P1.10 Synchronization of Multiple Radar Observations in 3-D Radar Mosaic

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1 INTRODUCTION

Because of the high spatial and temporal resolutions of radar data, they have been widely used in many meteorological applications such as severe storm monitoring and warnings, convective scale numerical weather predictions (NWP), as well as quantitative precipitation estimation (QPE) and forecast (QPF). The National Weather Service (NWS) has implemented the communication infrastructure that facilitates the central collection and distribution of base level data in real time from ~140 WSR-88D (Weather Surveillance Radar – 1988 Doppler) sites to several centralized locations or hubs (http://www.roc.noaa.gov/NWS Level 2/AMS.asp).

End users from government agencies, universities and private industries can access and retrieve the base level data in real-time from the centralized hubs. The National Severe Storms Laboratory (NSSL), utilizing the communication infrastructure, has instituted a National multi-sensor QPE Mosaic and (Quantitative Precipitation Estimation), or NMQ, system and research program (Zhang et al. 2004, Seo et al. 2005). The NMQ system takes base level data from all available radars at any given time, performs quality control, and then combines reflectivity observations from individual radars onto a unified 3-D Cartesian grid that covers the contiguous United States (CONUS). The 3-D CONUS radar mosaic has provided users with high-resolution radar reflectivity data that are comparable to the raw data with the advantage of a Cartesian coordinate svstem.

The WSR-88D radars operate in six different scan modes, or Volume Coverage Patterns (VCPs). The time that a radar takes to complete a full volume scan is different for each VCPs. For examples, VCP 11 consists of 14 elevation scans and it takes 5 min to complete a volume scan, while VCP 12 consists of 15 elevation scans with one volume scan taking 4 minutes to complete (Table 1). Different radars in the network operate in different VCPs depending on the weather in the vicinity of the radars. Further, the volume scans from adjunct radars do not start and end at the same times. The current NMQ 3-D mosaic scheme performs spatial objective analysis of multiple radar data by assuming that all the observations are valid at the same time. For slowly evolving, slowly moving precipitation systems, neglecting the time differences between different radar observations should not have significant impact on the accuracy of the final analysis. For fast evolving, fast-moving storms, however, combining observations from different times may result in inaccurate depictions of storm structure in the final analysis. For instance, one small storm cell would be observed by two radars at two different locations if the two radars volume scans were observed at different times. When combining the two volume scans, the one storm cell at different locations will become a larger cell, or even two small cells if the cell observed by one radar had moved outside the cell's echo region observed by the other radar. Thus synchronizing radar observations in the mosaic is important.

Table 1 Operational scan modes used in the WSR-88D network

VCP	Used For	Number of	Time to	
	Used For	Elevations	Complete	
VODA	Clear air	F	10 min	
VCP31	Light snow	5		
	Clear air		10 min	
VCP32	Light snow	5		
	Large velocity			
VCP21	Precipitation	9	5 min	
VCP11	Severe storms	14	6 min	
	Severe storms		4 min	
VCP12	Rapid Update	14		
VOF 12	Higher resol. at	14		
	low levels			
VCP121	Precipitation	9	6 min	
	Mitigate			
	range/velocity	5		
	aliasing			

The purpose of this study is to evaluate a synchronization scheme in the NMQ 3-D radar mosaic system (see paper p1.8 in the current preprint volume). The synchronization is aimed specially at building accurate 3D radar mosaic grid that is representative of fast evolving convective storms. The synchronization of the 3-D mosaic includes several procedures: 1) storm tracking using history data to obtain storm motion vector fields; 2) linearly advecting/ extrapolating data from the observational time to a given reference time for

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synchronization; and 3) mosaicing synchronized data to obtain the final analysis.

The following section, section 2, provides a brief description of the storm-tracking algorithm. A set of experiments was carried out to evaluate the impact of the synchronization scheme. The experimental design and case study results from a squall line event are presented in section 3 and a summary is provided in section 4.

2 MULTI-SCALE STORM TRACKING

A multi-scale storm-tracking algorithm developed by Lakshmanan (2003a, b) has been adapted for deriving storm motion vector fields used by the synchronization. The algorithm includes the following steps:

- Identify individual storm cells at a small scale (pre-specified) based on reflectivity and its spatial gradient fields;
- Merge storm cells into lager scale storm entities based on their spatial consistency;
- Estimate storm motions, one vector for each storm cell/entity, by minimizing the difference between consecutive reflectivity images (Fig.1);
- Estimate growth/decay rate of the storm intensity for each cell/entity;
- Analyze/interpolate the storm motion vectors to obtain a gridded motion vector field (Fig.1);
- A Kalman filter is applied to a time series of the motion vector fields to remove random errors in the motion estimates (Fig.1);

7) Extrapolate the latest reflectivity observations using motion vectors at different scales into the future time to get a forecast. The small-scale motion vectors are used for short-term extrapolations/forecasts and large-scale motion vectors are used for relatively long-term forecasts. The growth/decay factor is also considered in the forecasts.

The multi-scale storm-tracking algorithm has been evaluated using several precipitation events that include 3 typhoon and one tornadic supercell cases. Figures 2 and 3 show the critical success index (CSI) scores for reflectivity forecasts of 20dBZ or higher for one of the typhoon cases and for the tornadic supercell case. The forecasts did very well for the typhoon case given the relatively slow movement and large area of the precipitation. The CSI scores are higher than 0.6 for most of the forecasts, including the 3-h forecasts (Fig. 2b). For the tornadic supercell case, however, the performances of the forecasts are mixed. When the storms are relatively isolated and scattered, the CSI score is relatively poor (e.g., before 2100Z, Fig.3). When the storms are well organized, the CSI score is relatively qood (e.g., around 2300Z. Fig.3). Nevertheless, the average CSI score is ~0.5 for the 20 min forecasts (Fig.3). This indicates that the motion vectors are representative of storm movements within 20 min. Thus, using the vector fields to synchronize the multiple radar volume scan data in the 3-D Mosaic will likely provide positive impact since the difference between the radar volume scans are usually less than 20 min.



Fig. 1 A flowchart shows the process of estimation of storm motion vectors.



Fig. 2 Composite reflectivity image (a) of the typhoon Nari that affected Taiwan on 16 September 2001 and the CSI scores (b) for forecasts of composite reflectivity of 20dBZ and higher. The forecast lengths are 10, 20, 30, 40, 50, 60, 120, and 180 min, respectively. The abscissa is the beginning time of the forecasts.



Fig. 3 Composite reflectivity image (a) of the Oklahoma tornado case that occurred on 8 May 2003 and the CSI scores (b) for forecasts of composite reflectivity of 20dBZ and higher. The forecast lengths are 10, 20, 30, 40, 50, and 60 min, respectively. The abscissa is the beginning time of the forecasts. The red errors indicate the beginning time of the 60 min forecasts valid at 2150Z and 0010Z, respectively, on 8 May 2003. The composite reflectivity images valid at the 2150Z and 0010Z on 8 May 2003 are shown in panels a₁ and a₂, respectively. It is apparent that the poor CSI score (at a₁, panel b) is associated with isolated and scattered storms (panel a₁) while the good CSI (at a₂, panel b) is associated with well-organized storms (panel a₂).

3 EXPERIMENTS AND EVALUATION

3.1 The data

Base level data from four radars (KDYX, KFWS, KEWX, and KSJT) for a squall line event occurred on 1 June 2005 in central Texas were used for the study of synchronization in the 3-D Mosaic. The radar observations covered a half hour time period between 06:00 to 06:30UTC (see table 2). Figure 4 shows composite reflectivity fields from the four radars around 06:00UTC. Table 2 lists all the volume scans from the four radars that are used in the current study.

Table 2 List of volume scans of data that were used in
the study of synchronization in the 3D Mosaic.
Note that the time in the table indicates
minutes and seconds after 06:00UTC on June
1, 2005.

Radar	KDYX	KFWS	KSJT	KEWX	
Scan Strategy	VCP11	VCP11	VCP12	VCP21	
Number of Vol. Scans	6	5	6	5	
	06'43'	03'17"	05'08"	04'47"	
Time at the	11'47"	08'14"	09'28"	10'35"	
Middle of Each	16'52"	15'57"	13'48"	16'22"	
Volume Scans	21'58"	-	18'06"	22'11"	
Volume Scans	27'03"	25'12"	26'44"	-	
	32'09"	29'10"	31'03"	27'58"	

3.2 Experimental design

The following steps were involved in the study:

- Each volume scan of reflectivity data were analyzed onto a common 3-D Cartesian grid separately (Fig. 4). The valid time of each analysis grid was determined to be the center point between the start and end times of the volume scan.
- 2) The KDYX composite reflectivity fields from the 3D analysis grid were used for verification or truthing of the synchronization. Composite reflectivity analyses (with and without advection in time) from other three radars were compared with the "true" fields from the KDYX radar analysis. A correlation coefficient, ρ , is computed between the "true" composite reflectivity and the testing composite reflectivity analyses. The correlation coefficient ρ is by definition the ratio

$$\rho_{xy} = \frac{\sum_{i=1}^{N} (x_i - \eta_x)(y_i - \eta_y)}{\sqrt{\sum_{i=1}^{N} (x_i - \eta_x)^2} \sqrt{\sum_{i=1}^{N} (y_i - \eta_y)^2}}$$
(1)



Fig. 4 Composite reflectivity fields from KDYX (a), KFWS (b), KEWX (c), and KSJT (d) around 06:00UTC on June 1, 2005. The red boxes in panels a and b indicate the common Cartesian grid for all four radars.

Here *N* is the total number of valid composite reflectivity data pairs in the analysis domain. η_x and η_y are the mean of two random

variables x (i.e., composite reflectivity from KDYX reflectivity analysis grid in the current study) and y (i.e., composite reflectivity from any other radars analysis grid before and after synchronization). The means are calculated by:

$$\eta_x = \frac{1}{N} \sum_{i=1}^N x_i$$
 (2a)

$$\eta_y = \frac{1}{N} \sum_{i=1}^N y_i$$
 (2b)

3) The analysis grids from the three testing radars (KFWS, KEWX, KSJT) were advected forward in time to match the nearest validation radar (KDYX) grid. Correlation coefficients were calculated for each pairs of the testing and validation fields. Table 3 provides a list of all the experiments and the results are presented in the next section.

Validation Grid (KDYX)	Test Grid (KFWS)		Test Grid (KEWX)		Test Grid (KSJT)		
Time	Time	Time Exp. ID		Exp. ID	Time	Exp. ID	
06:07	06:03	KDYX(07)KFWS(03)	06:05	KDYX(07)KEWX(05)	06:05	KDYX(07)KSJT(05)	
06:12	06:08	KDYX(12)KFWS(08)	06:11	KDYX(12)KEWX(11)	06:09	KDYX(12)KSJT(09)	
06:17	06:16	KDYX(17)KFWS(16)	06:16	KDYX(17)KEWX(16)	06:14	KDYX(17)KSJT(14)	
06:22	06:16	KDYX(22)KFWS(16)	06:22	KDYX(22)KEWX(22)	06:18	KDYX(22)KSJT(18)	
06:27	06:25	KDYX(27)KFWS(25)	06:22	KDYX(27)KEWX(22)	06:27	KDYX(27)KSJT(27)	
06:32	06:29	KDYX(32)KFWS(29)	06:28	KDYX(32)KEWX(28)	06:31	KDYX(32)KSJT(31)	

Table 3 List of synchronization experiments and times of validation grid and testing grid pairs in the experiments. Note that the time indicates the UTC time (rounded to the nearest one) on 1 June 2005 at the middle of the volume scan.

3.3 Results

Table 4 compares correlation coefficients between the validation composite reflectivity field and the testing grid composite reflectivity field with and without synchronization towards the time of the validation field. Note that the correlation coefficients were for regions where both the validation and the test composite reflectivities are greater or equal to 30dBZ. All of the KFWS experiments and majority of the KEWX experiments show that there is better correlation between the validation field and the synchronized field than with un-synchronized field. For the KSJT experiments, however, the un-synchronized field was better correlated with the validation field than the synchronized field. One possible cause may be that the KSJT clock is incorrect and perhaps too fast and requires further investigation. Another important factor that affects the correlation coefficients is the sampling characteristic of each radar when they observe the storms. For instance, KFWS and KDYX were close to the northern part of the squall line and captured the convective rain band very well in the reflectivity observations (Figs.4a and 4b). The correlation coefficients showed very good consistence between the two radars composite reflectivity fields, especially when they were synchronized. For KEWX radar, however, the large part of the convective rain bands were missing in the reflectivity observations (Fig. 4c), resulted in poor correlation coefficients between the KEWX and the KDYX composite reflectivities (Table 4) even with the synchronization between them. KSJT radar observations, on the other hand, captured the squall line rain band better than the KEWX radar (Fig. 4d), which resulted in better correlation coefficients with KDYX data (Table 4).

Table 4 Correlation coefficients between the validation composite reflectivity field and the testing composite reflectivity
with synchronization (i.e., advected to the time of the validation grid) and without synchronization.

Validation Grid (KDYX)	Test Grid (KFWS)			Test Grid (KEWX)			Test Grid (KSJT)		
Time	Time	Corr.	. Coef. Time		Corr. Coef.		Time	Corr. Coef.	
		No Sync	Sync	TIME	No Sync	Sync	TIME	No Sync	Sync
06:07	06:03	0.575	0.647	06:05	0.511	0.523	06:05	0.603	0.566
06:12	06:08	0.513	0.613	06:11	0.501	0.493	06:09	0.645	0.618
06:17	06:16	0.602	0.645	06:16	0.559	0.546	06:14	0.687	0.664
06:22	06:16	0.437	0.600	06:22	0.507	-	06:18	0.667	0.640
06:27	06:25	0.569	0.609	06:22	0.464	0.525	06:27	0.657	-
06:32	06:29	0.548	0.627	06:28	0.522	0.574	06:31	0.693	0.669

A series of forecast experiments were carried out in association with those listed in Table 3. In each experiment, the testing grid was advected forward in time at 1 min interval for up to 7 minutes. There were

7 forecasts for each experiment and the forecast lengths were 1, 2, 3, 4, 5, 6, 7 min, respectively. For instance, in the experiment "KDYX(07)KFWS(03)", the composite reflectivity from the KFWS valid at 06:03UTC on 1 June

2005 was extrapolated to 06:04, 06:05, 06:06, 06:07, 06:08, 06:09, 06:10UTC, respectively. Each of the 7 extrapolated composite reflectivity fields was then compared to a validation composite reflectivity field from KDYX valid at 06:07UTC and correlation coefficients were obtained (black line in Fig.6a). Note that the correlation coefficients were computed for various reflectivity thresholds.

Most correlation coefficients for the KFWS and KEWX radar experiments reached maximum when the forecast time was near the validation time. For instance, experiments "KDYX(07)KFWS(03)" (black line in Fig. 6a) and "KDYX(12)KFWS(08)" (red line in Fig.6a) both have the maximum correlation coefficients around 4 min. Experiment "KDYX(07)KFWS(05)" (black line in Fig. 6b) has a maximum correlation coefficient at 2 min and experiment "KDYX(32)KEWX(28)" has a maximum at 4 min. This indicates that the vector fields used for extrapolation were representative of the storm movements. In addition, the clocks of the two radars are well synchronized. However, the maximum of correlation coefficients for the KSJT experiments were not consistent with validation data time. The cause of the inconsistency may be due to the incorrect clock of KSJT radar and will be further investigated in future work.

4 SUMMARY

A synchronization scheme has been developed for the NMQ 3-D CONUS reflectivity mosaic. The synchronization scheme includes three steps: 1) storm tracking using history data to obtain storm motion vector fields; 2) advecting/ extrapolating data from the observational time to a given reference time for synchronization; and 3) mosaicing synchronized data to obtain the final analysis. The storm tracking is based on a multi-scale algorithm that tracks storms and obtain motion vectors at different spatial scales. Small-scale motion vectors are used for extrapolating/forecasting storms for shorter time periods (e.g., \leq 30min) and large-scale motion vectors are used for longer time periods.

The current study evaluated the multi-scale storm tracking algorithm and its application in the synchronization of the 3-D mosaic. The results showed that the motion vectors obtained from the tracking algorithm are representative of the storm movements. The reflectivity fields from different radars correlated better when they are synchronized than when they are not, indicating that synchronization provides improved depictions of storm structure.

Future work will include investigations of the impact of radar clocks on synchronization. Evaluation of multiple radar mosaic with and without synchronization will also be carried out.



Fig. 6 Correlation coefficients between the composite reflectivity fields from KDYX observations (used as validation) and the extrapolated (in time) composite reflectivity fields from KFWS (*a*), KEWX (*b*), and KSJT (*c*). The correlation coefficients were calculated in regions where the KDYX composite reflectivity is greater than 30dBZ. Detailed descriptions of experiments can be found in the text.

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