Optimization of Aircraft-based Meteorological Data Collection with a GIS-based Simulation Model

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Abstract

The Tropospheric Airborne Meteorological Data Reporting (TAMDAR) system is envisioned as a new automated, on-board system that will gather meteorological data as aircraft fly in the troposphere and transmit this data to the National Weather Service. This paper reports on an element of this project that aims to demonstrate the feasibility of a prototype TAMDAR economic analysis tool, which will help decision makers to determine the best strategy for system operation. Time correlated position and altitude data for TAMDAR equipped aircraft are generated and entered into the decision aiding software to build a dynamic model of the geographical distribution of the data, at any point of time, generated by a fleet of independent TAMDAR equipped aircraft. Operational costs and data utility are integrated into the decision aiding software to generate a quantifiable value to be assigned to the TAMDAR data supplied by each flight segment. This decision support system helps decision-makers to process different operational alternatives efficiently. The main objective of this paper is to describe the roles of the simulation and visualization components in TAMDAR DSS and illustrate its utility with selected examples.

INTRODUCTION

TAMDAR (Tropospheric Airborne Meteorological Data Reports) is a new airborne weather data acquisition system, which is currently studied by NASA. The TAMDAR concept consists of meteorological sensor packages, information processors, and communications equipment carried aloft by participating aircraft. As these aircraft complete their missions, the TAMDAR system reports meteorological data to ground-based receiving stations that process and distribute this data into a national system for dissemination of weather information. The Federal Aviation Administration (FAA), National Weather Service (NWS), and NASA have concluded that TAMDAR systems have potential to contribute to the accuracy and completeness of weather data and the resulting weather forecasts. Improved aviation safety, along with other benefits for various groups (general society benefits), is anticipated as a result of these improved forecasts. The weather information, that TAMDAR will generate, may be a critical element in enhancing the accuracy and completeness of weather data and resulting forecasts. In turn, this better weather information may lead to improved aviation safety, and other benefits to various groups, and society in general [Ozan and Kauffmann, 2001]. As a first phase, TAMDAR equipment will be installed in commuter and package carrier aircraft since they fly in lower altitudes, which are preferred by meteorologists. They can also provide better spatial and temporal coverage compared to their alternatives (e.g. general aviation aircraft).

The TAMDAR Decision Support System (DSS) is currently being developed by Old Dominion University. The data transmission costs constitute an important part of the total operational costs. In fact, the annual data acquisition cost is estimated as $1,400,000 [Kauffmann and Ozan, 2001]. TAMDAR DSS aims to reduce the data transmission costs of daily meteorological data collection by optimizing data collection scheme. In other words, the TAMDAR DSS is designed to help decision makers to select the flight segments, which would provide the most valuable meteorological information to meteorologists. In order to optimize the data acquisition process, one has to assign utility values for each candidate data point. To value the individual data points, we have to understand the underlying mechanism [Katz and Murphy, 1997]. Despite the lack of guiding principles for valuing meteorological data, one can still derive main attributes based on the current weather forecasting practice. The utility of a meteorological data package is typically related to its following attributes:

- Spatial Coverage
- Temporal Coverage
- Proximity to significant weather events
- Proximity to climatologically priority regions
- Subjective priority attributed by forecasters
- Altitude Attribute
Utility values are evaluated by using a multi attribute utility model, which is mainly based on the expert opinions. The TAMDAR DSS, which is essentially a spatial multicriteria decision model, has three main elements: simulation, data visualization and optimization. The primary focus of this paper is to describe the simulation and data visualization component of TAMDAR DSS.

Figure 1. General structure of TAMDAR DSS.

SIMULATION COMPONENT

There are two main modules of the simulation engine in the TAMDAR DSS: flight pattern generator and scenario generator. The flight pattern generator provides the spatial and temporal distributions of the candidate aircraft's flights. This part of the simulation engine calculates the altitude and GPS position of the candidate aircraft and feeds the data to the optimization engine. The scenario generator creates different input configurations needed in error propagation analysis based on Monte Carlo techniques. Users can also access the controlling parameters of the scenario generator and design their own customized scenarios. All elements of the decision matrix and rules are accessible via the simulation engine. This feature provides extensive possibilities for post optimality analysis. The scenario generator and flight pattern generator are also linked together, therefore, various experiments can be designed in order to assess the weather data collection reliability and efficiency. For example, effects of the significant weather events can be studied by simulating a storm system via scenario generator. The communication between simulator engine and optimization engine is summarized in the diagram shown in Figure 1.

Flight Pattern Generator

The flight pattern simulator module generates the trajectories of flights together with the geographical data point location and acquisition time. The geographical location information includes latitude, longitude and altitude information for each data point collected during each candidate flight segment. The input file, which is fed to the flight pattern generator, includes the daily list of the candidate flights together with the following information:

- Codes of originating and destination airports
- Departure time
- Aircraft type

The flight pattern of an aircraft depends on various different parameters such as weather, air traffic, fuel consumption issues, air controllers and pilot decisions. To build a precise flight pattern simulator, which encompasses all these elements is a task beyond the scope of this study and adds unnecessary complexity. There are three main phases of a flight: ascend, en route, and descend. For simplification we assumed that all velocities (vertical and horizontal) are constant during each flight phase. Therefore, in order to compose a flight pattern we need to derive the following specific information for each flight by using the information, which is embedded in the input file:

- Vertical speeds during ascend ($V_C$) and descend ($V_F$) (vertical speed is assumed to be zero during en route phase)
- Horizontal speed during ascend ($V_A$), en route ($V_E$), and descend ($V_D$) phases
- Flight level (flight level is assumed to be constant during en route phase)
- Distance (D) between two airports

Jet aircraft will typically fly at around 450 knots, turboprop commuters at around 250 knots, and smaller private airplanes from 90 to about 200 knots. Pilots and airlines determine a particular flight's ideal cruising altitude based on a number of factors, including distance, weather, aircraft load, and fuel consumption. Jet aircraft's cruising altitudes are usually between 25,000 and 41,000 feet. Commuter and business turboprops typically cruise at 10,000 to 25,000 feet, and small private aircraft usually cruise below 14,000 feet [Xavius Software. 2001].

One can also assign average climb rates to aircraft based on their types. B73S, B757, B767, A320, and most business jets are fast climbers. They climb at 1,500 feet per minute (FPM). On the other hand, jets, turboprops and the others, especially the jumbos (B747, DC10, MD11) have an average climb rate of 1,000 FPM [Xavius Software. 2001]. Ascend and descend rates can also change with the different air traffic conditions and specific approach and take off requirements of airports. However, the TAMDAR DSS does not require precise prediction of those values since the altitude based valuation of meteorological data is not
defined that precisely.

We can compute times spent during ascend (T_A), descend (T_D), and en route (T_E) as follows:

\[ T_A = h_E / V_C \]
\[ T_D = h_E / V_F \]
\[ T_E = (D - T_A V_A - T_D V_D) / V_E \]

where \( h_E \) is flight level.

In order to calculate the distance between two airports (D), one should consider the spherical geometry of earth’s surface. The following set of equations provides a simple method for this calculation. Let latitude1, latitude2, longitude1, and longitude2 represent the geographical coordinates of two airports.

\[ \alpha = 90 – \text{latitude1} \]
\[ \beta = 90 – \text{latitude2} \]
\[ \phi = \text{longitude1} – \text{longitude2} \]
\[ \cos \tau = (\cos \alpha) (\cos \beta) + (\cos \phi) (\sin \beta) (\sin \alpha) \]
\[ D = 60 \times \cos^{-1} \tau \]

Table 1. Equations for calculation of altitude during different flight phases.

<table>
<thead>
<tr>
<th>Flight Phase</th>
<th>Interval</th>
<th>Traveled Distance d(t)</th>
<th>Altitude h (t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ascend</td>
<td>( t_1 \leq t \leq t_2 )</td>
<td>( V_C \times t )</td>
<td>( h_C )</td>
</tr>
<tr>
<td>En route</td>
<td>( t_2 &lt; t &lt; t_3 )</td>
<td>( V_C (t - t_2) )</td>
<td>( h_C )</td>
</tr>
<tr>
<td>Descend</td>
<td>( t_3 &lt; t &lt; t_4 )</td>
<td>( V_C (t - t_3) )</td>
<td>( h_C )</td>
</tr>
<tr>
<td>End of flight</td>
<td>( t \geq t_4 )</td>
<td>D</td>
<td>0</td>
</tr>
</tbody>
</table>

We can find the altitude values, \( h(t) \) for any given time, \( t \) during each flight segment by using the equations given in Table 1. We can calculate the geographical coordinate (Lat, Long) of the aircraft for a given time value \( t \) as follows:

\[ \Delta \text{lat} = \text{lat2} - \text{lat1} \]
\[ \Delta \text{long} = \text{long2} - \text{long1} \]

where \( \text{lat1}, \text{long1}, \text{lat2}, \) and \( \text{lat2} \) are the coordinates of originating and destination airports respectively.

\[ \text{Lat} = \text{lat1} + [ (d(t) \times \Delta \text{lat}) / D ] \]
\[ \text{Long} = \text{long1} + [ (d(t) \times \Delta \text{long}) / D ] \]

ArcView is a geographical information system based software package, which is used in geographical data visualization and analysis. Figure 2 shows an ArcView image of typical simulated data point patterns for hypothetical flights between seven airports (Chicago O’Hare, Cincinnati, Cleveland, Norfolk, Washington Dulles, Newark, and New York JFK). Altitude values for each data point are color coded with a darker color representing higher altitudes. Similarly, users can also see color coded representation based on data acquisition time by using ArcView interface. Therefore, they can quickly assess the temporal distribution of the data.

**Post Optimality Uncertainty Analysis**

In order to analyze the effects of the uncertainty, which is introduced by the various factors (weather, air traffic, pilots etc.) to the system, one can basically use two approaches to handle uncertainties in decision analysis: sensitivity and error propagation analysis. The former incorporates uncertainty into the multicriteria decision rules directly. Sensitivity analysis is concerned with the way in which errors in a set of input data affect the error in the final output (criterion outcomes). On the other hand, error propagation methods are useful when we would like to know the combined effect of variations in two or more inputs. (Malczewski, 1999).

![Figure 2. An example of TAMDAR-DSS flight pattern simulator’s output.](image)

Error propagation methods are useful when we would like to know the combined effect of variations in two or more inputs. Monte Carlo simulation methods can be used to determine the sensitivity of the model to uncertainty associated with input data and model parameters propagated through MCDM analysis. Broadly speaking, Monte Carlo simulation is a way of evaluating a large number of possible scenarios. A scenario represents one possible set of levels for each random variable and the calculation of the levels of all variables involved in an MCDM decision rule that depend on the random variables. The method selects parameter values using a stochastic selection scheme. The distribution can be sampled using the random sampling method. Typically, parameter values are selected prior to the start of each simulation. The term *Monte Carlo* reflects the fact that random numbers are used to generate the scenarios. The computer solves the MCDM model over and over again,
each solution being a trial of the simulation, which is a randomly sampled scenario. After running a large number of trials, the results are collected in the form of a frequency distribution (or histogram) for one or more selected attributes (Malczewski, 1999).

The basic steps of Monte Carlo simulation are the following: (1) formulate an MCDM deterministic model; (2) identify the probability distribution; (3) use random numbers to simulate the probabilistic events; and (4) simulate the MCDM model by combining the probabilistic events.

In TAMDAR decision support system, simulation engine is the designated module for handling the error propagation techniques. It will be capable to generate Monte Carlo based experiments, which facilitates the generation of the stochastic functions.

Figure 3. A screenshot showing 3D VRML data visualization

3D VISUALIZATION COMPONENT

3D data visualization technology provides a rich and informative medium to analysts. VRML is an acronym for the Virtual Reality Modeling Language. VRML can be described as a 3D analog to HTML. It provides the technology that integrates three dimensions, two dimensions, text, and multimedia into a coherent model [Web 3D Consortium, 2000]. Different layers of data can be observed in VRML viewers with an enhanced 3D spatial awareness [VRML, 1996].

VRML viewers are suitable to be used in order to study the flight patterns in a 3D setting. Input and output flight pattern data files are converted to VRML files by using simple scripts [Kim et al., 1998, Huber, 2000]. VRML provides a rich environment to decision makers for exploratory analysis. Real time weather graphics, which are issued by Weather Service can also be imported into the 3D scene. This feature can help the users to evaluate the efficiency of the selected flights for data collection by observing the pictures of weather phenomena simultaneously. Figure 3 shows an example, which illustrates this concept. As shown, more than one weather graph can be embedded into 3D scene. By altering their opacity rates, they can be observed by the users at the same time. Real time weather graphs used in this example can be accessible via NOAA’s web site [NOAA, 2002]. VRML file includes hyper links to NOAA’s weather graphics in order to achieve automatic inclusion of the latest weather graphics in the 3D scene. The same visualization approach can be used in order to communicate other data to the decision makers such as utility maps and statistical information about the data.

CONCLUSION

This study develops a practical and simplified simulation approach for the optimization of the aircraft-based meteorological data collection. Although this study is based on airborne sensors, the same approach can be adapted to other weather sensors (surface and/or satellite). The utilities of this study's findings are not limited to weather-related activities. The TAMDAR problem, in essence, is a decision-making problem related to information acquisition systems. There are various types of information gathering systems in today's information-oriented economies. These include market data collection activities, environmental data acquisition systems, defense-related information gathering, security or safety related information collection, Internet based data-mining systems etc. The general framework, which will be showcased in this project, can be adapted to these and other similar areas.

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REFERENCES


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