Robustness Analysis of Terminal Area Scheduling Operations Using a Queuing Framework

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As a part of NASA’s NextGen research effort, the focus area of Airspace Super-Density Operations (ASDO) is researching scheduling tools to increase the efficiency of terminal area operations. It is critical that the schedules generated be robust to uncertainties such as wind. The objective of the current research is to evaluate the robustness of an “optimal schedule” to wind uncertainty. A queuing model of the terminal area suitable for performing stochastic analysis of terminal area operations is developed for this purpose. The queuing model is simulated using a discrete-event simulation framework. A detailed wind model consisting of nominal and uncertain components is used for modeling the nominal wind component. An autoregressive model from existing literature is used to model the the uncertain component of the wind. An elegant feature of the current queuing model involves generating a “zero-conflict” solution by post-processing of the discrete-event simulation data. In this work the “zero-conflict solution” is used as a placeholder for other optimal schedule planners that are currently being developed by NASA and its collaborators. Monte-Carlo simulations are conducted to evaluate the robustness of the schedule to wind uncertainties and performance metrics such as number of conflicts and delay are recorded.

Nomenclature

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tr>
<td>ASDO</td>
<td>Airspace Super Density Operations</td>
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<tr>
<td>DAFIF</td>
<td>Digital Aeronautical Flight Information Files</td>
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<td>DEQS</td>
<td>Discrete-Event Queuing Simulation</td>
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<tr>
<td>DP</td>
<td>Departure Procedure</td>
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<tr>
<td>d-TPP</td>
<td>digital-Terminal Procedures Publication</td>
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<tr>
<td>GPS</td>
<td>Global Positioning System</td>
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<td>IAP</td>
<td>Instrument Approach Procedure</td>
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<td>ILS</td>
<td>Instrument Landing System</td>
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<td>IMC</td>
<td>Instrument Meteorological Conditions</td>
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<td>NextGen</td>
<td>Next Generation Air Transportation System</td>
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<td>NOAA</td>
<td>National Oceanic and Atmospheric Administration</td>
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<td>NFD</td>
<td>National Flight Database</td>
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<td>RNAV</td>
<td>Area Navigation</td>
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<td>RNP</td>
<td>Required Navigation Performance</td>
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<td>RUC</td>
<td>Rapid Update Cycle</td>
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<td>SID</td>
<td>Standard Instrument Departure</td>
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I. Introduction

NASA and FAA have been involved in extensive research efforts to develop advanced concepts, technologies, and procedures for the Next Generation Air Transportation System (NextGen). Among the various areas explored under these research efforts, the research focus area ‘Airspace Super Density Operations (ASDO)’ seeks to develop efficient terminal area operations. The vision for NextGen Airspace Super Density Operations includes the following concepts:

1. Automation for optimal scheduling, sequencing, route assignment and runway assignment based on optimization algorithms.
2. 4D trajectory management for scheduling conflict free trajectories using Area Navigation (RNAV) and Required Navigation Performance (RNP) routes.
3. Conflict free continuous descent arrivals from the top of descent to the runway threshold for multiple flights to multiple airports of a metropole.
4. Ground based and flight deck based automation systems for conflict detection, separation assurance and merging and spacing operations.
5. Very closely spaced parallel runway operations and simultaneous operations on intersecting runways under instrument meteorological conditions (IMC).
6. Integrated arrival, departure and surface operations.
7. Optimal runway configuration management based on predicted weather and demand.

It is expected that multiple ASDO concepts will be interacting with one another in a complex stochastic manner. Therefore, the overall system performance may not be a straightforward combination of individual performance indices. It is also crucial that the overall system performance is robust to wind and operational uncertainties. Current research seeks to evaluate the robustness of a scheduler to wind uncertainties. The scheduling algorithms are expected to compute the following:

- Times of arrival at the metering fix which represent the entry points to the terminal airspace
- Times of arrival at merge nodes
- Times of arrival at the runway.
- Implicit in these schedules are the desired sequence in which aircraft cross the merge nodes.

A queuing framework-based discrete-event simulation is used to model the flights in the terminal airspace. A companion paper describes the queuing framework and the discrete-event queuing simulation in detail. The queuing model uses a queuing abstraction to model the tactical control mechanisms for separation assurance as illustrated in Figure 1.

![Figure 1. Queuing Abstraction](image)

Aircraft are expected to satisfy a 3 nmi inter-aircraft separation in the terminal area. A violation of this requirement is termed a conflict in this paper. Air traffic controllers typically vector the trailing aircraft in a conflict so that the aircraft does not violate the 3-nmi separation constraint (see Figure 1 left). Vectoring the trailing aircraft...
is equivalent to injecting a delay to the trajectory of the trailing aircraft. The figure on the right shows the queuing abstraction in which the terminal area routes are segmented into smaller sections called servers, with the length of each server being 3 nmi. Separation is ensured by enforcing the rule that only one aircraft can occupy a given server at a given time. Aircraft A1 in Server1 has to wait in queue until aircraft A2 has finished service at Server2. Thus, the wait in queue is equivalent to the delay incurred due to vectoring.

The queuing framework uses a detailed link-node model of the terminal area created using airspace data such as departure and arrival fixes, Standard Instrument Departure (SID), Standard Terminal Arrival Route (STAR), RNAV routes and procedures. Flights are characterized by a server sequence that depends on their arrival/departure route, arrival times at the entry server which could be computed by a scheduler, and service time distributions which are dependent on the aircraft type and the wind. A Discrete-Event Queuing Simulation (DEQS) can be used to propagate the flights through the link-node model of the terminal area. The output of the DEQS can be further processed to compute traffic flow efficiency metrics such as delay, throughput, and landing times. A key component of the DEQS is the wind model because the service time of queuing network servers depends on the aircraft type and the wind conditions. In this work the wind is modeled as having a nominal component and an uncertain component. RUC forecasts are used to represent the nominal component of the wind. An autoregressive model is used to simulate the uncertain component of the wind. Monte-Carlo simulations are conducted using the DEQS to test the robustness of the scheduling.

Stochastic analysis of terminal area operations using complex trajectory based models have been performed in the past. Simulations based on complex trajectory models generally require algorithms for trajectory prediction, conflict probing, and conflict avoidance. Tactical control mechanisms such as vectoring to maintain separation assurance have to be explicitly coded in the trajectory propagation equations. Stochastic analysis using such models performed through Monte Carlo simulations can be computationally intensive. Monte-Carlo simulations with DEQS on the other hand are computationally very efficient. The discrete event simulation does not propagate the aircraft at small time steps but jumps from one significant event to another. The significant event can be an entry of an aircraft into the network, the finishing of service of an aircraft at a server or a transition of aircraft from one server to another. Since the discrete event simulation jumps from one significant event to the next, it runs much faster than the aircraft propagation at small time steps. Hence, the Monte Carlo simulation using the discrete event simulation framework is expected to be much faster than the Monte Carlo simulation using detailed aircraft propagation models, without suffering a major loss in fidelity. An unoptimized MATLAB implementation of DEQS typically takes about 4 seconds to simulate a terminal area traffic over a 4 hr time period.

The remainder of the paper is organized as follows. Section II describes the link-node queuing network model for the SFO terminal area. The nominal wind model and the wind uncertainty model are described in Sections III and IV respectively. Section V describes the generation of a “Zero-Conflict Schedule” which in this paper is used as a placeholder for advanced “Optimal Schedulers” being researched by NASA and its collaborators. The simulation results are presented in Section VI, followed by summary and concluding remarks in Section VII.

II. Link-Node Queuing Network Model for SFO

The route structure for the SFO ‘West Plan’ configuration is illustrated in Figure 2. Terminal airspaces are typically described by published Standard Terminal Arrival Routes (STARs), Departure Procedures (DPs) and Instrument Approach Procedures (IAPs). Link-node models are created by splitting the pathways created by the STARs, DPs and IAPs into smaller segments while taking into account the minimum inter-aircraft separation requirements. The STARs, DPs, and IAPs consist of a sequence of waypoints described by the latitude and longitude coordinates. In this work only arrivals are considered, departures will be included in future work. Some waypoints such as “BOLDR” on the BIGSUR STAR shown in Figure 3 also have additional information such as altitude and speed restrictions. Data pertaining to the STARs is available from the FAA’s Digital Terminal Procedure Publication (d-TPP)\textsuperscript{27}, National Flight Database (NFD)\textsuperscript{27} and the National Geospatial-Intelligence Agency’s Digital Flight Information Files (DAFIF)\textsuperscript{28}.

The following STARs and approach procedures for SFO airport were obtained from References 26 and 28:

1. GOLDEN GATE5 Arrival (PYE-GOLDN, shown in colors green, magenta, black in Figure 4)
2. MODESTO Arrival (MOD-MOD3, shown in color cyan in Figure 4)
3. YOSEMITE Arrival (YOSEM-YOSEM1, shown in color blue in Figure 4)
4. BIGSUR Arrival (BSR-BSR2, shown in color red in Figure 4)
5. LOC RWY 28L (shown in light green in Figure 4)
6. RNAV (GPS ) RWY 28L (shown in light green in Figure 4)
The STARs are connected to the ILS and GPS approach procedures in consultation with a subject matter expert who is a Traffic Management Controller (TMC) at the Oakland ARTCC. The connected arrival pathways to SFO are shown in Figure 4. The GOLDN5 five arrival route is split into two routes at ‘DUXY’; one route travels over the bay and the other route travels over the peninsula.

![Figure 2. San Francisco Bay Area Terminal Airspace Routes: West Plan](image)

Figure 3. Snippet of the BIGSUR STAR at SFO

Five individual terminal area arrival pathways are thus created. These pathways are referred to as GOLDN_BAY, GOLDN_PEN, MOD, YOSEM, and BSR in the remainder of this paper. The subscripts ‘BAY’ and ‘PEN’ for the GOLDN route represent the two pathways resulting from the split at DUXBY. The pathways can be described by the following sequences of waypoints (marked by asterix (*) marks in Figure 4):

1. **GOLDN_BAY**: PYE→LOZIT→DUXY→GGB1→GGB2→DUYET→SFO
2. **GOLDN_PEN**: PYE→LOZIT→DUXY→SFO→GGB1→MENLO→CEPW→DUYET→SFO
3. **MOD**: CEDES→OOMEN→MEHTA→RAMND→CEPW→DUYET→SFO
4. **YOSEM**: STEEV→FAITH→MEHTA→RAMND→CEPW→DUYET→SFO
5. **BSR**: SKUNK→BOLDR→MENLO→CEPW→DUYET→SFO

Whereas most of the above waypoints are standard way points in DAFIF, additional way-points GGB1, GGB2, and GGP1 are created to connect the DUXBY waypoint to DUYET along GOLDN_BAY and GOLDN_PEN. The queuing network in Figure 4 consists of a total of 18 waypoints distributed over 12 constant heading branches. Individual pathways can be described by a sequence of waypoints - the number of which varies from 6 along BSR to 9 along GOLDN_PEN. Further discretization of the 12 branches is necessary to model the inter-aircraft separation requirements. To achieve this, the latitude and longitude coordinates associated with each waypoint of the pathway are converted to Cartesian coordinates (with origin chosen at the SFO airport) using equations (1) and (2).

\[ x_{wp} = R_e (\lambda_{wp} - \lambda_{SFO}) = R_e \Delta \lambda \]  
\[ y_{wp} = R_e \cos \lambda_{SFO} (\tau_{wp} - \tau_{SFO}) = R_e \cos \lambda_{SFO} \Delta \tau \]  

where, \( R_e \) is the radius of the Earth, \( \lambda \) is the latitude, \( \tau \) is the longitude, \( x \) is the North position and \( y \) is the East position and the subscript “wp” refers to waypoint.

The Euclidean distance between the waypoints is computed and each branch of the pathway is divided into links of length 3 nmi. Note that rounding approximations enter this network formulation due to the fact that integer number of links must be used for various branches of the network. The links are referred to as servers in accordance with queuing parlance. The servers are given a unique identification number and the arrival pathways are described by a sequence of server numbers. The servers are shown in Figure 5 by black dots; some server numbers are also labeled for the purpose of illustration. The server sequences thus created are referred to as the queuing network in
the remainder of this paper. The queuing network shown in Figure 5 consists of 53 servers. The number of servers along the arrival pathways ranges from 14 servers on BSR and YOSEM, to 23 servers on GOLDN\textsubscript{PEN}. The server sequences are not necessarily continuous sequence of integers, for example the server sequence for GOLDN\textsubscript{BAY} is as follows: \{1 2 3 4 5 6 7 8 9 10 35 36 37 38 51 52 53\}.

![Figure 4. Arrival Pathways to Runway 28L at SFO](image1.png)

![Figure 5. Numbers of Select Servers in SFO Terminal Area Link-Node Model](image2.png)

The link-node model presented in this section is suitable for DEQS. A detailed description of the DEQS is available in Reference\textsuperscript{23}. The DEQS computes the service times for individual flights at each server as part of the simulation. Wind can have considerable effect on these service times. Therefore, it is imperative that terminal area schedulers and simulators both take it into account. However, the knowledge of wind can be very uncertain. Therefore, it is essential that schedules generated using nominal wind be robust to wind uncertainties. With this motivation, wind is modeled as the sum of nominal and uncertain components. Details of these components are discussed in detail in the following sections.

### III. Nominal Wind Model

The National Oceanic and Atmospheric Administration’s (NOAA) Rapid Update Cycle (RUC) data is used for simulating the nominal wind. The raw data used in this work has a spatial resolution of 13 km on the horizontal plane. Discretization along the altitude dimension (50 levels) is based on the reference virtual potential temperature and does not result in uniform altitude spacing.

#### A. Spatial Variation of Wind

Bilinear interpolation is used to obtain the wind components at the specific latitude and longitude coordinates of the terminal area queuing network servers. To obtain the altitude coordinate for a server, a linear altitude variation starting from 10,000 feet at the entry server to zero feet altitude at the landing server is assumed in this work. It should be noted that this assumption is only made for sake of current research expediency and flight specific server altitudes can be used in future research. The wind components can be computed for each flight separately based on their individual altitude profile.

Figure 6 and Figure 7 show the North and East wind component variation respectively along the five different arrival pathways described in Section II. The wind variation is shown only with respect to altitude because each server along these routes is assumed to have a fixed altitude for all flights. For this specific data obtained on May 28, 2010, it can be seen that the wind only seems to vary with altitude and is more or less constant for all the arrival pathways. Figure 8 and Figure 9 show the wind speed and heading angle respectively along the arrival pathways. Whereas both speed and heading angle have segments of monotonic behavior, the heading angle is seen to depart from this pattern in the altitude range of 2000 to 5000 feet.
Figure 6. North Component of Wind along SFO Arrival Pathways

Figure 7. East Component of Wind along SFO Arrival Pathways

Figure 8. Wind Speed along SFO Arrival Pathways

Figure 9. Heading Angle of Wind along SFO Arrival Pathways

B. Temporal Variation of Wind

Spatial variations of the data along the different arrival pathways and at different altitude were presented in the previous section using 1 hour RUC forecast data. However, the RUC data is available for hourly forecasts from 1 hour to 12 hours into the future. Therefore, four dimensional wind patterns at all of the queuing network servers can be obtained using the RUC forecast data. Figure 10 and Figure 11 show the hourly forecasts along the GOLDN\textsubscript{BAY} arrival pathway. Considerable difference is noted between the 1 hour and 4 hour forecasts of the North wind component in Figure 10. Hourly forecasts of the wind speed and heading are shown in Figure 12 and Figure 13 respectively.

Four dimensional wind fields accommodating variations along the horizontal plane, vertical plane and time have been presented in this section. The North and East components of these wind fields can be expressed in the following functional form:

\[
W_{N - nom} = W_{N - nom}(\lambda_i, \tau_i, h, t) \quad W_{E - nom} = W_{E - nom}(\lambda_i, \tau_i, h, t)
\]

where, \(W_{N Nom}\) and \(W_{E Nom}\) are the North and East components of the nominal wind field, \(\lambda_i\) is the latitude of the \(i^{th}\) server, \(\tau_i\) the longitude of the \(i^{th}\) server and \(t\) is the time of interest.

The knowledge of these wind fields is crucial in designing terminal area operations such as scheduling and sequencing and runway configuration management. However, this is only a single forecast and the actual wind fields are expected to depart from this forecast, thereby introducing uncertainty into the system. Models for the uncertainty component of the wind will be discussed in the following section.

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IV. Wind Uncertainty Model

The wind uncertainty model used in this work is based on the model derived in Ref. 30. The uncertain wind components are synthesized as the sum of a DC signal, altitude dependent high frequency component generated by a second order auto-regressive model, and another altitude dependent low frequency component also generated by a second order auto-regressive model. It is assumed that the North and East components of the uncertainty model are uncorrelated.

\[ \Delta W_N(h) = \Delta W_{N,DC} + \Delta W_{N,HF}(h) + \Delta W_{N,LF}(h) \]
\[ \Delta W_E(h) = \Delta W_{E,DC} + \Delta W_{E,HF}(h) + \Delta W_{E,LF}(h) \]

where, \( \Delta W_N \) and \( \Delta W_E \) are the North and East components of the wind uncertainty, subscripts \( N \) and \( E \) stand for North and East respectively, \( HF \) and \( LF \) stand for high frequency and low frequency respectively. Altitude is discretized into uniform steps of 250 feet each and the corresponding difference equations for the autoregressive signals representing the high frequency and low frequency components can be written as follows \(^30\).

\[ \Delta W_{N,HF}[n] = a_{1,N,HF} \Delta W_{N,HF}[n-1] + a_{2,N,HF} \Delta W_{N,HF}[n-2] + \nu_{N,HF}[n] \]
\[ \Delta W_{E,HF}[n] = a_{1,E,HF} \Delta W_{E,HF}[n-1] + a_{2,E,HF} \Delta W_{E,HF}[n-2] + \nu_{E,HF}[n] \]
\[
\Delta W_{N\_LF}[n] = a_{1\_N\_LF}\Delta W_{N\_LF}[n-1] + a_{2\_N\_LF}\Delta W_{N\_LF}[n-2] + v_{N\_LF}[n] \\
\Delta W_{E\_LF}[n] = a_{1\_E\_LF}\Delta W_{E\_LF}[n-1] + a_{2\_E\_LF}\Delta W_{E\_LF}[n-2] + v_{E\_LF}[n]
\]

where \( a_{ij} \) are the correlation coefficients and \( v_{ij} \) are zero mean Gaussian white noise signals and \( n \) stands for the discretized altitude levels. The magnitude of the DC signal and the magnitude of the variance of the noise signals can be used to control the magnitude of the uncertainty terms.

Figure 14 and Figure 15 show three sample uncertain wind component profiles along North and East direction respectively generated using equations (8)–(9). The DC signal is set to 0.5 knots. Zero initial conditions are used for all the four difference equations given by equations (6)–(9). The coefficients of the autoregressive model and the variance of the noise signals are chosen as per Table 1 from Ref. 30. The data was fitted for the observed data at the Louisville International Airport for flights that are separated by less than 15 minutes. In this work the autoregressive model coefficients are retained, but the size of the noise variance is used to control the magnitude of the wind uncertainty signal.

![Figure 14. Sample North Component Profiles of the “Uncertain Wind”](image)

![Figure 15. Sample East Component Profiles of the “Uncertain Wind”](image)

Table 1. Autoregressive Model Coefficients and Noise Variance

<table>
<thead>
<tr>
<th>North/East</th>
<th>( a_1 )</th>
<th>( a_2 )</th>
<th>( V_{var} )</th>
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<tr>
<td>HF East</td>
<td>1.0139</td>
<td>0.3449</td>
<td>0.9282</td>
</tr>
<tr>
<td>HF North</td>
<td>1.0307</td>
<td>0.3748</td>
<td>0.9829</td>
</tr>
<tr>
<td>LF East</td>
<td>1.1205</td>
<td>0.1417</td>
<td>0.2932</td>
</tr>
<tr>
<td>LF North</td>
<td>1.112</td>
<td>0.1352</td>
<td>0.3366</td>
</tr>
</tbody>
</table>

The uncertain wind component signals shown in Figure 14 and Figure 15 stay on the same side of the origin for long stretches of altitude due to the correlated nature of the wind uncertainty model resulting both from high and low frequency signals. Figure 16 and Figure 17 show the North and East component of the actual wind (nominal + uncertain) along the GOLDN\textsubscript{BAY} arrival pathway. The red colored line is the nominal obtained from the forecast described in the previous sections. The blue colored plots are the sum of the nominal and the uncertain components shown in Figure 14 and Figure 15. Wind components such as those shown in Figure 16 and Figure 17 will be used in the Monte Carlo simulations in Section VI.
The overall block diagram for computing the wind speed components as a sum of nominal and uncertain components is shown in Figure 18. Also, the auto-regressive correlation coefficients are currently not available for all routes at SFO. Therefore, only one set of coefficients are used for all arrival routes. However, due to the random nature of the noise driving the auto-regressive model, the uncertain components will be different for all flight routes. Wind computations shown in Figure 18 are used in the stochastic robustness evaluation of flight schedule using the Monte Carlo simulation approach in Section VI.

V. Zero-Conflict Solution

An elegant and useful by-product of the DEQS framework developed under this work is the generation of a “zero-conflict schedule”. Flights passing through the queuing network experience delays at servers where they encounter separation related conflicts. These delays are recorded both flight-wise and server-wise in the DEQS. A flight schedule that absorbs all the flight-wise delay at the entry server is theorized to encounter no further conflicts in the queuing network. This assertion is valid for a network with merging intersections alone (no splits in the routes) and the assumption of first come first served at every server.
The algorithm for the generation of the zero-conflict solution is as follows:
1. Perform a discrete-event queuing simulation using the nominal arrival times of all flights at the entry nodes to the terminal area network.
2. Determine the delays encountered by every flight at every server in the network.
3. Calculate the sum of the total delays encountered by the flight and enforce the delays at the entry points to the network to determine the zero-conflict schedule.

Figure 19 shows the block diagram of the zero-conflict solution generation using the queuing simulation.

VI. Results

To test the zero-conflict assertion, a simulation involving four arrival pathways and 89 flights and a nominal schedule generated from trajectory propagation is considered. Eleven flights flying over GOLDN_{PEN} arrival pathway were eliminated to avoid the split in the network on the GOLDN arrival route. A total of 207 conflicts were encountered with the nominal schedule; the distributions of which server-wise and flight-wise are shown in Figure 20 and Figure 21, respectively. The distribution of flight-wise delays with nominal schedule is shown in Figure 22. The total delay encountered by the 89 flights is 2348 seconds.

A new schedule that shifts the sum total of flight-wise delay over all the servers to the entry server is created. It should be noted that 50 flights out of the 89 flights did not experience any delay. The median delay for the remaining 39 flights is 52 seconds and the maximum individual flight delay is 3.92 minutes. A simulation conducted with the new schedule results in zero conflicts. The overall delay is the same except that the delay is all shifted to the entry server and no additional delay is incurred within the network. The change in schedule also does not penalize the time taken to process the 89 flights which is a measure of the throughput.
A. Monte-Carlo Analysis

This section describes the Monte Carlo simulations that were conducted to verify the robustness of the zero-conflict solution described in the earlier, using the wind uncertainty model presented in the previous sections.

The following equation is used to compute the service time of the $i^{th}$ flight at the $j^{th}$ server:

$$\Delta T_{ij} = \frac{\Delta S}{V_{ij} + W_{ij} \cos \chi_{wind \_ij} - Z_{ij}}$$

(10)

where, $\Delta S$ is the server length or the mandated inter-aircraft separation (3 nmi), $V_{ij}$ is the airspeed of the $i^{th}$ flight at the $j^{th}$ server, $W_{ij}$ is the wind speed experienced by the $i^{th}$ flight at the $j^{th}$ server, $\chi_{wind \_ij}$ is the heading angle of the wind experienced by the $i^{th}$ flight at the $j^{th}$ server, and $\chi_{ij}$ is the heading angle of the $i^{th}$ flight at the $j^{th}$ server. Wind speed and heading angle are computed using the following equations:

$$W_{ij} = \sqrt{W_{ij \_N}^2 + W_{ij \_E}^2}$$

(11)

$$\chi_{wind \_ij} = \arctan 2\left(W_{ij \_E} \cdot W_{ij \_N}\right)$$

(12)
where \( W_{ij,N} \) and \( W_{ij,E} \) are the North and East components of the wind experienced by the \( i^{th} \) flight at the \( j^{th} \) server which are computed as the sum of a nominal and uncertain component as shown by the following equations:

\[
W_{ij,N} = W_{ij,N,nom} + \Delta W_{ij,N} \quad W_{ij,E} = W_{ij,E,nom} + \Delta W_{ij,E}
\]

Although, the nominal component can be computed as a function of time, in this simulation the forecast is held constant.

\[
W_{ij,N,nom} = W_{N,nom}(t, \tau, h_j, t = 1 hr) \quad W_{ij,E,nom} = W_{E,nom}(t, \tau, h_j, t = 1 hr)
\]

Uncertain wind components are generated as a function of altitude along North and East directions using Eqs. (4)–(9). Altitude histories of uncertain wind components are generated one for every 15-minute interval. For initial evaluation the uncertain wind components are not varied in the horizontal plane. The actual uncertainty signal at time \( t \) is computed using interpolation between two profiles generated 15 minutes apart as given by Eqs. (15) and (16). This ensures that two flights following each other closely are likely to experience a similar uncertainty signal.

\[
\Delta W_{ij,N}(h_j, k \times 15 \leq t \leq (k+1) \times 15) = \Delta W_{ij,N}(h_j, k \times 15) + (1 - \lambda) \Delta W_{ij,N}(h_j, (k+1) \times 15)
\]

\[
\Delta W_{ij,E}(h_j, k \times 15 \leq t \leq (k+1) \times 15) = \Delta W_{ij,E}(h_j, k \times 15) + (1 - \lambda) \Delta W_{ij,E}(h_j, (k+1) \times 15)
\]

where, \( \lambda \) is computed for the largest integer value of \( k \) satisfying the following equation:

\[
t = (k + \lambda)^{15}
\]

The uncertain components \( \Delta W_{ij,N}(h_j, k \times 15) \), \( \Delta W_{ij,N}(h_j, (k+1) \times 15) \), \( \Delta W_{ij,E}(h_j, k \times 15) \), \( \Delta W_{ij,E}(h_j, (k+1) \times 15) \) are generated independent of each other using Eqs. (4)–(9), using model parameters in Table 1, using zero initial conditions for the difference equations in Eqs. (6)–(9).

Monte Carlo simulations of the discrete-event queuing simulation are conducted to evaluate the robustness of an arrival schedule. For the purpose of evaluation, a zero-conflict schedule is generated using the nominal wind profile. Uncertain wind components generated using equations (13)–(17) are used in the Monte Carlo simulations. Different profiles of the uncertain wind components are obtained by the random nature of the noise terms in equations (6)–(9). The DC component of the uncertain wind component is set to either +0.5 knots or -0.5 knots chosen randomly with equal probability for both choices. The size of the uncertain wind components are controlled by controlling the magnitude of the variance terms in the last column of Table 1 using a multiplication factor. Four settings of a multiplication factor \( MF = 0.25 \) (25%), 0.5 (50%), 0.75 (75%), and 1 (100%) are used for the noise variance terms, one for each set of a 500 trial Monte Carlo simulation. The smaller the value of the multiplication factor, the smaller is the size of the wind uncertainty signal.

Total delay and total number of conflicts are used as the metrics of interest in the Monte Carlo simulations. Figure 23 and Figure 24 show the histograms of the total number of conflicts and total delays for different settings of the noise multiplication factor. As expected, the peak of the histogram shifts to a large number of conflicts when the size of the uncertainty increases. A similar trend is observed in the total delay as well.
The throughput or the total time to land all the 89 flights chosen in this scenario does not show any particular trend as evidenced in Figure 25 and Figure 26. This is due to the fact that sometimes the wind can act favorably and the large wind resulting from the uncertain component can result in faster traversal of the servers.

Currently, the zero-conflict solution is generated to result in the minimum required time spacing to avoid conflicts without considering uncertainty. Therefore, the schedule thus generated is sensitive to uncertainty and results in conflicts as seen in Figure 23. The actual solution is expected to have an additional buffer parameter which can be increased to avoid conflicts. Monte Carlo simulations can be conducted with a frozen setting of the uncertainty multiplication factor and different settings of the buffer parameter to identify the optimum choice of the buffer parameter. In this mode, the Monte Carlo simulation framework can serve as a real-time decision support tool.

VII. Summary & Concluding Remarks

A. Summary
The work presented in this paper deals with evaluating the robustness of a terminal area schedulers using a queuing framework. The approach is based on a network constructed from published terminal area routes such as STARs, DPs and IAPs. The routes are discretized into smaller servers to enforce separation requirements. Arrival flight routes from metering fix to the landing runway are characterized in terms of finite number of server sequences referred to as arrival pathways. Each flight is assigned a server sequence that is dependent on the direction in which the flight enters the terminal area. Flights are further characterized by their scheduled time of arrival at the entry server and a desired airspeed profile. Wind is modeled as the sum of nominal and uncertain components. The RUC forecast data from NOAA is used to generate nominal wind components that are function of all three spatial coordinates and time. A second order auto-regressive model is used to model the uncertain components of wind. A discrete-event queuing simulation framework is developed for the propagation of flights over different servers while satisfying the mandated inter-aircraft separation requirements. The discrete-event simulation detects conflicts and computes the minimum delay required at each server to maintain separation. The delay represents an abstraction of controller action such as path-stretching or speed reduction.

The DEQS framework was used to evaluate the robustness of a terminal area scheduling algorithm using a test case in the SFO terminal airspace. An elegant by-product of the queuing simulation framework is the algorithm for generating a schedule that results in zero-conflicts. The schedule—referred to as the “zero-conflict” schedule—is used as a place holder for optimal planners that are currently being developed at NASA and its collaborators. The Monte Carlo simulation approach is used to conduct stochastic analysis of the robustness of the zero-conflict schedule.

B. Conclusions
The queuing simulation developed under this work is a computationally efficient apparatus for predicting arrival times, conflicts, and delays in terminal area. The simulation currently executes in less than 4 seconds on MATLAB.
Therefore, it has very good potential for serving as a real-time decision support tool that is based on stochastic evaluation of terminal area traffic.

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IX. References


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