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ITWS GRIDDED WINDS PRODUCT

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1. INTRODUCTION

FAA systems are under development to automate air traffic control to optimize aircraft separations, scheduling, and fuel consumption, to reduce aircraft separations for wake vortex avoidance, to predict wind shifts leading to runway reconfiguration, and to predict the onset and dissipation of fog and low ceiling conditions. These systems are respectively, the Terminal Air Traffic Control Automation system, Wake Vortex Advisory System, ITWS[1] Wind Shift and Runways Winds prediction systems, and ITWS Ceiling and Visibility predictions, respectively. Each of these systems can benefit from detailed knowledge of the horizontal wind in the terminal airspace. Wind information is also useful to human air traffic controllers.

The ITWS Gridded Winds Product, Terminal Winds, obtains wind information from a number of sources:

- Mesoscale Analysis and Prediction System (MAPS) (Benjamin et al, 1991) – a prototype of the Rapid Update Cycle (RUC), a national scale forecast model (Benjamin et al, 1994).
- Terminal Doppler Weather Radar (TDWR) and WSR–88D (NEXRAD) – Doppler radars
- Meteorological Data Collection and Reporting System (MDCRS) – commercial aircraft
- Low Level Wind Shear Alert System (LLWAS) and Automated Surface Observing System (ASOS) – surface anemometer networks

The design of the Terminal Winds system takes into account the weather phenomena to be captured, sensor characteristics, nonuniform and dynamic data distributions, and provides the best possible product from the available suite of sensors, adding value to the national winds forecast in the terminal area as local sensors provide information.

The Terminal Winds analysis technique was developed to take advantage of the Doppler information available in the terminal area. This technique, Optimal Estimation (OE), uses a minimum error variance technique (least squares) and is closely related to both the state–of–the–art operational non–Doppler winds analysis technique, Optimal Interpolation (OI) (Gandin, 1963)(Daly, 1991), and standard multiple Doppler techniques (Armijo, 1969). This technique was evaluated on data collected in 1992–1993 in Orlando FL, and demonstrated in real time in the Orlando testbed during the summer of 1993 and in the Memphis testbed during the summer of 1994.

1. The Integrated Terminal Weather System (ITWS) (Sankey, 1994), currently in development by the FAA, will produce a fully–automated, integrated terminal weather information system to improve the safety, efficiency and capacity of terminal area aviation operations. The ITWS will acquire data from FAA and National Weather Service sensors as well as from aircraft in flight in the terminal area. The ITWS will provide products to Air Traffic personnel that are immediately usable without further meteorological interpretation. These products include current terminal area weather and short–term (0–30 minute) predictions of significant weather phenomena.

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2. DESIGN CONSIDERATIONS

There are a number of design considerations for a winds analysis system that will support aviation systems and operate with information from sensors in the terminal area. Ideally, users of the gridded analyses levy performance requirements for resolution, accuracy, and timeliness. However, the aviation systems which rely on these analyses are still under development, and have not yet stated performance requirements. We have taken the approach of basing resolution and timeliness on sensor characteristics and expected wind field phenomenology, with the goal of minimizing the norm of the wind vector error in the analyzed fields.

Meteorological Doppler radars provide estimates of the wind velocity component along the radar beam (radial velocities) as well as measurements of return intensity (reflectivity). Doppler radars can not directly measure the wind velocity component perpendicular to the radar beam. They provide accurate and dense measurements in regions with sufficient reflectors. The analysis is designed to extract horizontal wind information from these single component measurements.

The terminal airspace generally extends from the surface to 18,000 ft MSL, and is divided into two regimes. The planetary boundary layer (PBL) contains the atmosphere near the earth's surface, and often contains wind structures with spatial scales on the order of kilometers and temporal scales on the order of minutes. Above the PBL, wind structures typically have spatial scales of at least 10's of km and temporal changes occur over at least 10's of minutes. Doppler radars provide high resolution information in the PBL where small scale wind structures are expected. Above the PBL, Doppler information becomes more sparse and information from MAPS and MDCRS are important sources of additional information. A cascade–of–scales analysis is used to capture these different scales of atmospheric activity.

3. THE TERMINAL WINDS ANALYSIS

The philosophy of the Terminal Winds analysis is that the national scale forecast model provides an overall picture of the winds in the terminal airspace although painted in very broad strokes. The terminal sensors are then used to fill in detail and correct the broad scale picture. The corrections and added detail can only be provided in those regions with nearby data. What constitutes "nearby" depends on the spatial and temporal scale of the feature to be captured in the analysis. The refinement of the broad scale wind field is accomplished by averaging the model forecast with current data. This allows the analysis to transition gracefully from regions with a large number of observations to regions with very few observations or no observations at all, and enables the analysis to cope gracefully with unexpected changes to the suite of available sensors.

To account for the different scales of wind features and the differing resolution of the information provided from the various sensors, the analysis employs a cascade–of–scales. This cascade–of–scales uses nested grids, with an analysis with a 2 km horizontal resolution and 5 minute update rate nested within an analysis with a 10 km horizontal resolution and 30 minute update rate, which in turn is nested within the MAPS forecast with a 60 km horizontal resolution and 180 minute update rate. All of the data sources are used in the 10 km analysis, and data are allowed to be as old as 90 minutes. Only the information from the Doppler radars and LLWAS are suitable for the 2 km analysis. This cascade–of–scales is appropriate for the scales to be captured in the analysis, the different scales of information, and provides a uniform level of refinement at each step of the cascade (as shown in Table 1). An additional benefit is that the 10 km analysis acts as a stand in for the planned 10 km RUC forecast. When a 10 km national forecast becomes available, the 10 km ITWS analysis can be dropped.

Table 1: Scales of analysis for MAPS and Terminal Winds

	update rate	horizontal resolution	domain size
MAPS	180 min	60 km	national
Terminal Winds–above PBL	30 min	10 km	250x250 km
Terminal Winds–in PBL	5 min	2 km	120x120 km

An important goal is to minimize the error of the analyzed wind field. To achieve this goal we developed an analysis technique called Optimal Estimation. OE is a least squares technique designed to jointly average both vector quantities and single component quantities. Previous state–of–the–art operational winds analysis systems have used statistical techniques to great advantage. However, none has the ability to analyze directly the data from Doppler radars. Optimal Estimation provides a new capability which is important since increasing numbers of Doppler weather radars are being deployed.

The OE analysis accounts for the differing quality of the wind information, as well as errors arising from data age and using data at locations removed from the location at which the data were collected (displacement errors). The analysis also corrects for correlated errors in a similar manner to Optimal Interpolation. Highly correlated displacement errors arise frequently due to the nonuniform distribution of data from the Doppler radars. If these correlated errors are not accounted for, these data dominate the analysis to a greater degree than is warranted by their information content.

3.1 *Terminal Winds Interpolation Technique: Optimal Estimation*

The Terminal Winds analysis is dominated by Doppler radar data. In regions with coverage by two or more radars, the Terminal Winds system should provide winds with at least the quality of a traditional multiple Doppler analysis. The state–of–the–art analysis technique for non–Doppler meteorological data analysis is Optimal Interpolation. Optimal Interpolation is a statistical interpolation technique that under certain hypotheses gives an unbiased minimum variance estimate. We wish to build on the foundation laid down by both the multiple Doppler analysis and statistical interpolation techniques.

We have developed an unbiased minimum error variance technique that utilizes Doppler measurements directly. We call this technique Optimal Estimation (OE) to distinguish it from Optimal Interpolation. The initial focus is on analyzing horizontal wind data to a three dimensional grid, however, the method applies to other variables. The method is based on the Gauss–Markov theorem (Luenburger, 1969), and under suitable conditions gives an unbiased minimum error variance estimate of the horizontal winds. Optimal Estimation is an extension of both Optimal Interpolation and multiple Doppler analysis. It is the ease with which OE incorporates Doppler radar data that motivates its development.

OE has the following properties:

1. Dual Doppler quality winds are automatically produced in regions where dual Doppler is numerically stable.
2. Small gaps in dual Doppler radar coverage are filled to produce near dual Doppler quality winds in these gaps.
3. The analysis produces smooth transitions between regions with differing density of data.

Throughout this section we use the following notation:

- r denotes a radial wind component
- u denotes an east wind component
- v denotes a north wind component
- superscript a denotes an analyzed quantity
- superscript b denotes a background quantity
- superscript o denotes an observed quantity
- subscripts denote location, o denoting an analysis location

In order to apply the Gauss–Markov theorem, we need to pose the problem in the form

$$Ax = d, \text{ where} \tag{1}$$

$x = (u_o^a,\ v_o^a)^T$, is the unknown horizontal wind vector and

$$d = (u_o^b,\ v_o^b,\ u_1^o,\ v_1^o,\ \ldots,\ u_m^o,\ v_m^o,\ r_1^o,\ \ldots, r_n^o)^T$$

contains the background estimate at the analysis location, and observations in a data window centered on the analysis location. The form of the matrix A depends on the type of data, vector and/or radial, to be analyzed. The Gauss–Markov theorem states that the linear minimum variance unbiased estimate of $(u_o^a,\ v_o^a)^T$ is given by

$$(u_o^a,\ v_o^a)^T = (A^TC^{-1}A)^{-1}A^TC^{-1}d, \tag{2}$$

if each element of d is unbiased, and C is the error covariance matrix for the elements of d. The error covariance of the solution is

$$(A^T C^{-1} A)^{-1}. \tag{3}$$

When the data window contains m vector observations, and n Doppler observations, equation 1 has the form:

$$\begin{bmatrix} 1 & 0 \\ 0 & 1 \\ \cdot & \cdot \\ \cdot & \cdot \\ \cdot & \cdot \\ 1 & 0 \\ 0 & 1 \\ \cos\theta_1 & \sin\theta_1 \\ \cdot & \cdot \\ \cdot & \cdot \\ \cdot & \cdot \\ \cos\theta_n & \sin\theta_n \end{bmatrix} \begin{pmatrix} u_o^a \\ v_o^a \end{pmatrix} = \begin{bmatrix} u_o^b \\ v_o^b \\ \cdot \\ \cdot \\ \cdot \\ u_m^o \\ v_m^b \\ r_1^o \\ \cdot \\ \cdot \\ \cdot \\ r_n^o \end{bmatrix}$$

The minimum data window covers a 3x3 grid point region so frequently the data window contains several Doppler values.

In practice, C is not known and must be estimated. There are two types of errors to estimate. The first is the error that arises from imperfect sensors. The second is the displacement error due to the measurement being taken at some distance, in space and time, from the analysis location. Our initial error models are based on the following simplifying assumptions:

1. Observations are unbiased.
2. Sensor errors from different observations are uncorrelated.
3. Errors in u and v components, measured or background, are uncorrelated.
4. Displacement errors and sensor errors are uncorrelated.
5. Displacement errors are independent of the component being measured.

With these assumptions, the error covariance matrix C decomposes into the sum of a sensor error covariance matrix and a displacement error covariance matrix. The sensor error covariance matrix is diagonal, and the sensor error variances are known. The remaining task is the estimation of the displacement error covariance matrix.

The initial displacement error variance model is a linear function of the displacement between the observation location and the analysis location. The initial displacement error correlation model for two like components is a decreasing exponential function of the displacement between two observation locations. The displacement error covariance model for two non–orthogonal, non–parallel components must take into account the angle between the two components. We denote the angle between the observed component and the u axis by θ, with east at 0^0, and north at 90^0, and the displacement error in observation i by δ_i^o. Then the displacement error covariance for two observations is given by the following equation:

$$\mathrm{Cov}(\delta_1^o,\delta_2^o) = \cos(\theta_1-\theta_2)[\mathrm{Var}(\delta_1^o)\mathrm{Var}(\delta_2^o)]^{1/2}\mathrm{Cor}(\delta_1^o,\delta_2^o)$$

Unlike the multiple Doppler analysis, the OE analysis is always numerically stable due to the inclusion of the background wind estimate. The inclusion of a (u,v) data point provides two component estimates at right angles, giving a maximum spread of azimuth angles. Since the error variances of the Doppler data are usually much smaller than the error variances of the other data, the OE solution closely matches the multiple Doppler solution at locations where the multiple Doppler problem is well conditioned. Otherwise, the analysis gives a solution that largely agrees with the radar observations in the component measured by the radars. The remaining component is derived from the vector estimates. This feature of the analysis is demonstrated in an example below.

3.2 *A Comparison of Dual Doppler and OE Analyses*

We compare OE and dual Doppler analyses at a point with coverage from two radars to demonstrate their similarity, and to demonstrate the numerical stability of the OE analysis. We restrict our discussion to the case where we only have a background wind estimate and two Doppler observations at a fixed analysis location as in Figure 1. This situation holds for example if the data window only contains the analysis point.

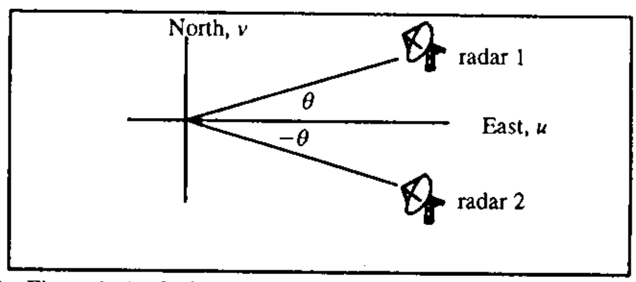

Figure 1: Analysis geometry for OE/dual Doppler comparison

The dual Doppler equations for this situation are

$$\begin{pmatrix} \cos\theta & \sin\theta \\ \cos\theta & -\sin\theta \end{pmatrix}\begin{pmatrix} u \\ v \end{pmatrix} = \begin{pmatrix} r_1 \\ r_2 \end{pmatrix}. \tag{4}$$

The solution to equation 4 is

$$\begin{pmatrix} u \\ v \end{pmatrix} = \begin{pmatrix} (r_1 + r_2)/2\cos\theta \\ (r_1 - r_2)/2\sin\theta \end{pmatrix}.$$

Let $u\varepsilon_{DD}$ and $v\varepsilon_{DD}$ denote the error in the u and v components of the dual Doppler solution. Let σ_R^2 denote the average of the error variances for the two radars. The dual Doppler error variances, provided that the radars have uncorrelated errors, are

$\mathrm{Var}(u\varepsilon_{DD}) = \sigma_R^2/2\cos^2\theta$, and
$\mathrm{Var}(v\varepsilon_{DD}) = \sigma_R^2/2\sin^2\theta$.

As θ approaches zero, the error in the solution for v becomes numerically unstable. To control this numerical instability the angle between radar beams, 2θ, is generally constrained to be greater than 30^0.

We use the assumptions listed above regarding the error models. That is, we assume the errors in the u and v components of the background are not correlated with each other or the error in the radar measurements, and we assume that the errors in the radar measurements are not correlated. We also assume that the error variance is the same for each component of the background wind, and that the error variance is the same for each radar. These are reasonable assumptions if the Doppler values are average (or median) values over a fixed region surrounding the analysis point, and the background is independent of the Doppler data. The background is independent of the Doppler data, for example, if the background comes from a forecast model or is derived from the radar reflectivity fields. Let σ_B^2 denote the error variance of the background components. This gives the error correlation matrix

$$C = \begin{bmatrix} \sigma_B^2 & 0 & 0 & 0 \\ 0 & \sigma_B^2 & 0 & 0 \\ 0 & 0 & \sigma_R^2 & 0 \\ 0 & 0 & 0 & \sigma_R^2 \end{bmatrix}.$$

Let $\varrho = \sigma_B^2/\sigma_R^2$ denote the relative quality of the radar observations vs. the background observations. Typically, ϱ is between 10 and 20. Then

$$C^{-1} = (1/\sigma_B^2)\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & \varrho & 0 \\ 0 & 0 & 0 & \varrho \end{bmatrix}.$$

With these assumptions, the OE solution is computed from equation 2 giving:

$$u_o^a = \alpha u_0^b + (1-\alpha)(r_1^o + r_2^o)/2\cos\theta, \text{ and}$$

$$v_o^a = \beta v_o^b + (1-\beta)(r_1^o - r_2^o)/2\sin\theta, \text{ where}$$

$$\alpha = (1 + 2\varrho\sin^2\theta)/(1 + 2\varrho + 4\varrho^2\cos^2\theta\sin^2\theta), \text{ and}$$

$$\beta = (1 + 2\varrho\cos^2\theta)/(1 + 2\varrho + 4\varrho^2\cos^2\theta\sin^2\theta).$$

The terms $1-\alpha$ and $1-\beta$ represent the fraction of the OE solution that is given by the solution to the dual Doppler equations for the u and v components. If α or β is zero the corresponding component of the OE solution is equal to the dual Doppler solution, and if α or β is 1 the corresponding component of the OE solution is equal to the background estimate.

We see that if ϱ is very large, i.e. the radar error variance is very small relative to the error variance of the background, and θ is not near zero, α and β are near zero; OE is nearly dual Doppler. If $\theta = 0$, then $\beta = 1$ and $\alpha = 0$, and OE returns a v component equal to the background. In this last case, the u component is the standard least squares solution, the background and Doppler values are weighted inversely to their variances. Figure 2 shows how $1-\beta$ varies with the angle between the two radar beams (2θ) for different values of ϱ. When the angle is greater than about 30^0, OE returns a value for v that is primarily the dual Doppler solution. As the angle decreases below 30^0, the weight given to the v component of the dual Doppler solution drops quickly to zero. In fact, as θ decreases to zero, $(1-\beta)(r_1^o - r_2^o)/2\sin\theta$ goes to zero, removing the dual Doppler instability for small θ.

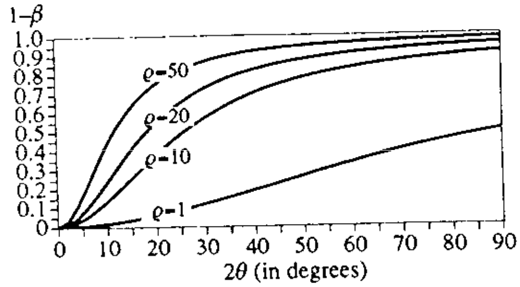

Figure 2: Weight given unstable dual Doppler component as a function of the angle between radar beams.

The error variances for the OE solution, computed from equation 3, are

$$\mathrm{Var}(u\varepsilon_{OE}) = \sigma_B^2/(1 + 2\varrho\cos^2\theta), \text{ and}$$

$$\mathrm{Var}(v\varepsilon_{OE}) = \sigma_B^2/(1 + 2\varrho\sin^2\theta),$$

again demonstrating the numerical stability of the method; the error variance of the OE solution is bounded above by the error variance of the background. It is also easy to show that the error variances are bounded above by the dual Doppler error variances giving:

$$\mathrm{Var}(u\varepsilon_{OE}) \leq \min\{\mathrm{Var}(u\varepsilon_{DD}), \mathrm{Var}(u\varepsilon_B)\}, \text{ and}$$

$$\mathrm{Var}(v\varepsilon_{OE}) \leq \min\{\mathrm{Var}(v\varepsilon_{DD}), \mathrm{Var}(v\varepsilon_B)\}.$$

4. EVALUATION RESULTS

The Terminal Winds 10 km and 2 km analyses and MAPS forecasts for the Orlando region were evaluated on the 1992–1993 data set. The basis of the evaluation is the comparison of observations with analyzed and forecast winds at nearly coincident points. This amounts to spot checks, since we cannot control the availability of observations, except to select days on which they were plentiful. Each algorithm was evaluated on a 20 day subset of the 1992 and 1993 MCO data archive. These days were chosen to include a variety of weather, and good comparison data.

Three comparison observation data sets were used, MDCRS reports, CLASS soundings (Cross–Loran Atmospheric Sounding System), and TDWR/NEXRAD dual Doppler wind fields. The MDCRS and CLASS sounding observations are independent of the analyzed wind fields. The data used to generate the dual Doppler data set were used in the Terminal Winds analyses so they do not provide independent observations. Since care was taken to ensure that dual Doppler winds were only produced when good Doppler data were available, and only in regions where the dual Doppler process is numerically stable, the ability to match the dual Doppler winds is important.

Comparisons between analyzed and forecast wind fields and observed winds were constrained to the 2 km grid to ensure consistent evaluation data sets and because product accuracy is paramount in this region. We used bi–linear interpolation of the 10 km analyses and MAPS forecasts to the 2 km grid. For each analysis, the observations were compared to the wind vector from the 2 km grid point nearest the observation.

The statistical evaluation indicates how well the Terminal Winds algorithm matches the comparison observations over a large period of time. Statistics collected over a large period of time do not allow performance quantification for different weather situations. For example, when the winds are relatively uniform, a 2 km analysis is not expected to perform better than a 10 km analysis since the wind field does not contain structures smaller than 10's of km. When the wind fields are more complex, we expect to see a variation in performance.

The comparisons of the Terminal Winds analyses and MAPS forecasts to MDCRS, CLASS soundings, and dual Doppler winds are provided in Table 2. Figures 3–5 are cumulative probability plots for the norm of the vector difference between each analysis and forecast, and each of the three sets of comparison observation data sets. For example, figure 3 shows that the vector difference between MAPS forecasts and MDCRS is 5 m/s or less about 70% of the time.

Table 2: RMS and median (in parentheses) values for the norm of the vector difference between the Terminal Winds analyses and MAPS forecasts, and the comparison observations (m/s)

	2 km	10 km	MAPS
MDCRS	4.1 (3.1)	3.8 (2.8)	4.6 (3.6)
CLASS	2.9 (2.2)	2.7 (2.2)	3.7 (3.0)
Dual Doppler	2.0 (1.0)	3.8 (2.6)	5.4 (4.1)

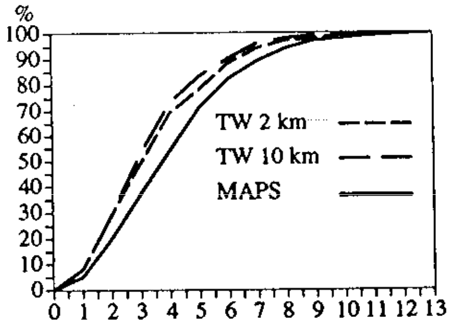

Figure 3: Performance vs. MDCRS

The comparisons to MDCRS and CLASS soundings indicate that both the 2 km and 10 km analyses consistently have better agreement with the observations than do the MAPS forecasts. These comparisons do not indicate that the 2 km analysis provides an improvement over the 10 km analysis. This is not too surprising since these are average values over all weather situations. The similarity in performance of the two scales of analysis may also reflect that we have reached the limit of these data sets to discern algorithm performance. Against MDCRS the two analyses have approximately a 4 m/s RMS error, and against CLASS the two analyses have approximately a 3 m/s RMS error, which are the reported RMS accuracies of the MDCRS and

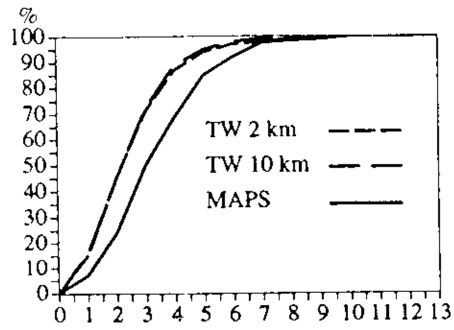

Figure 4: Performance vs. CLASS Soundings

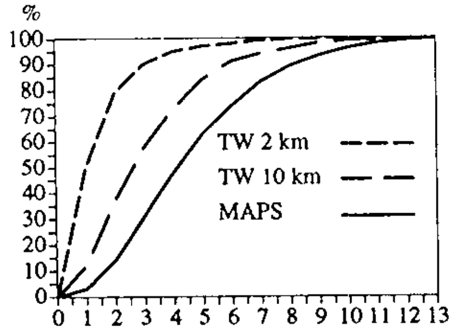

Figure 5: Performance vs. Dual Doppler

CLASS observations. The wind fields, including MAPS forecasts, agree more closely with the CLASS soundings than the MDCRS reports. This may be due to superior accuracy of the CLASS sounding measurements, or it may be due to the expected variation in the statistics when small data sets are used.

The comparison with the dual Doppler winds analysis provides greater distinction between the various analyses; the 2 km analysis matches the dual Doppler winds more closely than the 10 km analysis. The 2 km analysis matches the dual Doppler winds more closely than the RMS vector error of the dual Doppler winds (2.4 m/s) reflecting the statistical dependence between the two estimates of the wind field. Both scales of Terminal Winds analyses show a greater improvement over MAPS forecasts than shown in the earlier comparisons. This is expected. The dual Doppler data set contains observations from more complex wind fields than the other two comparison data sets since the Doppler data are dominated by observations in the PBL, and relatively more Doppler returns are available during and near convective weather than in weather with more clear air. Thus, the dual Doppler data set contains observations in regions where MAPS is not expected to perform well. The relationship between the OE algorithm and the dual Doppler algorithm is also in evidence.

5. FUTURE WORK

The ITWS gridded analysis system is undergoing refinement and testing. A number of analysis upgrades are planned, including the use of the last analysis to refine the background wind field, the estimation and removal of errors arising from using an observation at locations away from the observation location, and the use of ITWS gust front detections to increase the wind field accuracy. A major effort will be undertaken to add surface forcing to refine the winds in the PBL. We are also assessing the ability of developing technologies to derive wind information from radar reflectivity fields (Tuttle and Foote, 1990)(Qui and Xu, 1992). When sufficiently developed, these technologies will be an important new source of wind information. An FAA Demonstration and Evaluation of the ITWS was conducted in Memphis in the summer of 1994. The Demonstration and Evaluation will continue in Orlando in the fall of 1994, and possibly in Dallas – Fort Worth starting in the summer of 1995.

6. SUMMARY

The Terminal Winds analysis is an important component of the ITWS. The Terminal Winds provides an accurate, high resolution analysis of the horizontal winds in a three dimensional terminal domain. The wind information from this system is provided to a number of users, including air traffic automation systems and other ITWS algorithms. This system combines wind information from a national scale numerical forecast model, meteorological Doppler radars, commercial aircraft, and anemometer networks. It is flexible enough to run reliably with any available subset of these data, adding value to the national winds forecast in the terminal area as local sensors provide information. The Terminal Winds system operated in the summers of 1992 and 1993 in the Lincoln ITWS testbed at Orlando, FL, and in the summer of 1994 in the Lincoln ITWS testbed at Memphis TN, demonstrating a reliable operational system incorporating data from multiple sources, including TDWR and NEXRAD radars.

The terminal airspace is divided into two regimes. The planetary boundary layer (PBL) contains the atmosphere near the earth's surface, and often contains fine scale wind structures. Above the PBL, wind structures typically have larger scales. Doppler radars provide high resolution information in the PBL, but above the PBL, Doppler information becomes more sparse and the MAPS and MDCRS are important sources of additional information. An analysis cascade–of–scales is used to capture these different scales of atmospheric activity.

A new winds analysis technique, Optimal Estimation, was developed for the Terminal Winds product that is an extension of both Optimal Interpolation and multiple Doppler analysis. The ITWS will usually have data from at least two Doppler radars. Under certain restrictive hypotheses, high quality estimates of the horizontal winds can be derived from multiple Doppler data sets. Optimal Interpolation, a statistical interpolation technique, provides the current state–of–the–art operational non–Doppler winds analysis. Optimal Estimation provides wind estimates that are of higher quality than multiple Doppler analysis, and does not suffer from the numerical instabilities that arise in multiple Doppler analysis. The OE analysis also produces smooth transitions between regions with differing density of data.

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