WIND ANALYSIS IN AVIATION APPLICATIONS

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Abstract

The Rapid-Update-Cycle (RUC) and Rapid Refresh (RAP) weather products provide a valuable source of data for evaluating environmental winds in the aviation domain. This paper identifies techniques for wind analysis, including interpolation techniques and patterns for distributed computation. These techniques are useful in a number of aviation applications, a subset of which are described: New instrument procedure designs benefit from historical 5-year wind profiles. Wind characterization and visualization techniques facilitate the selection of representative environmental conditions for simulations. Wind forecasts are uplinked in real-time to support trajectory-based operations. These applications leverage the RUC and RAP weather products to provide valuable technical insights. The paper concludes with areas for future research.

Background

Wind considerations are important for aviation applications. Winds directly impact groundspeed, and are taken into account during modeling, simulation, and procedure design. Numerical weather predictions facilitate quantitative wind analysis. The National Centers for Environmental Prediction (NCEP), a division of the National Oceanic and Atmospheric Administration (NOAA), operates several numerical weather prediction services. The RUC and RAP products provide gridded weather data covering the continental United States (CONUS) region.

Rapid Update Cycle

The RUC product is an operational regional analysis-forecast weather product. RUC is distinctive for its hourly assimilation cycle and hybrid-isentropic vertical coordinate system. Each hour, measurements from aircraft, weather stations, radar winds, satellite imagery, as well as other sources are assimilated to produce a RUC best estimate of current conditions (often referred to as zero-hour analysis, or nowcast). This analysis serves as the initialization for a numerical weather prediction model, which produces near-term hourly forecasts for 1 to 18 hours in the future [1]. The entire process repeats each hour.

Figure 1 illustrates various aspects of the model. RUC is available in two vertical coordinate systems: Hybrid-isentropic (50 Level, Native, *bgrb*) and Isobaric (37 Level, Pressure, or *pgrb*). The vertical perspective (Figure 1, top right) shows a cross section comparing these vertical grids. The hybrid *bgrb* grid provides a higher fidelity representation of the atmosphere [2]. RUC is also available in a range of lateral grid resolutions; including 13 km, 20 km, and 40 km [3]. The lateral perspective (Figure 1, top left) illustrates the RUC 13 km spacing with an overlay of a radar track for a flight from San Diego, CA arriving into Seattle, WA. The RUC model produces 3-dimensional gridded outputs, including wind, temperature, pressure, geopotential height, as well as 2-dimensional outputs such as precipitation mixing ratios and surface conditions. This output data is saved into a separate file for each model run and for each forecast outlook (Figure 1, bottom right).

Rapid Refresh

On May 1st, 2012, NOAA transitioned from RUC to the Rapid Refresh (RAP) forecast product. RAP is a gridded weather product similar to RUC, with a number of technical enhancements including the use of a Weather Research and Forecast (WRF) model and Gridpoint Statistical Interpolation (GSI) for data assimilation [4] [5]. RAP is available in the same vertical coordinate systems (*bgrb*, *pgrb*) and lateral grid formats (13 km, 20 km, 40 km) as the legacy RUC product. RAP provides a direct replacement for RUC from an applications development and analysis perspective. Additional versions of RAP will provide extended coverage for all of North America, and higher resolution (3 km) in the form of High-Resolution Rapid Refresh (HRRR). These are not yet available in production status [6].
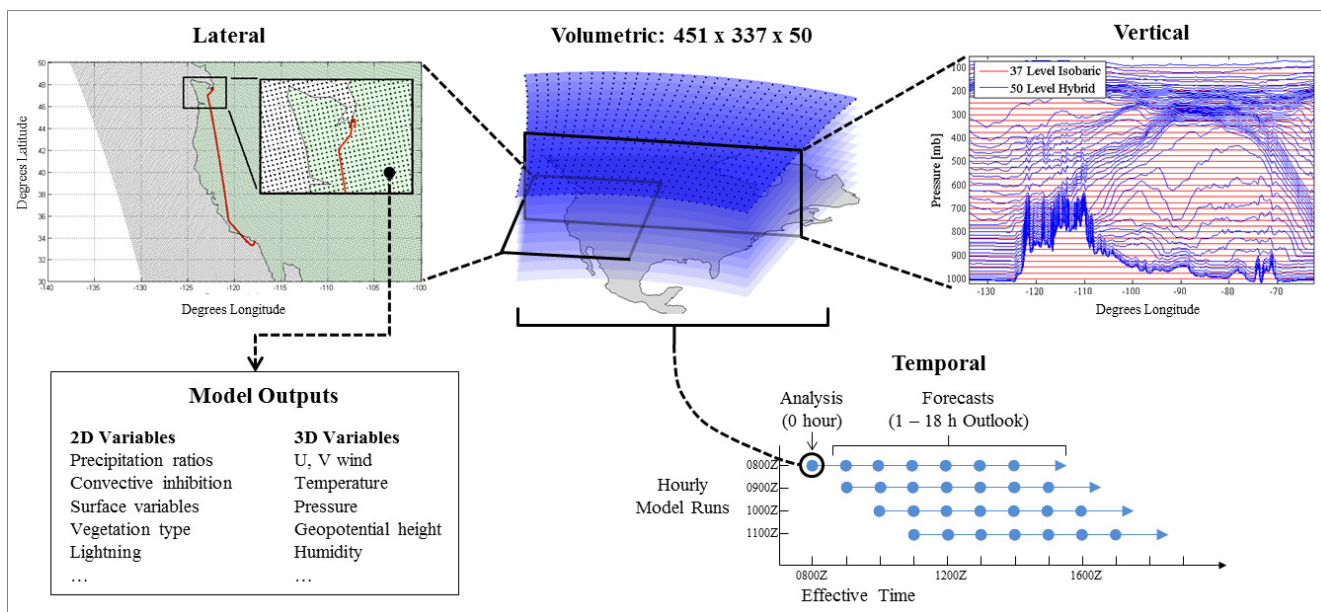
Figure 1. Visualization of model perspectives (RUC/RAP *bgrb130* grid)

Data Sources

The RUC forecast model has been operational at NCEP since 1998 [1], with archive forecasts from 2004 to the present openly available through the National Archive and Model Operational Distribution System (NOMADS), at http://nomads.ncdc.noaa.gov. The NOMADS service provides several download interfaces, including File Transfer Protocol (FTP), Hyper Text Transport Protocol (HTTP), and FTP on demand. Figure 2 shows a summary of zero-hour data availability. The NOMADS archive contains sufficient data to support large-scale historical atmospheric analysis.
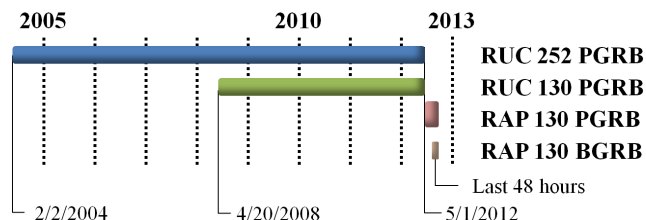

Figure 2. Data Availability

RAP is also available at the NOAA realtime production server, ftp://ftpprd.ncep.noaa.gov. This server provides access to both the *bgrb* and *pgrb* files for the most recent 48 hours. For the highest-fidelity analysis, these native grid files must be downloaded daily from the realtime production server. Figure 3 summarizes the realtime production server filename conventions. Files are organized into folders by model run-date. The research presented in this paper uses a locally cached copy of the RUC/RAP dataset, from January 1st, 2005 through July 31st, 2012, consisting of the highest resolution analysis-only data available for each hour. Storage requirements are approximately 1.5 TB of disk space.

Model		Vertical	
rap	– Rapid Refresh	*bgrb* – Native (50 Level)	
ruc	– Rapid Update Cycle v1	*pgrb* – Isobaric (37 Level)	
ruc2	– Rapid Update Cycle v2	*sgrb* – Surface only	

Physics	Hour
awp – Atlantic Warm Pool	*t00z* - *t23z* – Hour, GMT

Domain		Outlook
130 – 13 km CONUS		*f00 (anl)* – Nowcast
252 – 20 km CONUS		*f01 – f18* – Forecast
236 – 40 km CONUS		
242 – 11 km Alaska		**Format**
221 – 32 km North America		*grib (grb)* – GRIB1 File
200 – 16 km Puerto Rico		*grib2 (grb2)* – GRIB2 File

Figure 3. NCEP Naming Conventions

Methods

This section describes methods for atmospheric data interpolation and a distributed computing approach for large-scale wind analysis.

Interpolation

This research proposes 4-D interpolation as a fundamental technique for large scale atmospheric analysis. Many aviation problems, such as evaluating winds along a flight route, or constructing historic wind histograms, can be easily expressed as interpolation at a discrete set of points:

$$interpolate(\ time,\ lat,\ lon,\ alt,\ options\ ) \qquad (1)$$

Options can include which variables to interpolate, vertical and lateral interpolation methods, and vertical frame of reference. Alternative techniques include higher dimensional methods, such as slice-based and volumetric data extraction. These methods can provide greater efficiency for some applications, with the tradeoff of reduced flexibility. These higher-dimensional methods can be fundamentally expressed as a set of interpolations. Figure 4 shows an overview of the interpolation steps, addressed in detail below.
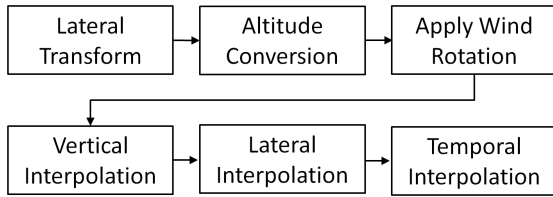

Figure 4. Interpolation overview

Software Libraries

Several software libraries provide support for accessing gridded weather data. NOAA provides a command line tool, WGRIB, which can output decompressed variables as text [7]. The University Corporation for Atmospheric Research (UCAR) has developed the Unidata Network Common Data Format (NetCDF) libraries, which provide object-oriented access to gridded scientific data [8]. Nctoolbox, an open source project, builds upon the NetCDF libraries, supporting data access from MATLAB® [9]. This work uses the Nctoolbox and NetCDF libraries.

Lateral Transform

The first step in interpolation is to load the grid properties and express the latitude/longitudes of interpolation points in terms of the RUC/RAP Lambertian Conformal grid index [1] [10]. The conformal property of the projection means that distances remain proportional after the transformation; interpolation weightings calculated in Lambertian space are still valid in Cartesian space. Figure 5 shows a visual representation of the transform.
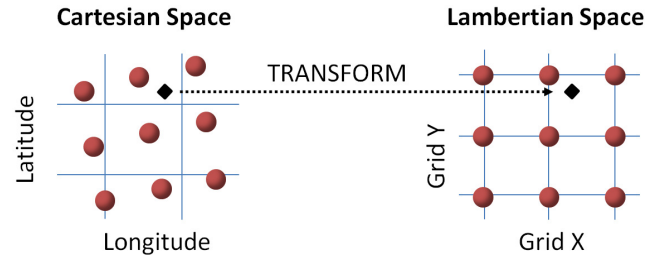

Figure 5. Lateral Transform

Transform equations are described in [10]. Alternatively, the NetCDF libraries provide a built-in set of projections, available through the interface:

$$Projection.latLonToProj() \qquad (2)$$

Grid parameters are stored within the RUC/RAP metadata. The NetCDF projection methods read the parameters and automatically apply the appropriate transformation [8]. This abstraction ensures compatibility across all grid definitions (130, 252, 236, 242, 221, 200 – see Figure 3 for definitions), and also supports future grid definitions without requiring software changes.

Vertical and Lateral Interpolation

Both RUC and RAP are uniformly vertically spaced in either hybrid coordinates (*bgrb*) or pressure coordinates (*pgrb*). However, vertical spacing is non-uniform in geometric height; each vertical column has uniquely defined spacing. This presents a software challenge, since non-uniform interpolation is significantly more computationally intensive.

This is addressed by separating vertical and lateral interpolation. First, apply the lateral transform to identify the grid indexes for the 4 columns surrounding the interpolation point. Then, interpolate each column vertically, using either pressure or

geometric height. Figure 6 shows a visualization of the interpolation process. This approach simplifies the problem to a one-dimensional, increasing value, non-uniform spacing interpolation. Lastly, laterally interpolate the results from each column using standard two-dimensional uniformly spaced interpolation techniques.
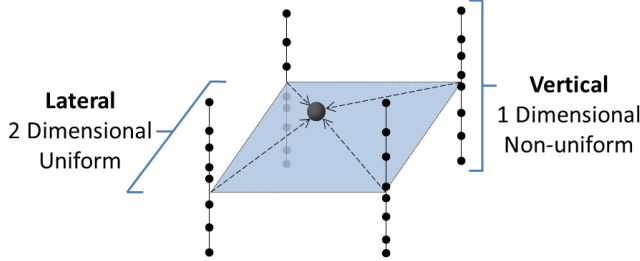

Figure 6. Interpolation

Temporal Interpolation

The RUC/RAP model produces output files hourly (0 - 23). Wind values for an arbitrary time t are obtained by interpolating the results from the two surrounding hours [10]:

$$D(i,j,k,t) = (1 - \alpha)D(i,j,k,t_n) + \alpha D(i,j,k,t_{n+1}) \quad (3)$$

$$\alpha = \frac{t - t_n}{t_{n+1} - t_n} \quad (4)$$

$$where: \quad t_n < t < t_{n+1} \quad (5)$$

These equations describe linear interpolation; alternative definitions for alpha can support *floor()*, *nearest()*, or *spline()* temporal interpolation. This temporal interpolation technique can also be used to compensate for small gaps in the dataset, such as a single missing hour, by selecting data from the two nearest surrounding hours.

Geopotential Height to Geometric Height

Applications such as simulation and modeling often express altitude in terms of geometric height. Altitude conversion is required to convert the RUC/RAP geopotential height into geometric height. The equations and associated parameters are described in detail by Hofmann-Wellenhof and Moritz [11] and summarized by Zhang and McGovern [10]. This work uses functions available in the MATLAB® Mapping Toolbox.

Corrected Pressure Altitude

Data sources such as radar track data commonly express altitude as corrected pressure altitude. Corrected pressure altitudes can be interpolated by first performing the inverse calculation to identify the aircraft-measured pressure, and then interpolating using pressure as the vertical index.

The equations are as follows. In the United States, altitudes above 18000 feet are reported using a standard atmosphere assumption:

$$P_s = 101315 \; Pascal \quad (6)$$

For altitudes below 18000 feet, P_s is set to the locally reported surface pressure. The value of P_s used internally by the aircraft is not typically available with radar track data, but it can be inferred by cross-referencing local recorded pressures from the Automated Surface Observing Systems (ASOS) database. If observations are unavailable, the surface pressure can also be estimated directly from the RUC/RAP file by interpolating pressure using geometric height to find the surface pressure at the nearest local airport. This provides a best-estimate of pressure correction setting. The next step is to calculate the temperature ratio, θ, from the input height h, and lastly to calculate the aircraft measured pressure, P. Table 1 lists the corresponding parameter values for the troposphere (0 to 36000 MSL):

$$\theta = 1 + \frac{h\lambda_0}{T_0} \quad (7)$$

$$P = P_s \, \theta^{\left(\frac{-g}{\lambda_0 R}\right)} \quad (8)$$

Table 1. Standard Atmosphere Parameters

Parameter	Symbol	Value
Geometric Height	h	(input)
Pressure Surface	P_S	(input)
Lapse Rate	λ_0	-6.5 K/km
Standard Temp.	T_0	288.15° K
Gravity	g	9.80665 m/sec^2
Gas-Constant	R	8.31432 J/mole-K
Pressure	P	(output)

Wind Rotation

RUC/RAP wind outputs are relative to the Lambertian Conformal projection (u_{Lamb}, v_{Lamb}), whereas the meteorological standard represents wind relative to true north. Winds are transformed by applying a rotation matrix:

$$\alpha = \sin(Latitude_o) \cdot (Longitude - Longitude_o) \qquad (9)$$

$$u_{TrueNorth} = \cos(\alpha) \cdot u_{Lamb} + \sin(\alpha) \cdot v_{Lamb} \qquad (10)$$

$$v_{TrueNorth} = -\sin(\alpha) \cdot u_{Lamb} + \cos(\alpha) \cdot v_{Lamb} \qquad (11)$$

The parameters for the RUC/RAP 130 Lambertian Conformal Grid are defined as:

$$\begin{aligned} Latitude_o &= 25\ degrees \\ Longitude_o &= -95\ degrees \end{aligned} \qquad (12)$$

and *Longitude* is the location of the grid point. NOAA provides a FORTRAN reference software implementation Lambertian Conformal wind rotation [12]. Similar to the lateral grid conversions, the grid rotation parameters can be extracted directly from the data files using the NetCDF libraries. This abstraction approach produces robust interpolation.

Distributed Analysis

Large scale atmospheric research can benefit from the use of distributed computing. Performing tasks on a single computer can be bandwidth and compute-resource intensive. For example, creating a 7-year wind histogram involves reading 1.5 TB of compressed weather data, decompressing that data, and performing a non-trivial amount of computation to interpolate the data for each hour. On a single threaded process (Xeon 3.0 GHz, 16 GB RAM) this requires an average of 5 days of processing time. Distributed computing (40 nodes, 16 quad-core Xeon 3.0 GHz processors per node, 50 GB RAM per node) reduces this task to 3 hours, a *40x* linear speedup.

Atmospheric data is well suited for efficient distributed processing using frameworks such as MapReduce. MapReduce is a programming model for batch processing large datasets using parallel computing, in which the data is processed in two steps. The map step divides the data into smaller sub-problems, which are distributed among the cluster nodes. The reduce step combines the resulting calculations and returns a result. This work uses the Apache™ Hadoop™ implementation of MapReduce.

Parallel algorithms are developed by defining map and reduce functions such that the problem is efficiently allocated to computing resources. Figure 7 shows a MapReduce implementation for the efficient processing of atmospheric data.
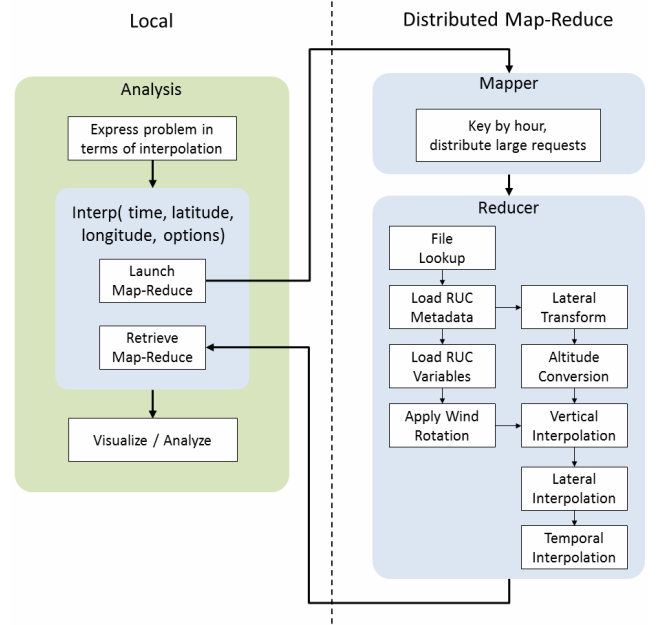

Figure 7. Processing Architecture

The RUC/RAP data is organized with each file containing the complete 3-dimensional data for all variables, for a single hour and forecast outlook. Applications such as computing weather statistics over time require iteratively processing hourly files. Other applications, such as simulation and visualization, may require evaluating a large number of points within a small number of files. Both applications can be efficiently accommodated with a single mapping method:

$$key = floor(timeInHours) \qquad (13)$$

A limit is set on the number of requests mapped to an identical key; requests beyond the limit are assigned a new key. This limit ensures that processing requests having many points in the same hour are distributed among reducer processing nodes.

Interpolation locations along with interpolation options are passed in to the reducer (Figure 7). The reduce method performs the interpolation and writes the results, which are post-processed by the local analysis software.

Applications

This section discusses several examples of applications for wind data in aviation, including instrument flight procedure design, aviation simulation, and trajectory based operations.

Instrument Flight Procedure Design

Instrument flight procedure design benefits from the use of historical wind information. The Federal Aviation Administration (FAA) publishes instrument flight procedure criteria guidelines to ensure that new procedures are safe, efficient, and meet operation needs. Performance Based Navigation (PBN) instrument flight criteria include provisions to account for the impact of wind on procedure flyability. Wind assumptions influence maximum groundspeed calculations, turn radius, and minimum leg length. From a practical perspective, the procedures must be designed with a built-in tolerance such that the aircraft can maintain procedure conformance even in adverse wind conditions. Figure 8 shows an excerpt from an FAA memo providing detailed guidance on tailwind assumptions (V_{KTW}) for procedure design (Figure 8, Equation 2) [13].

STEP 1: Determine Ground Speed (V_{ground})

a = turn altitude in feet

f = MSL field elevation

V_{KIAS} = appropriate value from 8260.54A, table 2-3

(1) $V_{KTAS} = \text{round}\left[\dfrac{V_{KIAS} \times 171233 \times \sqrt{303 - 0.00198 \times a}}{(288 - 0.00198 \times a)^{2.628}}, 0\right]$

(2) $case\ (a - f \leq 2000)$: $V_{KTW} = 30$

$\quad case\ (a - f > 2000)$: $V_{KTW} = round\left[a \times 0.00198 + 47, 0\right]$ *

Note : Lower V_{KTW} values may be used if the last 5 year weather history at the turn fix location and turn altitude indicates the lower value maximum value is typical. Record the value used and justification in procedure documentation.

(3) $case\ (a \leq 19500)$: $V_g = V_{KTAS} + V_{KTW}$

$\quad case\ (a > 19500)$: $V_g = round\left[0.9941 \times \dfrac{a}{100} + 287, 0\right]$

$V_{ground} = min\left[V_g, 570\right]$

Figure 8. PBN Wind Guidance Criteria [13]

Additional criteria guidance specifies that V_{KTW} can also be calculated from historical data, using the 99th percentile wind magnitudes from 5-year histograms [13] [14]. Figure 9 shows an example histogram of the wind distributions for a single altitude at Denver International Airport (KDEN).
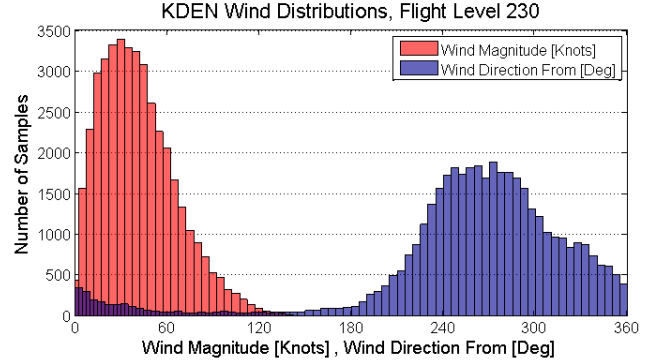

Figure 9. Historical Wind Histogram

Winds aloft vary by location, making it difficult to represent all locations with a single wind model. Consequently, the use of a single wind model for V_{KTW} can lead to overly conservative wind assumptions. Figure 10 compares historical winds at KDEN (black) against criteria winds (V_{KTW}) (red). For the range of 2000 – 13000 feet, criteria winds are approximately 10 knots greater than historical winds. Higher wind assumptions result in larger minimum turn radii and longer minimum leg lengths for procedures. The use of historical winds in criteria design can provide significantly more site-specific design flexibility while still ensuring appropriate flyability and safety.
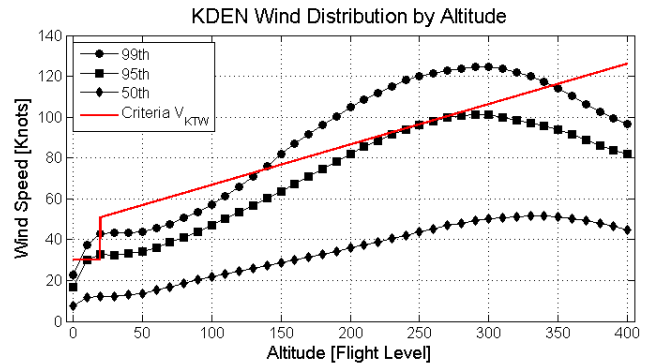

Figure 10. 5-Year Historical Winds, Criteria

Winds Simulation and Visualization

Environmental considerations such as wind are becoming increasingly important for high-fidelity modeling and simulation. Several MITRE-developed software tools, including high-fidelity Flight Management System (FMS) simulators and trajectory modelers, recently added the capability to represent both constant wind fields and gridded wind models [15] [16]. With these new capabilities, it becomes important to select appropriate atmospheric simulation conditions.

The first step is to characterize historical winds. This involves sampling the wind data at a given location or region of interest, at representative altitudes, across all available dates. The resulting wind distribution histograms can then be grouped by altitude, similar to instrument procedure design analysis techniques. These histogram plots are useful for identifying typical and atypical conditions. The magnitude distributions can be displayed as a rose plot, showing wind distributions by direction (Figure 11). This visualization technique is especially useful for analyzing procedure conformance sensitivity to adverse wind conditions. Research has shown that both wind magnitude and direction are important factors in evaluating procedure conformance [17]. Directional wind distribution analysis provides a more precise quantification of procedure conformance as compared to omnidirectional wind assumptions.
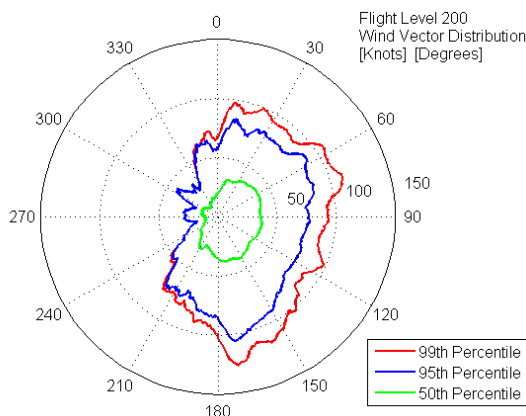

Figure 11. Directional Wind Distributions

The next step in simulation preparation is to select a representative wind value. For simple simulations, this may be a single wind magnitude and direction, which can be selected directly from the wind histograms. More complex simulations may require a full gridded wind input for realistic scenario generation. This involves either generating a wind field from system dynamics, or selecting a file from the archive. Using archive data has the advantage of being inherently realistic. The challenge is to identify an appropriate file for simulation.

The algorithmic approach for data selection involves selecting a set of constraints, creating a cost function, and minimizing or maximizing cost. Figure 12 shows an example, using the histogram distributions to identify a RUC file during 2007 with winds between the 95th and 99th percentiles. Suppose the worst-case procedure deviation occurs with a wind from due west. An optimal test dataset can be selected by projecting the winds along this direction and identifying the hour with maximum projected winds, subject to the previous constraints. Additionally, this concept can be extended to capture more subtle atmospheric conditions such as wind shear, by defining a cost function as the magnitude of the vector difference in wind between two altitudes.
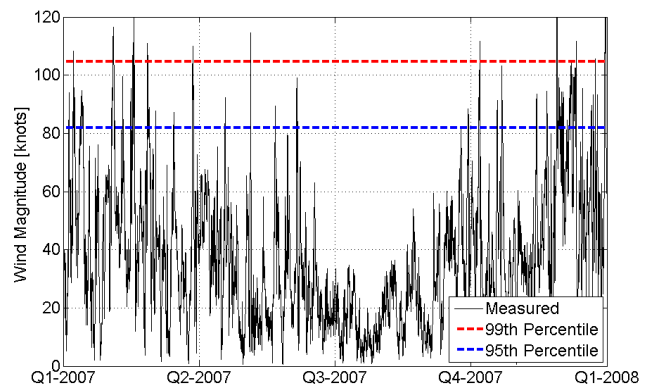

Figure 12. File Selection Using Wind Magnitude

The task of sample selection can also be addressed visually rather than algorithmically. Figure 13 shows a jet stream visualization in which the color indicates wind magnitude, and the vectors indicate wind direction and relative magnitude. Jet stream images can be compiled across time to produce an animation. This technique is especially helpful for identifying wind conditions which may be difficult to express as a formal cost function, such as dynamically changing weather conditions. Many atmospheric phenomena, such as hurricanes and large storms, can be more easily identified visually.
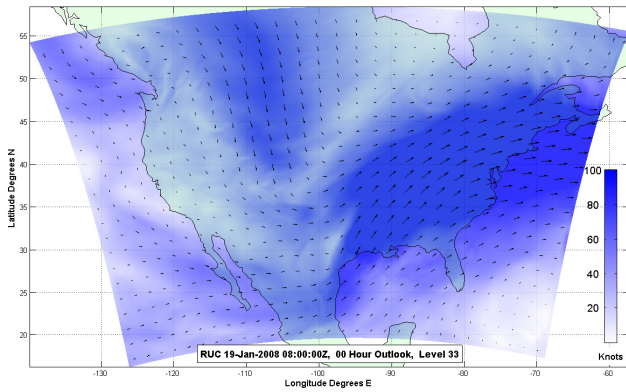
Figure 13. Jet Stream Visualization

Trajectory Based Operations

Wind forecast information is useful for enabling Trajectory Based Operations (TBO). One potential mid-term TBO application is metering into the terminal area through the use of the aircraft Required Time of Arrival (RTA) function. In this operational concept, the controller issues an arrival time, and the aircraft FMS automatically adjust the aircraft throttle to achieve the required arrival time. The FAA has sponsored two sets of flight trials to further develop this operational concept and associated standards requirements [18]. Figure 14 shows a summary of the operational concept for the 2011 Flight Trials. Aircraft arriving into Seattle-Tacoma Airport (KSEA) were issued metering times for the fixes OLM, RADDY, and JAKSN [19].
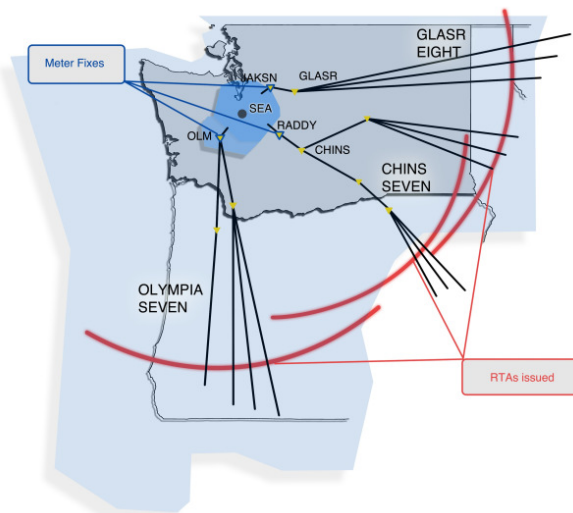

Figure 14. Flight Trials Overview [19]

Results from the 2010 TBO Flight Trials indicated that forecasts have a significant impact on RTA performance [20]. In preparation for the 2011 trials, MITRE developed a flight trials wind service to provide the FMS with timely and accurate wind forecasts, enabling the use of RTA for metering [19].

Figure 15 shows an overview of the flight trials wind service [19]. The system works as follows: The aircraft sends a wind request message to the Aircraft Communications Addressing and Reporting System (ACARS) messaging service, accompanied by the flight trajectory (1). The Wind Dispatcher software continuously monitors and processes new wind requests as they arrive (2). Flight trajectory is parsed to extract latitude, longitude, altitude, and time for all waypoints (3). Wind values along the flight path are interpolated using the latest 2-hour outlook RUC forecast data (4). The resulting wind forecast values are compiled into an ACARS wind uplink format and sent to the Airline Operational Control (AOC) (5). The AOC uplinks the wind messages to the aircraft through the ACARS service (6). On the aircraft, the pilot can choose to accept the new winds, and then they will be automatically loaded into the FMS (7). The FMS uses the wind forecasts to calculate an ETA. The aircraft then optimally adjusts the throttle to achieve the RTA [19].
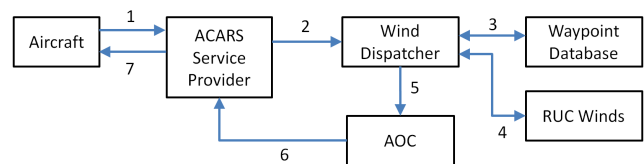

Figure 15. Wind Service Diagram

The wind service was successful in supporting the 2011 Flight Trials, sending over 2500 automated wind uplinks over the duration of the trials. These uplinks improved Estimated Time of Arrival (ETA) synchronization between air and ground systems, reducing the average discrepancy from 24 seconds to 7 seconds for aircraft receiving wind uplinks. This enabled 833 aircraft to participate in the trials, with a total of 514 aircraft successfully executing the RTA and crossing the meter fix within a 20 second tolerance of the assigned time [19].

Conclusion and Remarks

The Rapid-Update-Cycle (RUC) and Rapid Refresh (RAP) weather products provide a valuable source of data for evaluating environmental winds in the aviation domain. Many aviation weather analysis problems can be expressed in terms of interpolation. This approach enables large-scale analysis of historical wind data, supporting applications such as instrument procedure design, simulation and visualization, and trajectory based operations. Future research will investigate forecast accuracy as compared to aircraft measurements and explore visualization techniques using distributed computing.

References

[1] Benjamin, Stanley, et. al., 2004, An Hourly Assimilation-Forecast Cycle: The RUC, Mon. Weather Review, vol. 132, pp. 495 – 518.

[2] Benjamin, Stanley, et. al., 2004, Meso-scale Weather Prediction with the RUC Hybrid Isentropic-Terrain-Following Coordinate Model, Mon. Weather Review, vol. 132, pp. 473-494.

[3] Wynnyk, Chris, 2011, Wind Research in Support of Four Dimensional Flight Management System (FMS) Trajectory Based Operations (TBO), MP110250, The MITRE Corporation, McLean, VA.

[4] Benjamin, Stanley, et. al., 2007, From the radar-enhanced RUC to the WRF-based Rapid Refresh, 18th Conf. Num. Wea. Pred., Park City UT, AMS, J3.4.

[5] Devenyi, Dezso, et. al., 2007, Hourly data assimilation with the Gridpoint Statistical Interpolation for Rapid Refresh, 19th Conf. Num. Wea. Pred., Park City, UT, AMS, 4A.2.

[6] Benjamin, Stanley, and Susan Sahm, 2012, Earth System Research Laboratory: Rapid Refresh (RR), retrieved from http://rapidrefresh.noaa.gov on 8/1/2012, Boulder, CO.

[7] WGRIB homepage, 2012, National Weather Service Climate Prediction Center, http://www.cpc.ncep.noaa.gov/products/wesley/wgrib.html (Accessed on 8/9/2012).

[8] Unidata NetCDF (Network Common Data Form) Homepage, 2012, University Corporation for Atmospheric Research, Unidata Program Center, http://www.unidata.ucar.edu/software/netcdf/, (Accessed on 8/9/2012).

[9] Nctoolbox, A Matlab toolbox for working with comman data model datasets, 2012, http://code.google.com/p/nctoolbox/, (Accessed on 8/9/2012).

[10] Zhang, Yan, Seamus McGovern, 2008, Application of the Rapid Update Cycle (RUC) to Aircraft Flight Simulation, Proc. of IMECE2008, Boston, MA.

[11] Hofmann-Wellenhof, B. and H. Moritz, 2005, Physical Geodesy, Springer Wien, New York.

[12] Benjamin, Stanley, 2012, RUC Frequently Asked Questions, National Oceanic and Atmospheric Administration, http://ruc.noaa.gov/RUC.faq.html (Accessed on 8/9/2012).

[13] Anderson, Chas. Frederic, 2012, FAA Memorandum: Performance Based Navigation (PBN) Instrument Procedure Minimum Segment Length Standard, Flight Technologies and Procedures Division, AFS-420, Washington, DC.

[14] Smith, Leslie H., 2011, FAA Memorandum: Revised Performance Based Navigation (PBN) Fly-By (FB) /Radius-to-Fix (RC) Turn Maximum Bank Angle Limits; Omni-Directional Tailwind Requirements; and Minimum Initial Departure Leg Segment Length Design Criteria, Flight Technologies and Procedures Division, AFS-420, Washington, DC.

[15] Kirkman, Robin, 2012, Analysis of FMS Vendor-Based Test Bench Capabilities, MP120217, The MITRE Corporation, Mclean, VA.

[16] Amezcua, Juan, Stuart Bowman, Chris Dorbian, Eric Zakrzewski, 2011, Operational Evaluations of Airline Flight Simulators in Procedure Development, MTR110342, The MITRE Corporation, McLean, VA.

[17] Cramer, Mike, Al Herndon, Kevin Sprong, Analysis of Radius-To-Fix (RF) Leg Bank Angle Margin Requirements, MP090076, The MITRE Corporation, McLean, VA.

[18] Becher, Thomas, Paul MacWilliams, Mahesh Balakrishna, and Roland Sgorcea, 2011, 4D Flight

Management System (FMS) Standards Validation and Demonstration Plan Version 2.0, MP110002, The MITRE Corporation, McLean, VA.

[19] Wynnyk, Chris, Dave Gouldey, 2012, 2011 Seattle Required Time of Arrival (RTA) Flight Trials Analysis Report, MP120061S1, The MITRE Corporation, McLean, VA.

[20] GE Aviation Systems, 2011, Flight Trials Assessment for 4 Dimensional Flight Management System Trajectory Based Operations, Grand Rapids, MI.

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