediction process, which results in the ETAs; the second is the scheduling process, which determines the STAs from the ETAs; and the third is the guidance and navigation process, which results in the ATAs. The following factors influence the overall arrival system performance:

1. Difference in mean wind between prediction and actuality
2. Presence of wind variations (random gusts) along the arrival route
3. Navigation performance
4. Surveillance performance
5. Timing variability introduced by operators
6. Aircraft trajectory prediction model and performance data

Within a model it is possible to know what the ideal time of arrival is and thus this knowledge can be used as the basis for perfect predictions. As described in the Arrival Planning Process section, trajectory prediction error is modeled using a parameter ε added to a perfect prediction. However, because a part of the error is reflected in the navigation process, only effects 1, 4, 5 and 6 influence the shape of the distribution from which ε is sampled. It should be noted that the effects of speed and vertical profile variability are not directly modeled due to the lack of an aircraft performance model. The inclusion of an aircraft performance model in TAME is planned for future versions and, when it becomes available, the model will be changed to remove those effects from ε.

Low delivery accuracy results in more potential separation violations at the planning points and thus requires larger buffers. As buffers increase so does delay, and thus high delivery accuracy is required to minimize delay.

Experiment set-up

The analysis was performed using two different traffic scenarios. The first scenario, used to perform deterministic analysis to discover the basic behavior of the system, involved a full day of scheduled arrivals to IAH. The other scenario, used for the stochastic technical performance analysis was a busy yet balanced single arrival rush, with arrivals scheduled at the gate between 2:02 pm and 3:16 pm local time. This rush includes 75 aircraft arriving into IAH from 67 airports. Each arrival was assigned a route based on shortest distance from the origin airport to its entry point in the simulation. This rush has 37% of the traffic arriving over the NW quadrant (RIICE arrival), 32% of the traffic over the NE quadrant (DAS arrival), with the rest of the traffic spread over the remaining two meter fixes.

The technical performance analysis presented here is based on a Monte-Carlo simulation methodology. The arrival rush is simulated repeatedly for a given case, each case representing a set of performance parameters characterizing the arrival management system. The performance parameters evaluated are:

1. Mean wind prediction bias
2. Lateral navigation performance using Actual Navigation Performance (ANP) metric
3. Wind variability (size of gusts)
4. Trajectory prediction error

The number of Monte-Carlo simulation runs needed is determined using a convergence process for a set of metric based on statistical t-tests. The metrics used for this convergence process are:

1. Probability of meter fix separation violations
2. Probability of runway separation violations
3. Average aircraft delay (for delayed aircraft)
4. Mean aircraft delay (all aircraft)
5. Mean of meter fix delivery accuracy
6. Standard deviation of meter fix delivery accuracy
7. Mean of runway delivery accuracy
8. Standard deviation of runway delivery accuracy

Confidence intervals for each metric are computed at the 95% confidence level using t-tests during the Monte-Carlo process. The process terminates when half of the confidence interval is within a specified tolerance for each metric. This guarantees that at convergence each metric is within the threshold level with 95% confidence.

Analysis Results

The analysis reported here was performed in three steps. The first step established the baseline performance of the arrival management process under ideal conditions, i.e. no disturbances. This included a look at the effect of discretization in speed clearances on overall arrival delay. The second step was an analysis of the effect of errors in the prediction of the mean wind field vs. the actual mean wind encountered by the aircraft. The third step was a Monte-Carlo simulation analysis of the effect of the stochastic parameters affecting the system.

Baseline Performance Analysis

A baseline of system performance under ideal conditions was first established. A run was made with a full day's arrival schedule, 3 arrival runways, 7 nm separation target at each meter fix and IFR separations at the runways. All error sources and the mean actual wind were zero. This run served to illustrate the baseline arrival delay level, verify that the arrival planner produces correctly spaced traffic at all meter fixes and runways and that aircraft execute the plan perfectly.

Table 1 summarizes performance statistics obtained from the baseline run. The minimum Inter-Arrival Time at all fixes and runways is shown to be equal or larger to the minimum required (87 s at meter fix for all pairs, 72 s at runways for large-large lead-trail combinations and 62 s for small leading pairs). Average delay results per meter fix and runway were produced but are not shown here due to space limitations. They indicate that delay at the meter fixes is concentrated on the North-side (DAS and RIICE) as expected, as traffic into and out of Houston is predominantly from/to the North. It is also observed that delay taken at the runways, i.e. delay in the TRACON, is extremely low, indicating a configuration that is severely constrained by the North meter fixes, and thus not achieving good runway utilization.

	STROS	DAS	RIICE	GLAND	Rwy26L	Rwy26R	Rwy27
Min IAT	88	87	87	87	73	72	67
Av. Delay	37	258	281	35	9	4	5

Table 1. Baseline Spacing and Delay Results

Discretization of delay options has an effect on overall arrival delay, as discussed in [17]. Thus it is important to understand the performance of the path and speed option set created for this scenario. Table 2 and Figure 5 show the results of four different levels of delay discretization, created by varying the descent speed decrements available to the Center Planner. The case where only 250 kts and 290 kts are available options produces an average delay granularity of 9.4 s, and leads to an increase in average delay for the entire scenario of 23% compared to the case with 8 speed decrement options (which was used for the remainder of the analysis reported in this paper).

# of Speed Decrements	Descent Speed Options (kts)	Mean Center Delay Discretization (s)
8	250,255,260,265,270, 275,280,285,290	2.1
4	250,260,270,280,290	3.7
2	250,270,290	6.2
1	250,290	9.4

Table 2. Discretization Cases for Figure 5

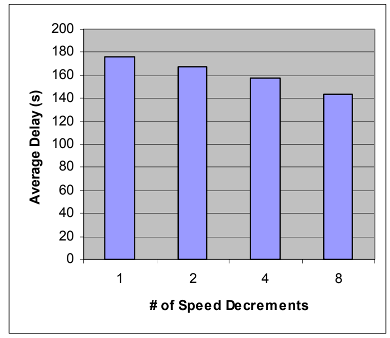

Figure 5. Effects of Path and Speed Discretization on Arrival Delay

Effect of Errors in Mean Wind Prediction

Analysis was performed to show the effect of errors in mean wind prediction on spacing violations at the runways. Note that the model applies the same wind prediction bias to all aircraft on the same meter fix, so this will not have an effect on meter fix spacing, only at the runways where arrivals from different meter fixes are merged. Meter fix separation requirements were removed for this analysis, to provide maximum load on the runways, and the wind bias was as follows:

- Wind bias=[x,x,-x,-x] for [STROS, DAS, RIICE, GLAND]; i.e. East-West wind bias
- Wind bias=[x,-x,-x,x] for [STROS, DAS, RIICE, GLAND]; i.e. North-South wind bias
- Values of wind bias x=[0,10,20,30] s

The following traffic and runway cases were used:

Case 1

- Center Planner optimizes runway assignment using all three runways
- Full daily traffic schedule over all meter fixes

Case 2

- Only one runway used
- Only traffic over North meter fixes retained

Case 3

- Two runways used with runway optimization
- Only traffic over North meter fixes retained

Figure 6 shows the resulting spacing violations statistics at the runways, caused by the misleading mean wind information on which the Center Planner bases its arrival plan. Note that violations will occur when in-trail pairs arrive from opposite wind bias directions and when the lead arrives later than the Planner thought and the trail arrives sooner. If the traffic was evenly distributed and tightly spaced, this would be expected to be about 25% of the pairs. In Case 1 all runways are available to traffic coming from all directions, and the rate of separation violations due to the wind prediction bias is about the same for both East-West and North-South bias. This is as expected, because the Center Planner assigns runways to minimize total delay and the sequence to each runway is about equally likely to contain pairs from East and West as from North and South.

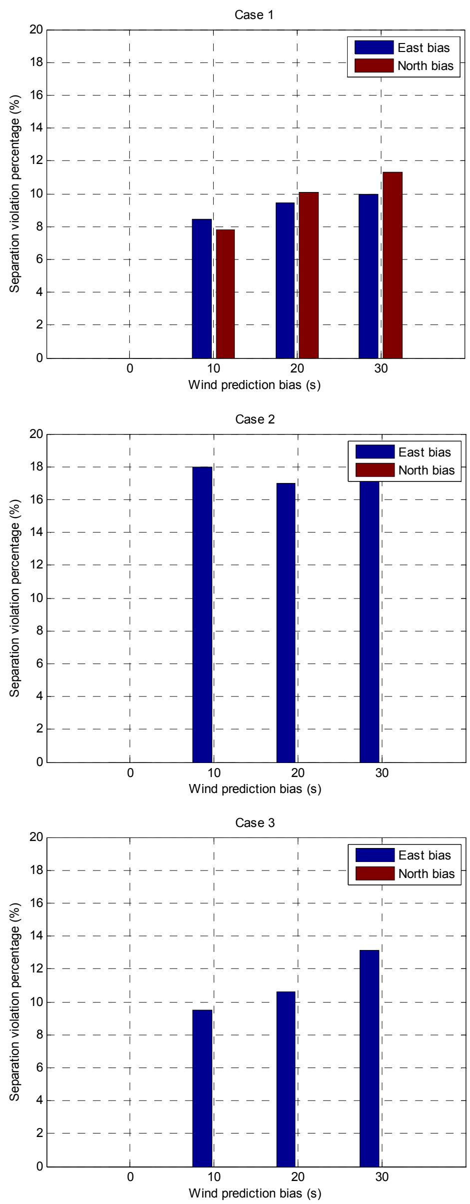

Figure 6. Separation Violation Trends with Mean Wind Prediction Bias.

Case 2 shows a higher rate of separation violations, owing to the fact that all traffic from the North must be sequenced to one runway, causing significant congestion during arrival rushes. The statistics are closer to the 25% maximum, and there is some variability in the numbers for different values of wind bias due to the coincidental nature of pairing for each sequence produced by the Planner. Cases 2 and 3 also show that the North bias has no measurable effect when all the traffic is affected by the same bias. Finally, Case 3 shows a reduction in the rate of violations due to the availability of a second runway to reduce runway congestion. Overall this analysis highlights the sensitivity of the arrival process to inaccuracy in prediction information, particularly for cases when the system is running close to maximum capacity.

Effects of Stochastic Errors

The following cases were used to investigate the effect of navigation accuracy and wind gusts on meter fix and runway delivery accuracy:

1. Navigation performance ANP=[0,0.15, 0.3,1.0] nm
2. Wind gust variability σ_w=[0, 5, 10, 15] kts

These values of ANP correspond to typical aircraft performance values. An ANP of 0.15 nm corresponds to the high range for GPS equipped aircraft; ANP of 0.3 nm corresponds to the mid-range of radio navigation aircraft (DME-DME or DME-VOR); ANP of 1.0 nm corresponds to the high-range of radio navigation aircraft.

This analysis includes cases with no trajectory prediction error (i.e. ε=0) and cases where trajectory error is present. The epsilon values used are derived from the results in [16], where the timing variability at the meter fix due to the prediction for aircraft flying conventional FMS arrivals (LNAV and VNAV) is reported to have a one sigma value of 13.9 s. The referenced work also conducted a principal error component analysis to attribute fractions of this error to the effects of wind, temperature, lateral navigation, initial ground speed (surveillance errors), altitude and airspeed profile clearance timing and prediction variability. A standard deviation of 7.5 s for the ε distribution at the meter fix was arrived at by backing out the variance due to wind and turn overshoot from the 13.9 s, since these effects are modeled directly in the aircraft model, and by also removing the reported experimental and residual error. No values for timing variability at the runway were reported in [16], so an estimate was made based on an assumption that altitude and speed profile effects dominate between the meter fix and the runway. The ε value used at the runway was 8.75 s, corresponding to 4.5 s of additional prediction variability in the TRACON.

Figure 7 displays the results of this analysis for all meter fix and runway thresholds, for both the cases with trajectory prediction error, and those without. The figure also includes red lines at the top of each bar indicating the confidence interval in delivery accuracy at the 95% confidence level resulting from the Monte-Carlo process.

The results show a strong influence of wind gust strength on delivery time accuracy, and deterioration in accuracy from the meter fix to the runway. Lower accuracy at the runway is caused by increased flying time through the wind disturbances, as well as by the additional turns the aircraft must navigate through between the meter fix and the runway. Most of the error due to navigation can be attributed to variability in execution of turns in the procedure. The growth in error between the meter fix and the runway indicates a need for a TRACON re-planning stage where the error at the meter fix can be corrected to maximize accuracy in delivering aircraft to the runway. It is also noted that in the cases with trajectory prediction error, the influence of wind variation is attenuated due to the addition of the prediction timing variance. In fact, as expected, the timing variance in the case with trajectory prediction is the sum of the variance for the runs without trajectory prediction and the ε value used.

The cases with no trajectory prediction error and no ANP error were compared with the data in [16]. The effect of wind variability alone on timing is reported to be 10 s (one sigma) in [16]. In the worst wind gust case tested here (15 kts), the meter fix timing variability does not exceed 6 s. This difference can be attributed to the difference between the TAME wind gust model and the actual test conditions in [16], with the primary difference probably being that the wind gust model in TAME currently does not vary by altitude. Thus the effect of the wind gusts at higher altitudes is likely to be lower than actual atmospheric gusts, and in this simulation scenario this is where the aircraft flies approximately a third of its trajectory. Future work will consider enhancements to the wind model.

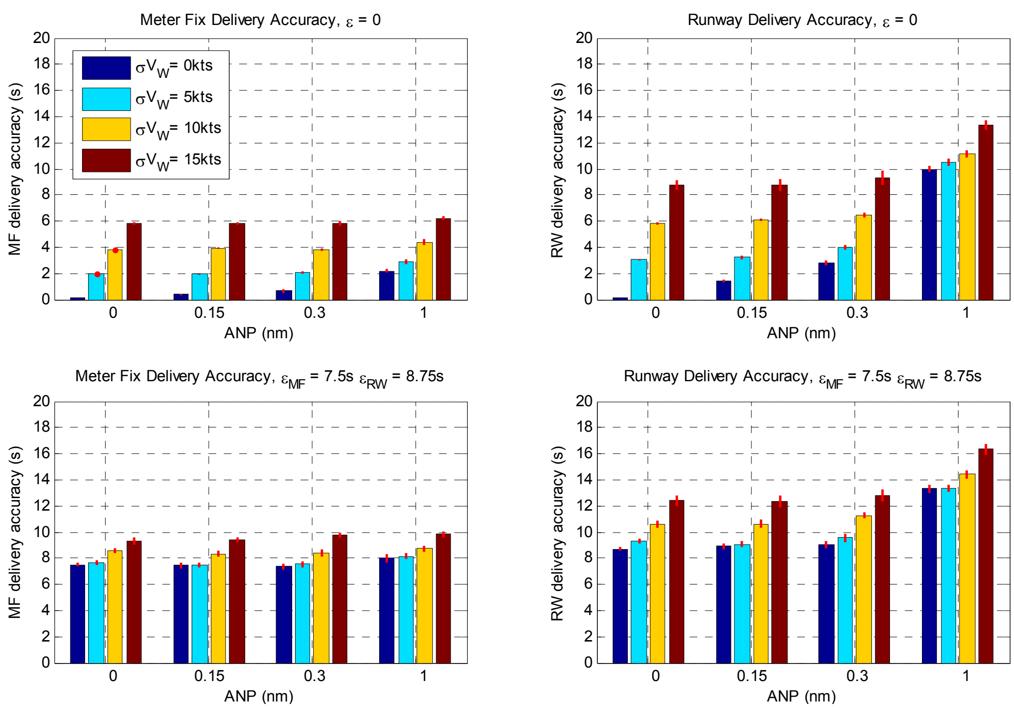

Figure 7. Meter Fix and Runway Delivery Accuracy

The relationship between lateral navigation performance (ANP), flight technical error (FTE) due to wind variability, and cross-track containment, leads to a measure of RNP. Each bar in Figure 7 corresponds to a level of RNP, but since ANP dominates, a direct ANP to RNP relationship can be derived, as shown in Table 3.

ANP (nm)	RNP (nm)
0	0
0.15	0.1
0.3	0.16
1.0	0.51

Table 3. Relationship Between ANP and RNP

Required buffers

To conclude this study, an analysis was performed to determine the spacing buffers that would be required to absorb the delivery variance at the meter fixes. The runs presented in Figure 7 used 7 nm as the planned meter fix separation, representing the 2 nm buffer that center controllers use today, to ensure the minimum radar separation of 5 nm. For a representative case (ANP=0.15 nm, wind gust=10 kts), the separation violation percentage (i.e. percent of arrival pairs separated by less than 5 nm) is 0.4%, indicating that a 2 nm buffer is sufficient to absorb the delivery inaccuracy at the meter fix. To confirm this, a Monte Carlo analysis of the representative case was run using 5 nm as the planned meter fix spacing. This resulted in much less delay (~70% less) but had 15.2% separation loss due to the delivery variance. To determine the exact required buffer an iterative Monte-Carlo process was used until the probability of spacing violation at the meter fix was close to 0.5%. This process converged to a meter fix buffer value of 25 s, with a separation loss probability of 0.56%. In fact, 25 s at the 250 kts indicated airspeed over the 10,000ft altitude at the meter fix corresponds almost exactly to 2 nm.

Summary and Conclusions

This paper presented an operational concept based on the integration of advanced navigation performance with ground automation capabilities to achieve airport and airspace capacity and efficiency benefits. This concept provides a significant step towards the future trajectory-based vision of NextGen and implementation is technically feasible in the 2008-2012 timeframe.

An analysis of the performance of this concept as applied to arrival management was presented in this paper. Results of an analysis of the effects of discretization of speed options were shown, indicating guidelines for the design of delay options for high-performance arrival airspace. The paper also presented analysis showing the effect of errors in the mean wind forecast on separations at the runways, highlighting the importance of accurate wind forecasts in trajectory-based operations, and the potential need for tactical adjustments to compensate for wind prediction errors.

The paper concluded with an analysis of the effects of stochastic error parameters representing wind gusts, navigation performance and trajectory prediction performance on timing delivery accuracy. The analysis showed that trajectory prediction error and wind gusts are the predominant influence factors on delivery accuracy, which is in agreement with conclusions reported in [16]. The effect of lateral navigation performance is shown to be minimal to the meter fix, but plays a larger role in the TRACON where speeds are low and the number and magnitude of turns are greater. This effect can be considerably reduced if turns are executed to a reference (e.g. fixed radius turns) using RNP procedures. Another way to mitigate this effect is with the introduction of a secondary planning stage just prior to TRACON entry.

The paper also demonstrated that 2 nm or 25 s of spacing buffer applied at the meter fix is necessary to mitigate the delivery variance that results from the effects of trajectory prediction error, lateral navigation performance and wind variability. The cost of this buffer for the arrival scenario studied is on average an additional 90s of arrival delay for each flight.

The contribution of the work reported here is in providing a fast-time analysis tool where trade studies involving these key trajectory performance parameters through the entire arrival phase can now be performed. A trade study examining the potential balance between spacing buffers, planned delay and tactical intervention is of significant interest for further work.

Preliminary benefits analyses of the arrival management concept presented here assumed a 12 s delivery accuracy at the outer marker [19]. The results presented here show that this delivery accuracy can be achieved with RNP values of 0.16 nm or below without the need for a secondary planning stage in the TRACON or high-precision turns. The exact value achievable with the concept in real-life wind conditions will be determined in field tests planned for 2009 in collaboration with FAA, NASA, JPDO and participating airlines.

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Key Words

Air traffic management, arrival management, required navigation performance, delay, modeling.

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