3.13 A STUDY OF TIME-TO-FLY ESTIMATES FOR RUC AND ITWS WINDS *

Rodney E. Cole and Steve Kim
Massachusetts Institute of Technology
Lincoln Laboratory
Lexington, Massachusetts 02420-9185
(781) 981-5018

1. INTRODUCTION

Automated air traffic decision support tools must compute the time it takes an aircraft to fly along a path. The estimation of Time-To-Fly (TTF) requires accurate knowledge of the wind (Jardin and Green, 1998). Two proposed sources of wind data for the Center-TRACON Automation System (CTAS) (Denery and Erzberger, 1997) developed by NASA are the Rapid Update Cycle (RUC) (Schwartz, et al., 2000) and the Integrated Terminal Weather System (ITWS) (Evans and Ducot, 1994). The RUC is a mesoscale numerical weather prediction model run by the National Centers for Environmental Prediction. The ITWS was developed by MIT Lincoln Laboratory for the FAA. The ITWS winds product, Terminal Winds (Cole, et al., 2000), takes in RUC forecasts and refines them using recent local measurements of the wind from Doppler radars, aircraft, and ground stations. This report examines the question: does the use of RUC and ITWS wind fields lead to different Time-To-Fly estimates? ITWS provides finer-grained and more accurate wind fields than the RUC, but at the expense of requiring greater bandwidth to disseminate. It is desired to understand if the extra cost of the ITWS winds provides a benefit.

An assessment of ITWS Terminal Wind (TW) accuracy versus RUC accuracy at points in space [using Meteorological Data Collection and Reporting System (MDCRS) as "truth"] has shown that ITWS Terminal Wind typically has an RMS error which is about 1.4 m/sec lower than that of RUC (Cole, et al., 1998). The space and time correlation of the point errors is not known along specific paths. Since the TTF represents a sum of errors for points that are close in space and time, the errors in TTF cannot be derived from the single point error distribution without the correlation. Assuming a constant error of 1.5 m/sec over 100 km at the airspeed of 100 m/sec, the TTF difference between RUC and ITWS winds of about 15 seconds is expected, or about 0.8 nmi.

Ideally, one would compare TTF estimates to measured TTF times. Without a research aircraft, this is a difficult comparison to make. There are a number of factors that influence actual TTF times; for example, pilot deviation from the expected route or aircraft being asked to change speed to maintain separation from nearby aircraft. Even with the proper data, due to the complexity of the CTAS software, a detailed analysis could be performed only for a limited data set. This study was envisioned to be a quick, low-cost look at the issue. For these reasons we chose to compare TTF estimates from RUC and TW computed using a simple path integral through the wind fields. If these TTF estimates are nearly the same, then right or wrong, we know that the ITWS winds did not provide a benefit. If instead the estimates are different, since we know that ITWS has recent local measurements, the hypothesis is that the ITWS-derived TTF estimates are more accurate. This methodology can be used to analyze a large number of wind fields and to identify times when more in-depth analyses using aircraft data would be useful.

We chose to use data archived from the ITWS Dallas/Ft. Worth prototype ITWS. We used the operational RUC-2 (40 km model grid) as provided by the NWS on an 80 km grid. The ITWS refines the RUC forecasts first to a 10-km grid and then to a 2-km grid using local measurements. We chose 11 days; seven days known to have a large shear in the vertical and four consecutive days with more benign weather. The days with large shear are expected to provide larger differences in TTF estimates than provided on an average weather day.

2. RUC OVERVIEW

The Rapid Update Cycle was developed at the National Oceanic and Atmospheric Administration (NOAA) Forecast System Laboratory (FSL). The RUC is a meso-scale numerical weather prediction model that uses measurements from twice-daily

---

* This work was sponsored by NASA Ames Research Center under Air Force Contract No. F19628-95-C-0002. Opinions, interpretations, conclusions, and recommendations are those of the author and are not necessarily endorsed by the U.S. Government. Corresponding author address: Rodney E. Cole, Massachusetts Institute of Technology, Lincoln Laboratory, 244 Wood Street, Lexington, MA 02420-9185; e-mail: rodc@ll.mit.edu

balloon soundings, Doppler wind profilers, satellites, commercial aircraft, and surface stations. The RUC domain is the continental U.S. and adjacent oceanic area, using a computational grid with a nominal horizontal resolution of 40 km and 40 vertical levels. The model is run every hour, producing hourly forecasts. The model run generally finishes within an hour of starting, so the one-hour forecast is generally available in time to be of use. Because the data ingest into the model cuts off data starting an hour prior to the nominal run time, there is a gap of two hours between the cut-off of data into the model and when the model output is available for use.

3. ITWS TERMINAL WINDS OVERVIEW

The ITWS terminal winds product uses a RUC forecast as an initial estimate and refines that with measurements collected after the RUC run was started. The measured winds in DFW come from two Terminal Doppler Weather Radars (TDWR), one National Weather Service Doppler (WSR-88D) radar [NEXt generation weather RADar (NEXRAD)], commercial aircraft, and surface stations. The Doppler data are generally more numerous than the other data, but often do not extend above a few thousand feet AGL. Figure 1 provides a data flow diagram for the Terminal Winds processing, showing the relationships between RUC, the 10-km horizontal resolution TWIND product, and the 2-km resolution TWIND product.

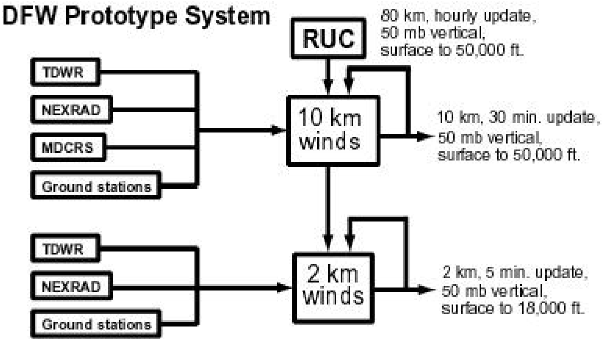

Figure 1. ITWS Terminal Winds overview. The 10-km TWIND uses RUC as the background wind and uses coarsely resampled radar data, aircraft reports, and ground station reports to produce wind fields every 30 minutes up to 50,000 feet. The 10-km TWIND, in turn, becomes the background wind for the 2-km TWIND. Finely resampled radar data and the ground station data are added to the 10-km TWIND to produce the 2-km TWIND every five minutes up to 18,000 feet.

The RUC forecasts are generated every hour and are usually received by ITWS near the hour. To accommodate forecasts that may be slightly late, Terminal Winds takes in the RUC data at 10 minutes after the hour. The 10-km resolution wind field is generated at 10 and 40 minutes after the hour. The 2-km resolution wind field is generated every multiple of five minutes.

Each TW analysis starts with an initial estimate which is refined using recent measurements by applying the Gauss-Markov theorem. This is a version of least-squares that accounts for sensor error variance, initial estimate error variance, and the correlation among these errors. The initial estimate is formed from the last analysis at that scale and a coarser resolution wind field if available. For example, at 10 after the hour, the 10-km initial estimate is formed from the last 10-km TW field and the new RUC forecast.

4. ASSESSMENT OF ITWS TW ACCURACY VERSUS RUC ACCURACY

ITWS TW and RUC winds were compared against independent aircraft data (Cole, et al., 2000). The ITWS 10-km TWIND was produced by augmenting the then-operational 60-km RUC-1 winds with near-real-time MDCRS reports in the Denver Center airspace. The Doppler radar data were not used for this comparison. To determine wind field accuracy, the wind fields are compared to 1.2 million aircraft reports that are not used in generating the wind fields to which they are compared. Figure 2 shows that the TWIND RMS error was approximately 1.5 to 3.0 m/s smaller than the RUC RMS error. The TWIND 90th percentile error was about 2 to 4 m/sec smaller than the RUC 90th percentile error.

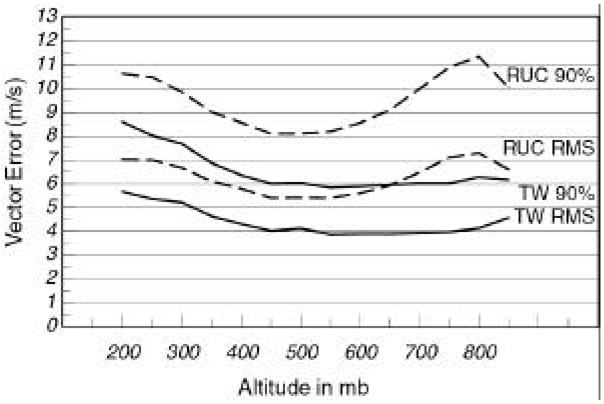

Figure 2. Vector error vs. altitude for 10-km TWIND and RUC. The vector error against MDCRS data was computed at various altitudes for 10-km TWIND and RUC winds. The 10-km TWIND used for this comparison was produced by augmenting the RUC data with the MDCRS data; radar data were not used. The TWIND RMS error was about 1.5 to 3.0 m/sec smaller than the RUC RMS error. The TWIND 90th percentile error was about 2 to 4 m/sec smaller than the RUC 90th percentile error.

Figure 3 shows the result of comparing 2-km TWIND, 10-km TWIND, and RUC winds against dual-Doppler data. Ten summer days in Memphis were used for this comparison. The 10-km TWIND shows an accuracy improvement of approximately 2 to 4 m/sec over RUC, and the 2-km TWIND shows an accuracy improvement of approximately 3 to 5 m/sec over RUC.

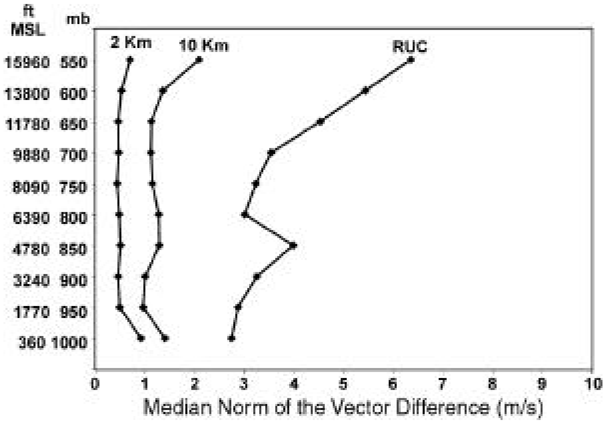

Figure 3. Performance vs. dual Doppler for 2-km TWIND, 10-km TWIND, and RUC. Ten summer days in Memphis were selected, and 2-km TWIND, 10-km TWIND and RUC winds were compared against dual-Doppler data. The 10-km TWIND shows accuracy improvement of approximately 2 to 4 m/sec over RUC, and the 2-km TWIND shows accuracy improvement of approximately 3 to 5 m/sec over RUC.

5. METHODOLOGY

Eleven days were selected from ITWS DFW archives. Seven of the days had winds greater than fifty knots for some portion along the flight paths while the remaining four days had winds less than fifty knots. Four of the seven days with strong winds also showed sizable vertical shear.

Ten nominal arrival flight plans were obtained for the DFW terminal (Figure 4.). To compute the TTF, each flight plan was divided into a series of line segments equivalent to 4.8 seconds of flight at nominal airspeed. The airspeed was assumed to be 125 m/sec (243 knots) at the cornerposts, and was reduced in a step-wise fashion along the flight plan to the landing speed of 75 m/sec (146 knots).

The head wind for each segment along the flight plan was computed using the wind information from the eight TWIND analysis grid points surrounding the flight segment. The wind from a grid point was given the weight inversely proportional to the distance from the grid point to the beginning of the flight segment. Finally, the TTF for the flight plan was computed using the following formula:

$$\mathrm{TTF} = \sum_{i=1}^{n} \Delta t_i \ ,$$

where $\Delta t_i = \Delta d_i / (airspeed_i - headwind_i)$, and Δd_i is the length of a step along the flight path.

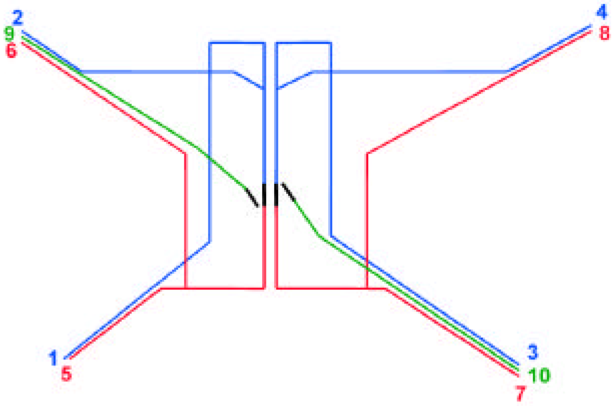

Figure 4. Flight plans. Nominal flight plans around the DFW Terminal Area were obtained from DFW controllers. Five plans from the north operation and five plans from the south operation were used for this study. The flight plans start from around 10,000 to 11,000 feet around the meter fixes and were assumed to descend to the runway in a piecewise linear fashion.

6. THE EFFECT OF DIFFERENT WIND SOURCES ON TTF

To examine the effect of the different wind sources on TTF, the difference in TTF between the 10-km TWIND and the RUC, the 2-km TWIND and the RUC, and finally the 2-km TWIND and the 10-km TWIND were computed. For RUC and 2-km TWIND, the wind fields valid on the hour were used, while for the 10-km TWIND, the wind fields closest to the hour, which are produced 10 minutes after the hour, were used.

The TTF difference between the 10-km TWIND and RUC showed the mean differences ranging from –5 to 25 seconds, and the mean ± one standard deviation ranged from –30 to 45 seconds. When the TTF differences were normalized by one minute of flight time, the mean ± one standard deviation ranged from –2 to 4 seconds.

The TTF difference between the 2-km TWIND and RUC was even more pronounced; the mean differences ranged from –25 to 30 seconds, and the mean ± one standard deviation ranged from –60 to 60 seconds. (See Figure 5.) On 22 February 1999, there was a significant directional vertical wind shear, and the mean difference ranged from –80 to 30 seconds, and the mean ± one standard deviation ranged from –95 to 40 seconds. The TTF differences normalized by one minute of flight time show the mean ± one standard deviation ranging from -3 to 5 seconds.

The TTF difference between the 2-km TWIND and the 10-km TWIND was smaller, but still significant. The mean differences ranged from –15 to 5 seconds, and the mean ± one standard deviation ranged from –35 to 25 seconds. The TTF differences normalized by one minute of flight time show essentially the same results, with the mean ± one standard deviation ranging from –2 to 2 seconds.

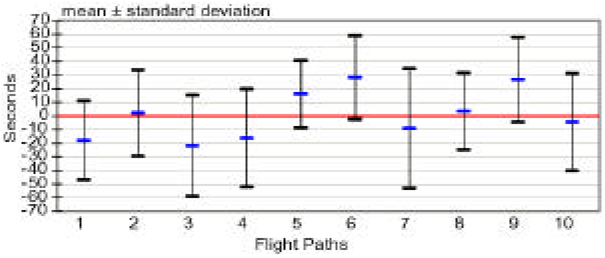

Figure 5. TTF Difference between 2km TWIND and RUC for All Days. The TTF difference is more pronounced between 2km TWIND and RUC than between 10km TWIND and RUC. The mean difference ranges from –20 to 30 seconds, and the mean ± one standard deviation ranges from –60 to 60 seconds.

7. THE EFFECT OF THE UPDATE RATE ON TTF

Figures 6 and 7 show examples of TTF change for the 2-km TWIND from 22:15 to 23:55 on 6 February 1999. Flight plans 5 through 10 have a relatively gradual TTF change with each TWIND update (flight plans 5 and 9 are shown in Figure 6). Typically, TTF varies by less than one percent with each update. However, there are several drastic changes in the TTF for the flight plans 1 through 4 (flight plans 1 and 4 are shown in Figure 7). All of these flight plans pass through the region north of the runways where there was a significant headwind change over time, mostly because of the changes in the wind direction. Some of the large changes in flight plans 1 through 4 correspond to about six-percent change in TTF over a five-minute period.

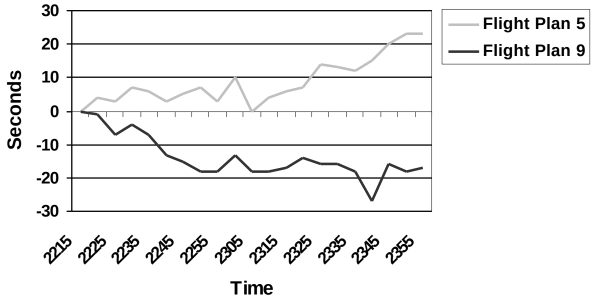

Figure 6. The TTF change over time for 2-km TWIND from 6 February 1999. The flight plans 5 & 9, in general, show relatively small differences with each new wind update. Typically, TTF's vary by less than one percent for these flight plans.

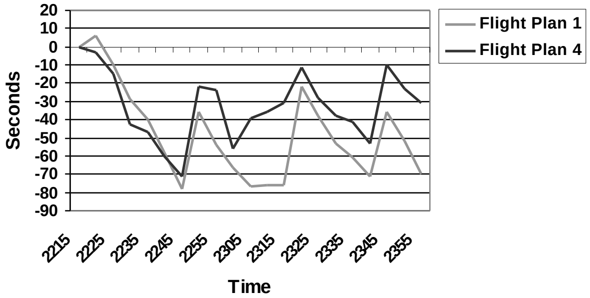

Figure 7. Flight plans 1 and 4 show significant changes in TTF with new wind updates. They pass through the area north of the airport, which had significant headwind variability due to the change in the wind direction. Some of the large jumps in these flight plans correspond to approximately six percent change in TTF.

The TTF differences between the series of 2-km TWIND files produced at the increment of five minutes after the hour and the RUC file produced on the hour were computed to examine the effect on the TTF of the update rate. Since all flight plans from all days were included, the difference from the south operation and the north operation cancel each other and the mean differences stay near zero. However, the standard deviation increases over time from about 30 seconds to 40 seconds. In certain cases this increase in the standard deviation of the TTF differences is more dramatic. One such case from 18 February 1999 shows the increase in the standard deviation of the TTF differences from 15 seconds to 50 seconds as time progresses (Figure 8).

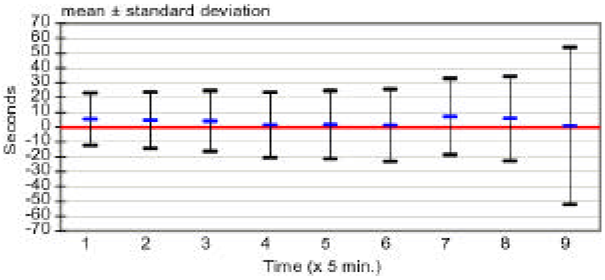

Figure 8. Change with time of TTF difference between 2km TWIND and RUC for 18 February 1999. The five flight plans from the north operation and the five flight plans from the south operation cancel the TTF differences, so that the mean values stay near zero. The standard deviation shows a significant increase from about 15 to 50 seconds over 40-minute period.

8. CONCLUSION

There are frequent, substantial differences between RUC TTF and ITWS TTF estimates. The TTF differences between the 10-km TWIND and the RUC were greater than 29 seconds 25 percent of the time. At a flight speed of 100 m/sec, this is an error in location of 2.9 km or about 1.6 nmi. The TTF differences between the 2-km TWIND and the RUC were larger; they were greater than 44 seconds 25 percent of the time. At a flight speed of 100 m/sec, this is an error in location of 4.4 km or about 2.4 nmi. Finally, the TTF differences between the 2-km TWIND and the 10-km TWIND were not as large, but still significant; they were greater than 17 seconds 25 percent of the time. At a flight speed of 100 m/sec, this is an error in location of 1.7 km or about 0.9 nmi. Because ITWS winds are more accurate, the hypothesis is that the ITWS TTF estimates are more accurate, and the RUC TTF differences from ITWS TTF primarily represent errors in RUC TTF estimates.

The more frequent update rate of ITWS winds also leads to the TTF differences from the RUC winds. Significant changes in the TTF were observed with each five-minute update of ITWS winds under time-varying wind conditions. Also, the variability of the differences in TTF estimates between the ITWS winds and the RUC winds increased from the RUC forecast time to the next RUC update time.

TTF differences may negatively impact the performance of an automated air traffic decision support tool. For example, two aircraft approaching the same runway from two different directions may experience headwind errors that are opposite in sign, effectively doubling the error in location. Such differences in TTF would reduce the effectiveness of a merging and sequencing tool or a conflict probe tool.

This study shows that the different wind fields give different TTF estimates. ITWS winds refine the RUC data using recent, local data with higher update rates, and previous studies have shown that ITWS winds have smaller vector differences than RUC when compared against independent MDCRS observations (Cole, et al., 1998). Therefore, it is plausible that the ITWS TTF estimates are more accurate than the RUC TTF estimates. However, more work is needed to quantify the difference between the estimated and the actual TTF.

In particular, the effect of the update rate on TTF can be further examined by using the archived 2-km ITWS winds in a simulated real-time fashion. A typical TTF ranges from 12 to 15 minutes; instead of using one wind file at the beginning of the flight for the TTF computation, an updated 2-km ITWS winds can be incorporated mid-flight to account for the changing wind conditions during the flight. The effect of the vertical resolution needs to be investigated as well. ITWS winds analysis can be performed at a higher vertical resolution to quantify the effect on the TTF of vertical wind shear using various interpolation methods.

REFERENCES

Cole, R.E., C. Richard, S. Kim, and D. Bailey, 1998: An Assessment of the 60 km Rapid Update Cycle (RUC) with Near Real-Time Aircraft Reports, MIT Lincoln Laboratory, Project Report NASA A-1.

Cole, R.E., S.M. Green M.R. Jardin, 2000: Improving RUC-1 Wind Estimates by Incorporating Near Real-Time Aircraft Reports. *Wea. Forecasting*, to appear.

Denery, D.G., and H. Erzberger, 1997: The Center-TRACON Automation System: Simulation and field testing. *Modeling and Simulations in Air Traffic Management*, L. Bianco, P. Dell'Olmo, and A. Doni, Eds., Springer-Verlag, 113-138.

Evans, J.E. and E.R. Ducot, 1994: The Integrated Terminal Weather System (ITWS) *Lincoln Lab. J.,***7** (2), 449474.

Jardin, M.R., and S.M. Green, 1998: Atmospheric data error analysis for the 1994 CTAS Descent Advisor preliminary field test. NASA Tech Memo-1998-112228. 24 pp. [Available from NASA Center for AeroSpace Information, 7121 Standard Dr, Hanover, MD 21076.]

Schwartz, B.E., S.G. Benjamin, S. Green, and M. Jardin, 2000: Accuracy of RUC-1 and RUC-2 wind and aircraft trajectory forecasts by comparison with ACARS observations. *Wea. Forecating,* 15.