17B.2 A STUDY OF DOPPLER RADAR WINDS IN HURRICANE WILMA (2005)

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I. Introduction

The purpose of this study is to document the maximum Doppler velocities observed by the Miami National Weather Service Doppler radar (WSR-88D) during Hurricane Wilma's passage across South Florida on 24 October 2005 These observations serve as a proxy for observations of surface wind in regions where surface observing systems either failed or were not deployed. This information will be used by engineers at Florida Power and Light Corporation to relate Hurricane Wilma's structure to damage to elements of the power grid.

2. Hurricane Wilma 2005

Hurricane Wilma started to affect the SW coast of Florida as early as 0700 UTC on 24 October. The western eyewall moved off the SE coast by 1700 UTC. During those 10 hours of passage across South Florida Wilma caused extensive damage, especially in Miami Dade, Broward and Palm Beach counties. Power outages were widespread and, because of the loss of main transmission lines, long-lasting. See Pasch et al (2007) for the Tropical Prediction Center's summary of the storm history for further details of the damage.

Because Wilma's eye was so large most of South Florida experienced the eyewall at some point. Figure 1 displays a sequence of reflectivity scans at roughly two hourly intervals. At 0703 UTC the eyewall was affecting the west coast of South Florida and the Keys while rainbands and isolated cells were moving across the Southeast coast (Fig. 1a). At 0902 (Fig. 1b) the eastern edge of the eyewall is just west of the radar and the high reflectivity indicate that western parts of Broward and Palm Beach counties are probably experiencing hurricane force winds. Wilma continued westward and by 1108 the radar was in the SE corner of the eyewall and the SE coastal regions were experiencing the full effects of Wilma (Fig 1c). The winds apparently affected the radar because between 1100 and 1200 there were numerous partial volume scans, where the radar would repeatedly try to start a sequence only to abort after a few sweeps. By 1303 the eastern eyewall was just moving off the coast while the western eyewall and rainbands were hitting the SW coast (Fig 1d). Wilma continued to the NE and by 1501 the radar and W coast were in the clear. As Figure 1e shows, though, the SE coast was now being lashed by the western eyewall. By 1702 UTC the eyewall had moved completely off the coast and only rainbands continued over Florida, NE of Lake Okeechobee.

Because the Doppler radar only measures the total wind speed when the wind is parallel to the radar beam, we can expect a fair estimate of the maximum wind speed when the radar beam is tangent to the eyewall. Consequently there are regions where the geometry precludes representative wind estimates. This is especially true of the region southeast of the radar, where the radar beams intersect the wind vectors at right angles. But the sequence of reflectivity images shows that we will get good estimates of wind speed in regions NW to N of the radar, which comprises the more highly populated areas of South Florida.

3. Data and Analysis Methods

WSR-88D

The primary data for this study were collected by the National Weather Service Doppler radar (WSR-88D) located in Miami, Florida (Figure 2). The WSR-88D collected radar reflectivity, Doppler velocity, and spectral width and transmitted them to the Miami Weather Service Forecast Office (WSFO) in real-time for operational use. These same data were also transmitted to the National Climatic Data Center (NCDC) for archival. We obtained the data from the NCDC a few days after storm passage.

The WSR-88D is a 10 cm Doppler radar with a 1 deg beam width. Doppler data are collected to 230 km (120 mi) in 250 m (813 ft) bins, and reflectivity data are collected to 450 km (280 mi) in 1 km (0.6 mi) bins. The lowest tilt angle is 0.5 deg and the highest tilt angle is 19.5 deg. The radar can be operated in several different scanning patterns called Volume Coverage Patterns (VCP), each consisting of a sequence of sweeps at several different tilt angles. A scan sequence completes every 5 or 6 minutes.

Doppler data can be collected at varying Pulse Repetition Frequencies (PRF). The PRF determines both the maximum unambiguous range and the maximum unambiguous velocity. Selection of the PRF involves the "Doppler dilemma": higher PRFs yield a higher velocity interval but a reduced maximum range. The PRF's used in the 88D yield maximum ranges from 115 km (1282 PRF) to 175 km (882 PRF), with corresponding velocity intervals of ±34 to ±23 m/s (76 to 51 mph). Radar reflectivity and Doppler velocity from weather beyond the maximum unambiguous range will be folded back into the interval. For example, if there is a strong cell 150 km from the radar and the maximum unambiguous range is 115 km, then the storm returns will be overlaid at an apparent range of 35 km. To resolve the range ambiguity a reflectivity sweep is collected at a lower PRF with range 400 to 465 km. By comparing reflectivity in this sweep with that in Doppler sweeps, the data are assigned to the correct distance – 'range unfolding'.

Similarly, Doppler velocities outside the maximum unambiguous velocity will be folded into the velocity interval. If the actual Doppler velocity was -60 m/s (where negative velocities are toward the radar) and the maximum unambiguous velocity was ±34 m/s, then the folded velocity would be recorded as +26 m/s. These Doppler ambiguities are more difficult to resolve than range ambiguities. A local wind estimate, often the wind at the radar, is used to seed an algorithm that adjusts the velocities to be close to the seed. Other Quality Control parameters are also satisfied and usually the velocity ambiguities can be resolved. Hurricanes cause problems to automatic velocity unfolding when the radar beam passes through the eye and the correction fails across the clear area of the eye. VCP 121 was designed to improve the automatic dealiasing by collecting data at different PRFs.

VCP 121

During hurricane landfalls the radars are operated in VCP 121. In VCP 121 the radar collects multiple sweeps at the same series of tilt angles, to enable automatic dealiasing of Doppler data by the MPI algorithm (Zittel 2005). Germane to this study, in VCP 121 the radar collects 4 sweeps at the lowest 0.5 degree tilt. The first sweep is a reflectivity sweep. The next three sweeps are collected at different PRF's to have different unambiguous Doppler velocities. The reflectivity are used to range unfold the second sweep in real time at he radar. The third and fourth sweeps are range unfolded later in the processing of the MPI algorithm. Unfortunately the archival Level II data do not have range infolded data in the third and fourth sweeps, so one of our tasks was to replicate the operational range unfolding before further processing of the data. Zittel (2005) describes the MPI algorithms and the details of the VCP 121 processing.

Doppler issues

Doppler radars measure the component of wind along a radar ray so the Doppler data represent the total wind only if the wind vector is pointed towards or away from the radar. Otherwise the Doppler velocity represents a lower bound on the total wind speed.

The antenna base is 30 m (98 ft) above ground level (AGL) and the beam's minimum tilt angle is 0.5 deg above horizontal so clearly direct observations of 10 m (33 ft) winds are not possible with standard WSR-88D radars. Any estimate of surface winds, even quite close to the radar, requires some adjustment factor.

Farther from the radar the beam height and volume of the radar bin increase. It is not clear what reduction factors are appropriate at different ranges. Fortunately there were some surface stations that we can compare Doppler radar data to at these further ranges.

Surface data

Data from ASOS and portable wind towers were required in order to derive adjustment factors for the Doppler data. Mark Powell provided quality controlled surface data that had been archived as part of the H*Wind project. As described in Powell et al (1994f) these surface observations were processed to yield a consistent set of 1 minute mean winds valid in open terrain exposures at 10 m altitude.

Data processing

We developed code to range unfold the third and fourth Doppler sweeps. These modified Level II data were then passed through the NCAR xltrs package to convert the data to DORADE format. Then

We derived a sequence of 100 m (328 ft) wind estimates by the VAD technique (Browning and Wexler, 1968) to use as seed values for Bargen Brown unfolding. Then each volume scan was passed through the NCAR SOLO Doppler editing package. This dealiased most of the winds to the correct Doppler velocity. Then SOLO was applied to manually correct incorrectly delaiased velocities. To speed up the dealiasing process we developed code that used previous volume scans to dealias or to delete bad velocities.

This data editing and cleanup yielded a set of synthesized sweeps that held the maximum Doppler velocity found in the three Doppler tilts for each volume scan. Figure 3 shows the reflectivity and synthesized data for 1150 UTC. Note the strong velocity away from the radar to the North and the strong velocities approaching from the West, both regions where the maximum Doppler velocity occurs in a region where the radar beams are probably parallel to the winds in the eyewall.

These sweeps hold Doppler data valid at the height of the beam. It was now necessary to estimate a surface reduction factor to relate the Doppler data to a 1 minute 10 m surface wind. To accomplish this we obtained the quality controlled data set of surface observations from the H*Wind database. Powell et al. (1994) describes how the raw observations are adjusted to10 m 1 min winds and Powell et al. (2004) describes the work to document the exposures of ASOS and CMAN stations that are used to produce the quality controlled winds. Of course some of these stations have the geometrical issues – wind directions significantly different from the radar beam direction. We computed two ratios. One is a straight comparison of surface wind speeds and Doppler velocities. The second comparison is the ratio of the component of surface wind parallel to the radar beam with the Doppler wind speed. In effect the first comparison assumes that the Doppler measured the total wind speed while the second comparison assumes that the wind direction was the same at both levels.

Table 1 lists these comparisons for several of the sites. The values shown were selected when the surface wind vector was closest to the radar ray direction (when the cosine of the angle was greatest. The comparisons were limited to those where the angle between radar ray and the surface wind was in the range 0 – 30 deg or 50-180 deg, and those where the surface observations were within 15 minutes of the radar values. Only 9 stations satisfied these criteria. The average ratio was .68 with a standard deviation of .1. For the FPL GIS data set we round the reduction factor up to 70%.

Another check of the reduction factor is provided by winds derived from the Velocity Azimuth Display algorithm (Browning and Wexler 1968) applied to the Miami Doppler data. This algorithm estimates a mean wind in cylinders from 5-12.5 km radius by fitting the sinusoid ally varying Doppler winds to expressions for the horizontal wind. When estimating VAD winds the first good wind estimates are 80 m or more AGL. Table 2 shows the winds estimated at 1000 m and 100 m and the ratios of the winds. When the wind speeds at the Miami radar were highest we see similar reduction factors as we found by comparing Doppler observations to the surface winds.

Should this reduction factor vary with range from the radar? To examine this consider a vertical profile of horizontal winds derived from Doppler data collected at 1150 UTC. The winds displayed in Figure 4 were computed using the VAD algorithm. The maximum winds speeds are fairly constant, ~60 m/s, above 1 km below that altitude the wind speed declines to ~40 m/s about 80 m AGL, which translates to a 66% reduction. The shape of the VAD wind profile is similar to profiles from GPS dropsondes in hurricanes, described in Franklin et al (2003).

We then sampled this profile as if it was located at various ranges from the radar. As shown in Table 3, the combined effect of beam spreading and rising beam height is to sample mostly the region above 1 km, where the speed varies little. So beyond 50 km or so the same surface reduction factor can be used to estimate the surface Doppler velocity.

To produce data that FPL could use, the synthesized sweeps were then passed through another procedure developed for this project that synthesized polar arrays of maximum Doppler velocity observed during the period 0900 to 1200 UTC. This synthesized data set also included the Time of the maximum Doppler velocity as well as Maximum dBZ. Finally, simple code developed at HRD, using public domain software, converted the synthesized data set to “shapefiles” that FPL could input to their GIS system. The shape files include Doppler velocities adjusted to the surface by the 70% factor.

4. Results

The highest surface winds occurred in SE Florida. ASOS station FLL near the Ft Lauderdale Airport had a peak 1 minute wind of 46.3 m/s at 1453 UTC, with winds greater than 37 m/s from 1343 to 1539 UTC. The PBI ASOS station, near the Palm Beach airport, had a maximum wind of 46.7 m/s at 1310 UTC, and winds greater than 37m/s from 1245 to 1326 UTC. These values are from the H*Wind quality-controlled observation set and represent 1 minute winds at 10 m elevation in open marine exposure.

The maximum Doppler velocities, adjusted by 70%, are displayed in Figure 5. Clearly most of the region experienced strong winds. The strongest Doppler returns are found in a strip along the east coast, from Fort Lauderdale (FLL) to north of Pompano Beach (PMP). A close-up of that region, shown in Figure 6, shows this strip of higher velocities. Unadjusted Doppler velocities had isolated values as high as 70 m/s, which yields 49 m/s when adjusted to the surface by 70%. This is close to the maximum surface winds at FLL.

The time (UTC) of the maximum Doppler observation is displayed in Figure 7. This shows that along the East Coast the highest Doppler velocities occurred from 1200 to 1400 UTC, when the eastern side of Wilma was impacting the region. This is consistent with the surface observations. Anecdotally some people felt that the western side of the eyewall was stronger, but this plot does not support that conclusion.

The best wind observations in a land falling hurricane will come from well calibrated surface stations deployed in open exposure. As more mobile platforms are developed and deployed by groups like Texas Tech University and the Florida Coastal Monitoring Project, we can expect better data sets in future storms. Doppler radar data will still be a valuable asset. As the data can fill in data voids as we attempted to do in the present study. In South Florida a valuable addition in 2007 will be the addition of the Terminal Doppler Weather Radar data from Miami, Ft. Lauderdale and Palm Beach to the radar data available in real time at the National Hurricane Center.

Future research should explore ways to merge the Doppler data with other observations to produce consistent estimates of surface winds. One technique might be to assimilate the Doppler data in a high resolution mesoscale model.

5. Acknowledgements

Paul Hebert, FPL, initiated this project and made many useful suggestions during the analysis. Brick Rule, FPL, helped clarify FPLs requirements for a product that could be integrated into their GIS. Dave Zittel at the NEXRAD Radar Operations Center provided useful information to decode the VCP 121 data Ian Giamanco. Texas Tech University and AOML/HRD scientists Shirley Murillo, Nick Carrasco, and Dr. Mark Powell provided quality-controlled surface observations to compare with the Doppler data. Prof. Forrest Masters, University of Florida, deployed FCMP towers that collected high-resolution data during Wilma’s transit of South Florida. HRD scientists John Kaplan, Jason Dunion and Eric Uhlhorn provided suggestions that improved the estimation of the surface reduction factor.

6. References

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Table 1. Wilma WSR-88D Doppler data compared with
Surface winds adjusted to 1 min mean at 10 m in open terrain

Sfc Site	angle cos	deg	Dop time UTC	time diff sec	dop m/s	ref dBZ	sfc m/s	sfc comp m/s	ratio	comp ratio
FLL	0.9992	2.4	133804	124.0	46.4	33.5	38.7	38.6	0.834	0.833
FWY	0.9696	14.2	170104	64.0	28.0	-1.0	21.5	20.9	0.769	0.745
LON	-.9999	179.2	110804	56.0	-45.9	20.5	30.7	-30.7	0.670	0.670
SMK	-.9995	178.1	100704	116.0	-44.4	37.0	33.8	-33.8	0.762	0.762
T0	-.9980	176.3	122804	179.0	-47.4	29.5	31.7	-31.6	0.669	0.667
T1	0.9765	12.4	121204	165.0	60.4	43.0	37.1	36.2	0.614	0.600
T2	-.9982	176.6	140604	426.0	-51.9	29.5	24.0	-23.9	0.462	0.461
T3	0.9994	1.9	122304	121.0	42.4	35.0	27.7	27.6	0.653	0.653
TMB	0.9987	3.0	090159	61.0	24.4	31.0	17.1	17.1	0.702	0.701

Average ratio: 0.68 Std dev: 0.10
Average comp ratio: 0.677 Std dev: 0.10
Note that the open terrain value for Fowey Rocks (FWY) was used, to be consistent with the observations collected on land.

Table 2. October 24 2005 VAD winds from KAMX

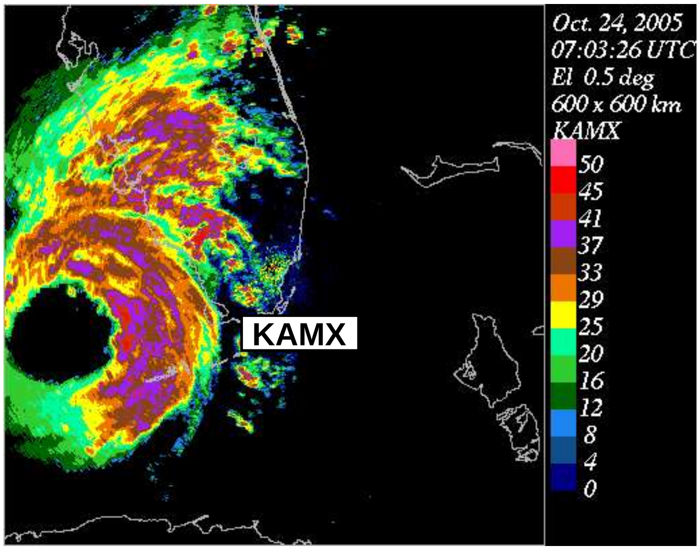
	100 m winds			1000 m winds				
	ht	speed	dir	ht	speed	dir		del dir
UTC	m	m/s	deg	m	m/s	deg	ratio	deg
09:02	101.4	20.8	153.7	989.1	40.0	167.7	0.52	-14.0
10:02	100.5	31.9	154.6	994.0	50.0	173.3	0.64	-18.7
10:28	99.5	33.5	159.4	994.0	52.9	177.5	0.63	-18.1
11:50	100.5	42.7	179.6	994.0	59.6	202.5	0.72	-22.9
12:07	100.5	42.0	188.0	994.0	56.9	212.9	0.74	-24.9
12:28	100.5	37.0	205.2	994.0	49.4	229.2	0.75	-24.0
12:57	100.5	24.8	237.4	994.0	50.1	253.9	0.50	-16.5
13:32	100.5	18.4	252.2	989.1	52.0	269.1	0.35	-16.9
14:01	99.5	32.8	258.3	993.0	50.3	280.6	0.65	-22.3
14:34	100.5	29.6	256.7	994.0	44.2	280.4	0.67	-23.7
15:01	99.5	22.1	260.9	993.0	40.1	283.5	0.55	-22.6

Ratio is comparison of VAD winds at levels closest to 1000 m and 100 m.

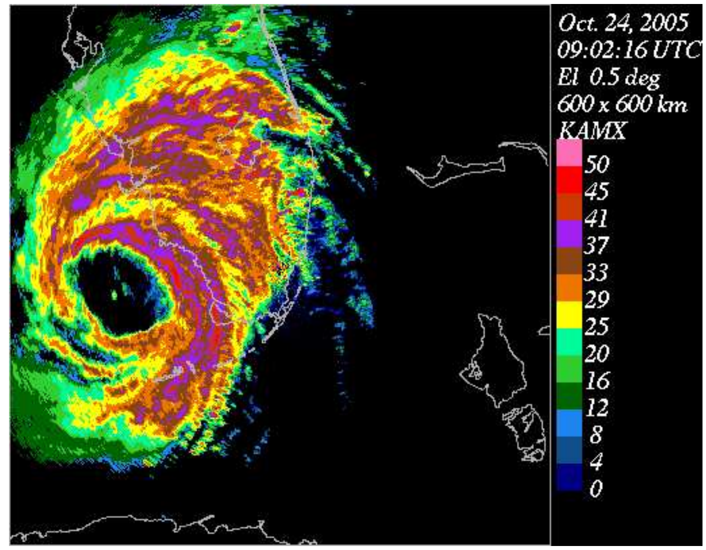
Table 3. Comparison of VAD profile winds with winds in layers.

	Beam Midpoint			Beam Volume			
range	ht_beam	spd	dir	bottom	top	spd	dir
km	m	m/s	deg	m	m	m/s	deg
50.0	614.0	58.6	194.8	177.5	1049.5	55.2	191.4
75.0	1015.4	59.6	203.3	361.1	1670.6	57.5	197.6
100.0	1490.9	59.5	211.3	618.9	2364.0	58.8	205.9
125.0	2040.7	59.5	216.7	949.9	3131.6	59.8	212.5
150.0	2663.8	61.4	216.1	1355.2	3972.4	60.6	216.4
175.0	3360.1	63.1	220.8	1832.7	4208.9	61.1	218.2

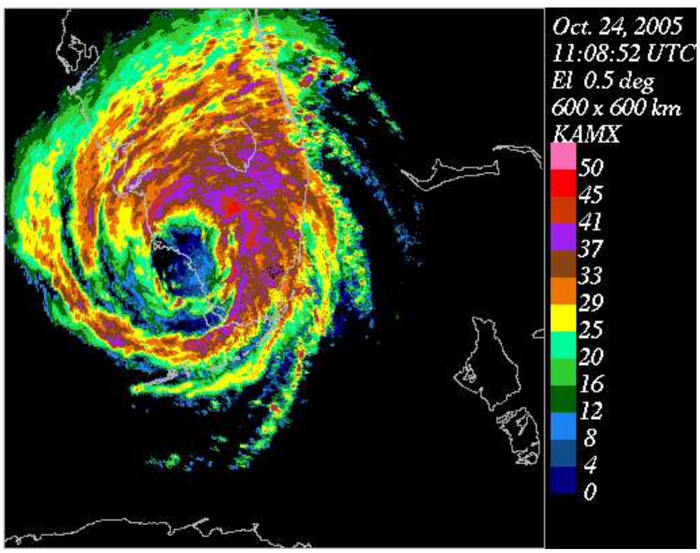
Table 3. Comparison of VAD profile winds with winds averaged over layers defined by 0.5 deg beam heeight at various radar ranges.VAD profile is for 1150 UTC, 24 OCT 2005 at the AMX WSR-88D radar, computed on rings from 5 12.5 km from the radar. VAD profile extends from 66.3 to 4208.9 m. Density-weighted averages of wind velocity were computed for each layer.



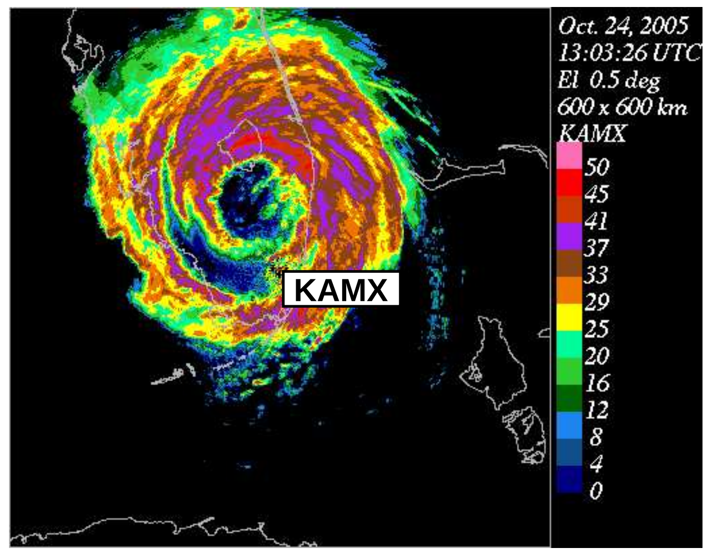
a.)0703 UTC



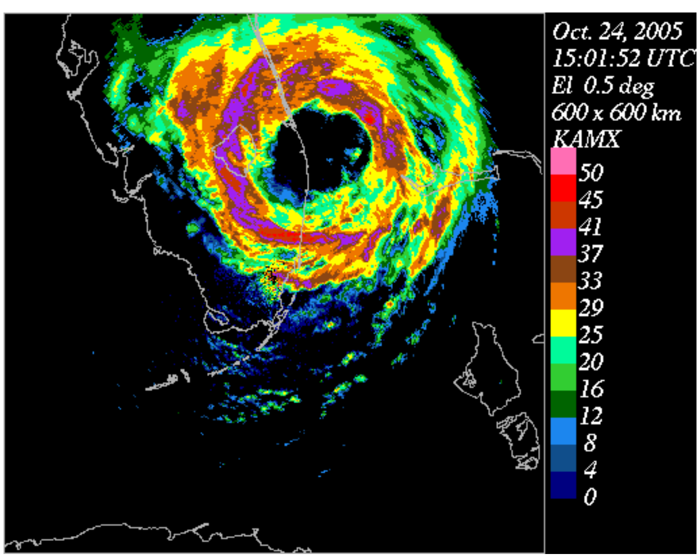
b.) 0902



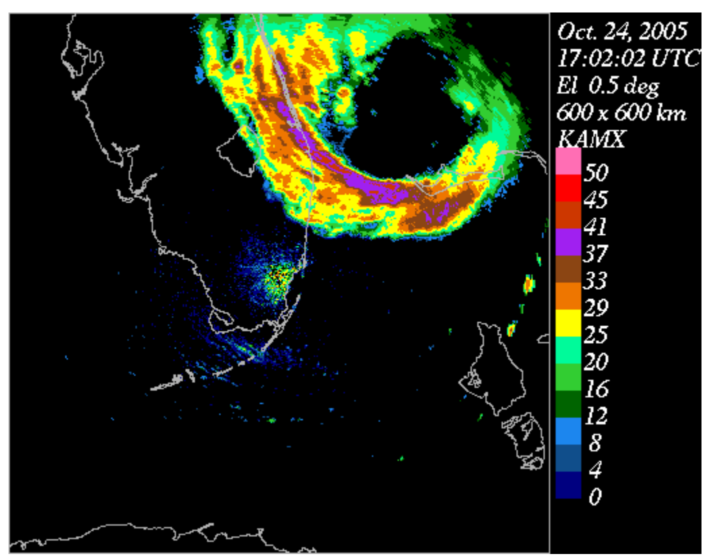
c.) 1108



d.) 1303



e.) 1501



f.) 1702

Figure1.. Sequence of reflectivity images from Miami WSR--88D, 24 October 2005. Radar is centered in 600 x 600 km domain.

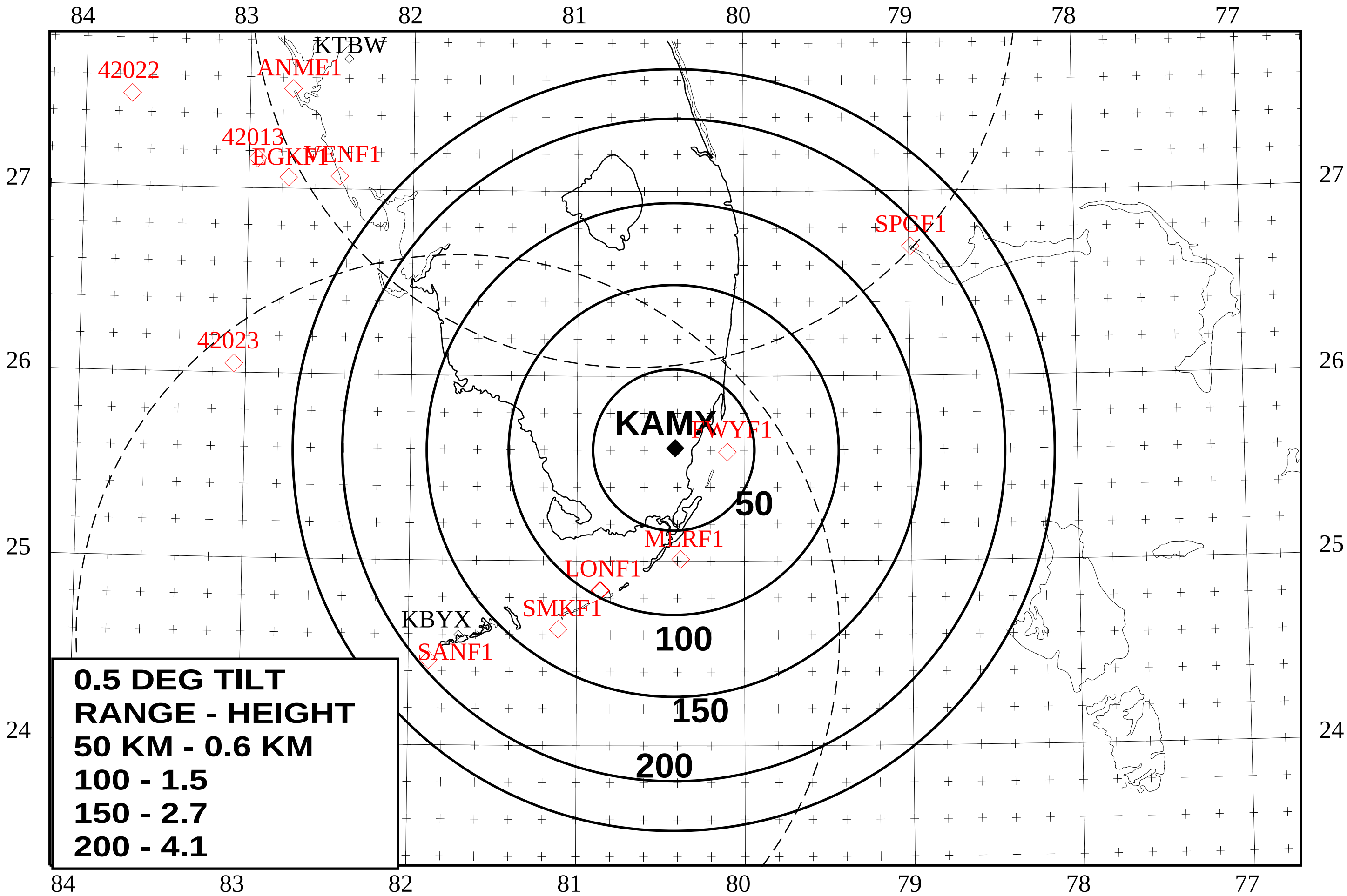


Figure 2. Miami WSR-88D coverage. Table lists the beam midpoint height at different ranges.

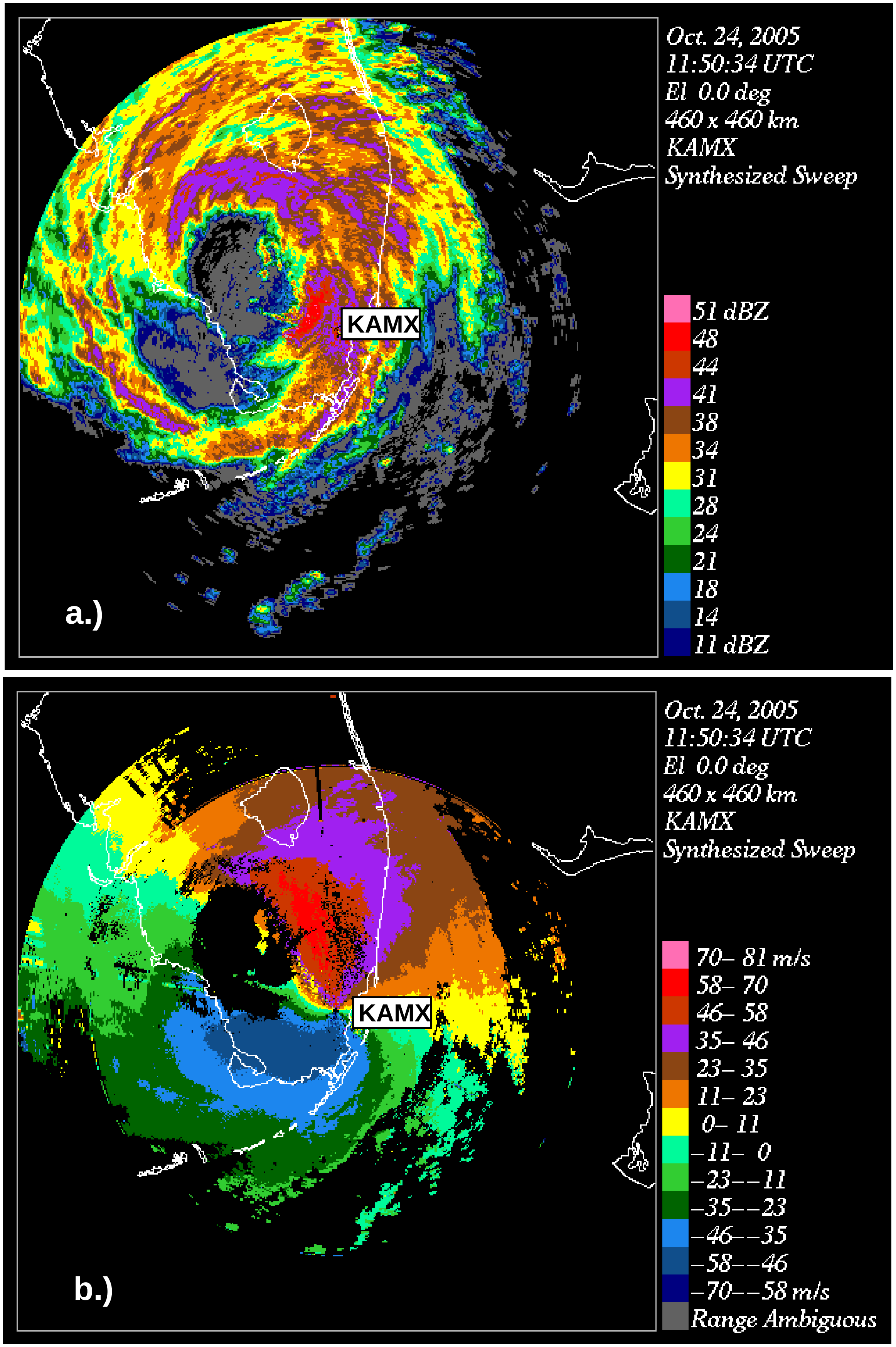


Figure 3.Radar images at 1150 UTC, 24 October 2005. Ilames from data synthesized form 0.5 degree sweeps. a.)Relectivity and b.) Doppler velocity. Doppler Data dealiased. Green and blues indicate flow towrds the radar and reds and oranges Indicate flow away.

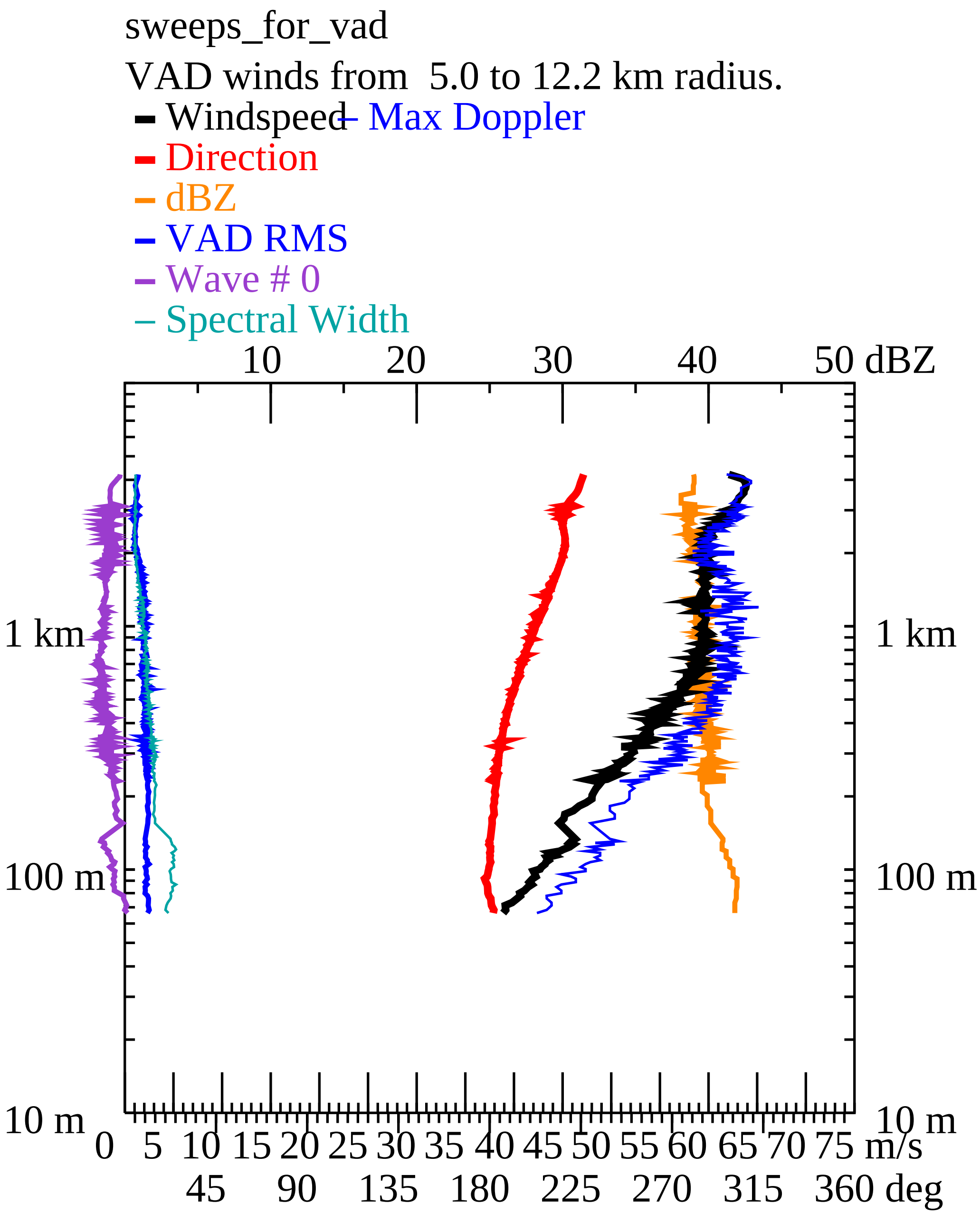


Figure 4. Vertical profile of horizontal winds at 1150 UTC, 24 October 2005, estimated by the Velocity-Azimuthm Display method. Winds were calculated in rings from 5 to 12 km from the Miami WSR 88D at tilt angles from 0.5 to 19.5 degrees. Valuse are plotted on a logarithmic scale to accentuate the structire below the 1 km height.

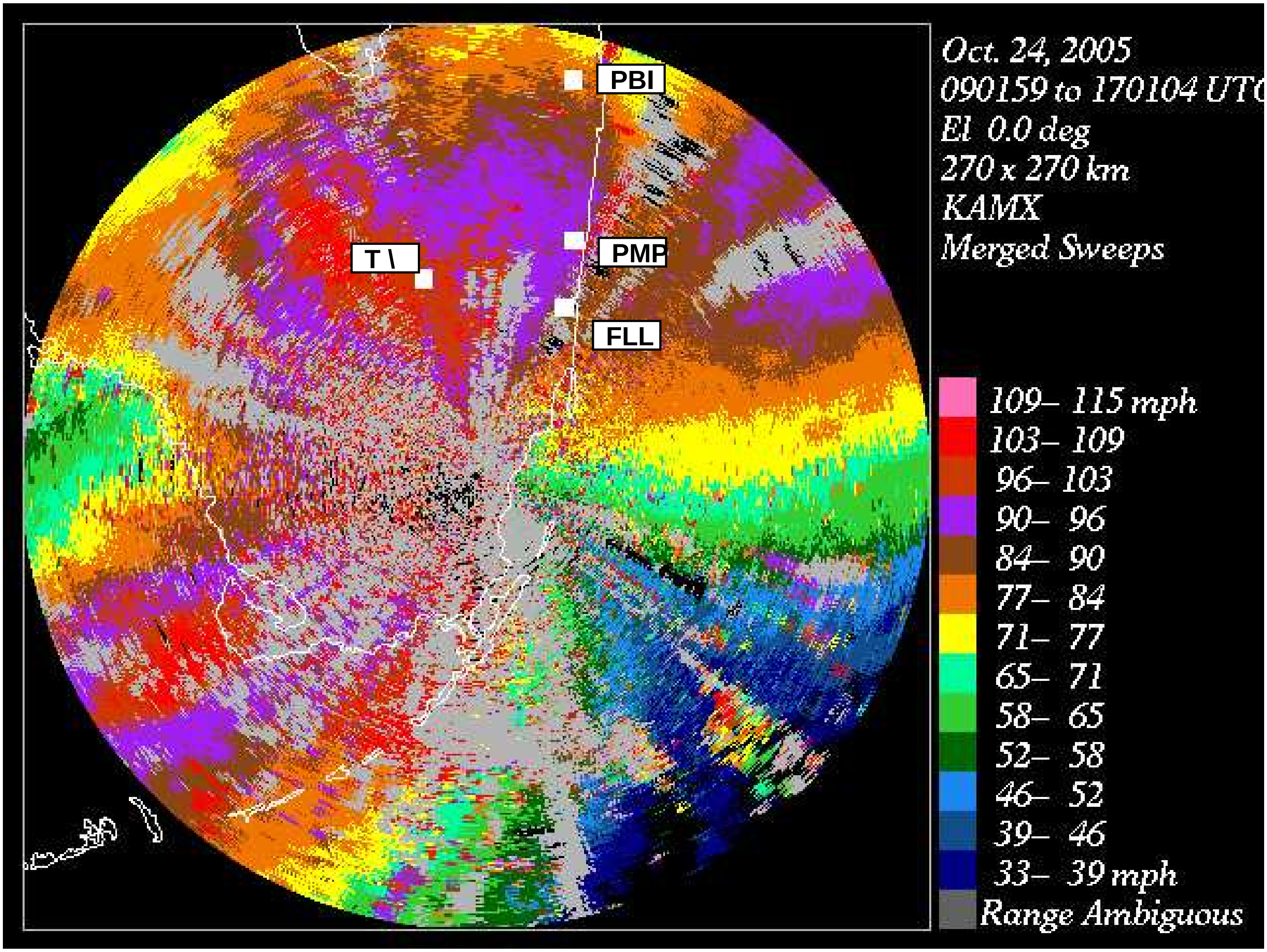


Figure 5. Maximum Doppler velocities within 135 km of Miami WSR-88D for the period 0900 to 1700 UTC, 24 October 2005. Valuse displayed are absolute values reduced by a surface reduction factor of 70% to approximate sustained surface winds at 10m. T 1 is an FCMP tower and PBI, PMP and FLL are NWS ASOS sites..

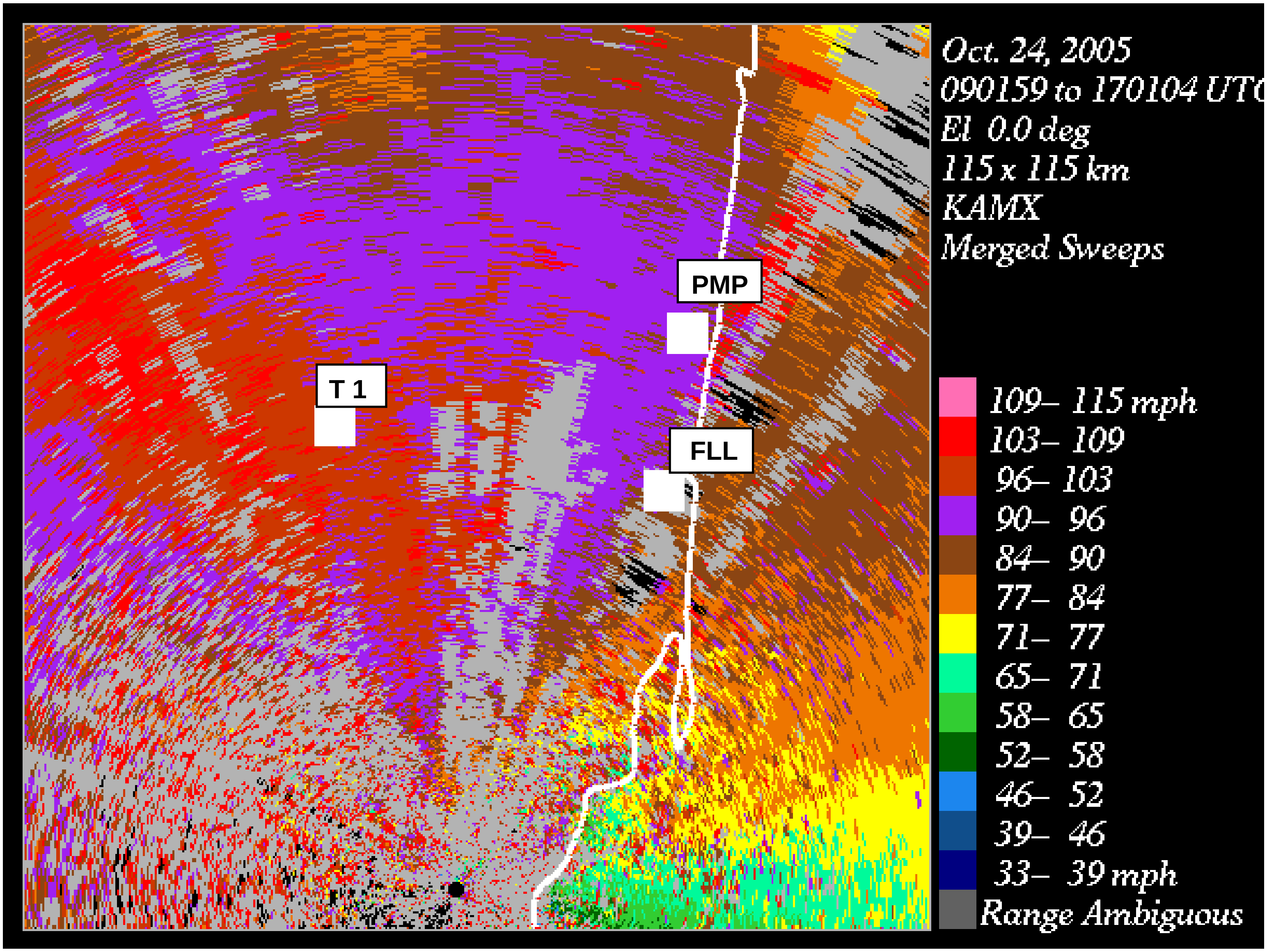


Figure 6. Closeup of maximum Doppler velocities. 115 x 115 km domain centered on Broward County. Time and adjustment as in Fig. 5.

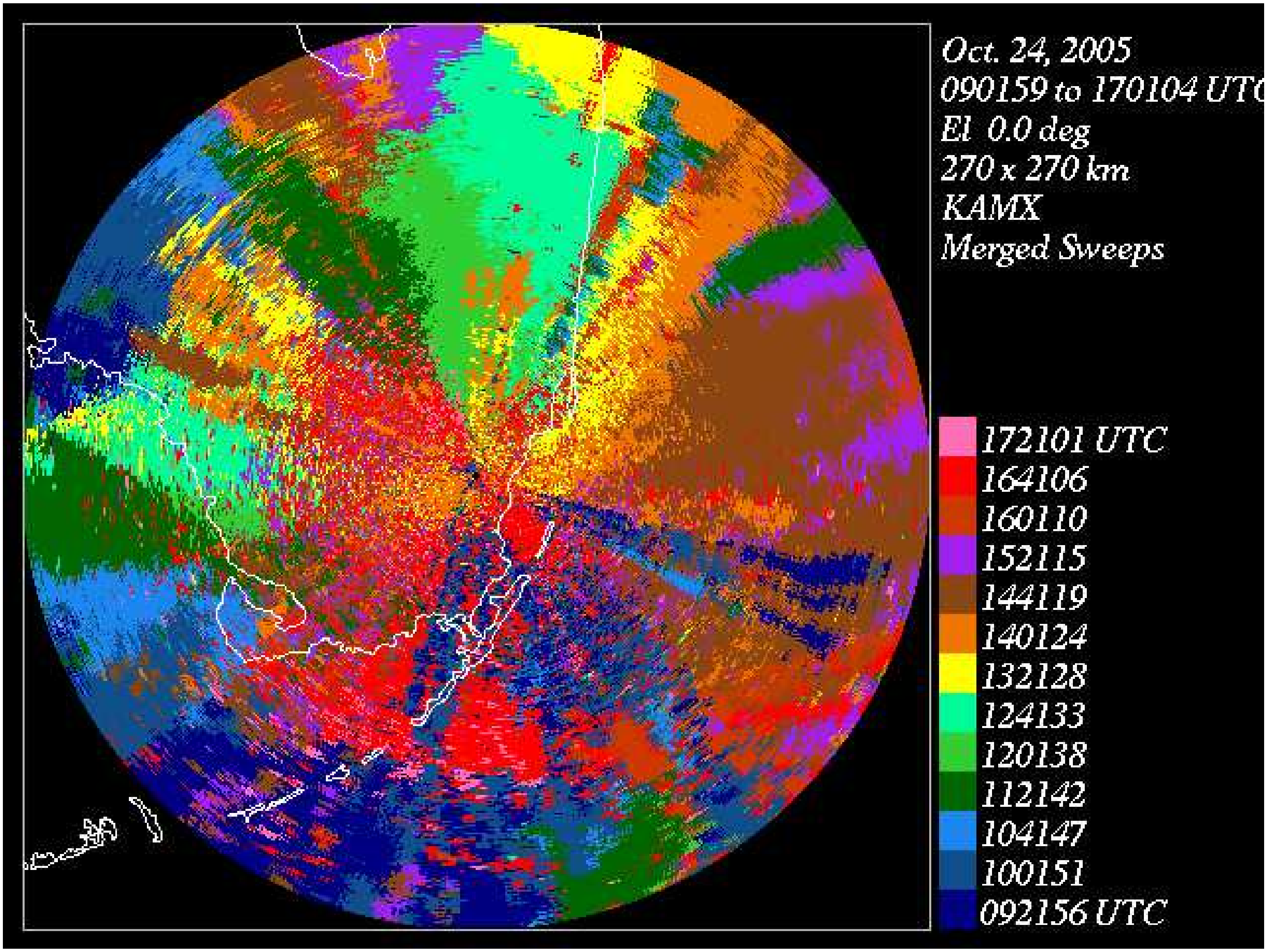


Figure 7. Time of occuence of maximum Doppler velocities within 135 km of Miami WSR-88D for the period 0900 to 1700 UTC, 24 October 2005.