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COLLABORATIVE ACTIVITIES OF THE NWS MDL AND NSSL TO IMPROVE AND DEVELOP NEW SEVERE WEATHER WARNING GUIDANCE APPLICATIONS

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1. INTRODUCTION

During 2004, a new collaborative partnership was forged between the National Weather Service (NWS) Meteorological Development Laboratory (MDL) and the National Severe Storms Laboratory (NSSL). This partnership began with the addition of an MDL staff scientist located at the NSSL. This new scientist serves as a liaison between NWS and NSSL on issues related to more rapid and seamless infusion of new science and technology to support the NWS's operational severe weather and flash flood warning decision making capabilities.

New Weather Surveillance Radar – 1988 Doppler (WSR-88D) algorithms (including multiple-radar algorithms), polarization diversity, phased-array radars, next-generation satellite sensors, 3D lightning networks, surface mesonets, and aircraft data, are all new high resolution data sources that are either already operational or due to be deployed in the next 10 years. There is a crucial need for research and prototyping of new applications that exploit and integrate these multiple-sensor observations for the benefit of NWS warning operations. Some of the new tasks to be carried out include working with NSSL scientists to establish a multi-sensor development testbed in order to prototype new multi-sensor applications suitable for short-fuse warning operations and short-range prediction with an emphasis on deep convection. New research and software development for Advanced Weather Interactive Processing System (AWIPS; Wakefield, 1998) decision assistance tools, including multiple-sensor severe weather warning decision-making applications (detection, diagnosis, and prediction algorithms) will be carried out.

Some of the current research and application development projects will be summarized. These will include the development of a new multiple-sensor hail diagnosis application and a multiple-sensor cloud-to-ground lightning prediction algorithm. Also being collaboratively developed are new display tools for viewing radar algorithm guidance information, such as new digital Mesocyclone Detection Algorithm products, and time-height algorithm trends. Additionally, work is underway to develop a novel 4D base radar data analysis tool, known as the Four-dimensional Stormcell Investigator (FSI). The FSI is being engineered to be an extension for the D2D display in AWIPS. The FSI plots native-resolution (spherical coordinate, or "8-bit") WSR-88D base data in 3D space, on a 3D representation of the Earth's globe, and users can interact with the data using a variety of tools (e.g., dynamic vertical and horizontal cross sections; 3D pan-zoom-pitch-yaw controls).

2. MULTIPLE-SENSOR WARNING APPLICATIONS

Currently, the algorithms and guidance tools available for NWS warning decision making are mostly based on single radar data, and algorithms generated by the WSR-88D Open Radar Products Generator (ORPG; Jain et al. 1998). Recent research has demonstrated that integration of multiple-radar (Zhang et al. 2001) and multiple-sensor (e.g., Mueller et al. 2003, Lakshmanan 2002) information for warning and short-tern nowcasting applications provides more accuracy and more-rapidly updating guidance output for warning decision making. Operational warning forecasters distinguish between severe and non-severe, and tornado and non-tornadic thunderstorms using a variety of data sources. Considering this, it only makes sense that the automated warning applications that are used to provide guidance also integrate multiple sources of information, including data from multiple-radars (WSR-88Ds, Terminal Doppler Weather Radars, etc), lightning, satellite, surface, upper air, and mesoscale model data. Multiple-sensor applications are not a new concept. Even though multiple-radar and multiple-sensor applications are being used to support other weather programs (e.g., aviation), the multiple-sensor concept has yet to be fully realized by the NWS severe weather and flash flood warning program.

In the past 4-5 years, NSSL has changed its emphasis in the development of new warning applications (Stumpf et al 2003a). A requirement for new warning application development includes the integration of multiple-radar and multiple-sensor information. No longer are new applications single-radar specific, except when only necessary (some radar data quality control applications fall into this category). Essentially, having more sensors "looking at" storm signatures provides oversampling of those signatures, both in time and space. This provides

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better accuracy in the detection and diagnosis of storm signatures.

Another requirement for new warning applications is to provide algorithm output at the most rapidly updating intervals possible, essentially providing ***live*** algorithm information. New applications utilize the "virtual volume" concept (Lynn and Lakshman, 2002), which essentially means that any portion of a data source (e.g., a single radar elevation scan of data) is used in any multiple-sensor integration until that data source is either replaced with new data, or the data source time "expires". Essentially, this is easiest envisioned using a single-radar data example. The algorithms are run on continuously-updating virtual volumes. Each time an elevation scan is updated, it replaces the older version, and the algorithm data are re-processed. This rapid-update capability provides longer lead-times, as users no longer have to wait until the end of single-radar volume scans for algorithm updates.

Let's consider the legacy single-radar ORPG algorithm disadvantages. Numerous NWS users have commented in online surveys that algorithm output tends to not be very useful for warning guidance, because the algorithm results are not processed until at the end of volume scans, typically 4-6 minutes after the 0.5° elevation scan data has already been made available. Algorithm updates are one volume scan apart (every 4-6 minutes), and storm evolution can sometimes be faster than that. There is poor radar sampling within cones-of-silence and at far ranges. And there is no automated tuning of algorithms (e.g., hail diagnosis) for different near-storm environments (NSE).

NWS warning meteorologists who use algorithm output to help guide their decisions may be faced with storms being sampled by more than one radar. They must make a decision as to which algorithm output from which radar ORPG to use, as these data from multiple-radars are not integrated. Do they choose the algorithm output from the nearest radar? They could be problematic if the storm is within the cone-of-silence, or a portion of the storm is obscured by terrain. Do they choose the algorithm output that signifies the "strongest" numbers? That might be at a range in which only a few elevation scans are sampling the storm, and the values may under-represent the total storm.

Multiple-radar integration offers better diagnosis of storms via over-sampling, especially in single-radar cones-of-silence, at far ranges from one radar, and in areas where terrain is blocking the beam from one radar. Multiple-radar over-sampling also has the effect of reducing, on average, the height estimates of radar information such as echo top levels (Howard et al. 1997). Output can be made available *live*, after any elevation scan from any of the radars updates. Multiple-radars and rapid updates provide for more stable tracks and trends. Products are keyed to an earth-relative coordinate system instead of the radar coordinate system. And the applications are designed to be Volume Coverage Pattern (VCP) independent. The data locations only need to be described by their physical location in 4D space, rather than which azimuth, range, elevation angle, and "volume scan number" from the single radar from which they are referenced.

Several new applications being developed at NSSL are being considered as new NWS warning applications. The first is a Multiple-Radar Storm Cell Identification and Tracking (MR-SCIT) algorithm (Stumpf et al. 2002). This algorithm extends the concepts of the single-radar SCIT (Johnson et al. 1998) into the multiple-radar realm, but combining elevation scan data (or "2D features") from multiple radars into rapidly-updating 3D and 4D detections.

An example of the benefits of multiple radar data integration is shown in Figure 1. Pictured is a comparison of one storm's cell-based VIL trend for a storm which passes through the cone-of-silence of a single radar. The single-radar SCIT trend shows a "trough" of Vertically-Integrated Liquid (VIL) values, while from the multiple-radar MR-SCIT trend we see that the storm VIL *peaked* during its passage through the cone-of-silence. The rapidly-updating output from the MR-SCIT also provided a smoother trend with more data points. The contribution of data from other radars provided a more-robust estimate of the VIL, and had the potential to significantly increase the warning lead time for this event.

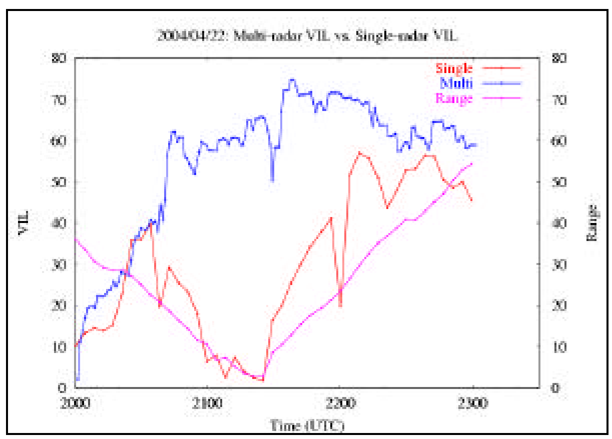

Fig. 1: Cell-based Vertically-Integrated Liquid (VIL) trends for a storm detected using a single radar (red; KINX) and using multiple radars (blue; KINX, KSRX, KTLX, KSGF, KICT). The range of the storm from the single radar is shown in magenta.

NSSL has also developed a multi-radar mosaicking application that integrates data from multiple radars (Zhang et al. 2001). The Level-II multiple-radar data are combined into a rapidly-updating 3D grid. The grids can be updated as fast as each new elevation scan update from one of the radars in the grid, making the data essentially *live*, and increasing valuable lead-time for warnings. Grid point locations sensed by more than one radar are assigned values based on various distance (via radar power) and time weighting schemes. It intelligently handles terrain blockage and interpolation in sparsely-sampled grid cells. Radar data that is several minutes old can also be advected using a sophisticated scheme that clusters reflectivity features at different size scales and compares these cluster images to images from previous times (Lakshmanan et al. 2003).

Using 3D mosaics, the advantage of multiple-radar integration in a graphical sense can be depicted. Figure 2 shows horizontal and vertical cross-sections of base radar data. Note how the data void in the cone-of-silence is filled via data from neighboring radars. The Bounded Weak Echo Region (BWER), or updraft vault, is clearly depicted in the multi-radar vertical cross section, as is a better estimate of the storm top.

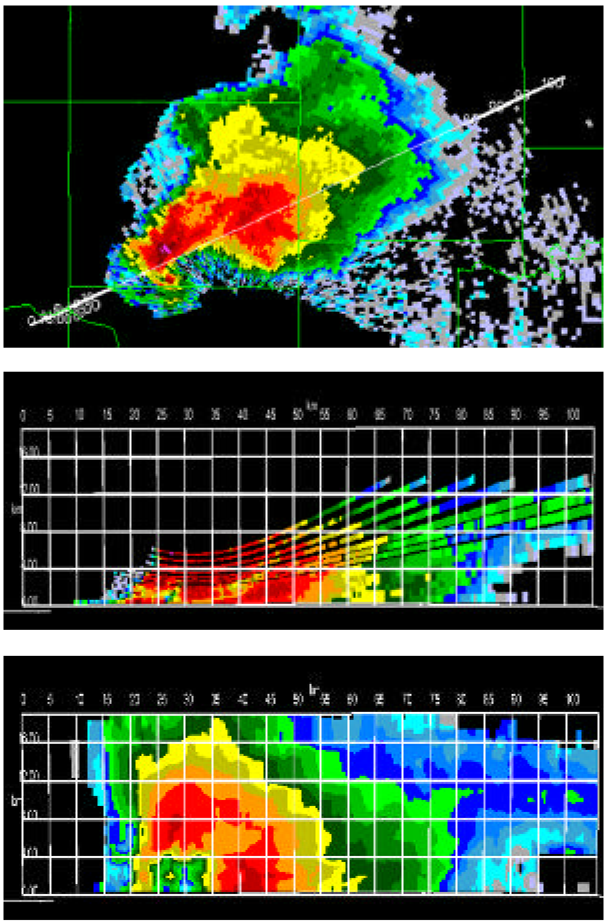

Fig. 2: Horizontal cross-section at 1 km AGL of a tornadic supercell (top). Vertical cross-section along the line shown in the top figure is shown for a single radar (middle) and for multiple radars (bottom).

The radar data are placed on a Cartesian grid, which facilitates integration with other data sources on earth-centric coordinates, including near-storm environment data from mesoscale models (important for hail diagnosis, precipitation estimation, and lightning prediction, among other things). A number of applications can then be run on the 3D multiple-radar grids, including multi-sensor storm cell detection, gridded hail diagnosis and hail swath products, and precipitation products. The mosaic can also be run on a CONUS grid, in order to provide seamless nationwide coverage of severe weather and flash flood products data (Zhang et al, 2004).

Stumpf et al. (2004) details the development of a number of new multi-sensor methods for diagnosing hail probability and size estimates, and providing geospatial gridded hail products, including time accumulations of hail swaths (Figure 3). Geospatial hail information has the potential to improve hail verification, as the location of the largest hail is more precisely known (as compared to cell-centroid based values). Ortega et al. (2005) have followed up this development work with an evaluation of the new products. Some of the basic gridded hail diagnosis products are slated to be integrated into AWIPS in the near-term (see next section).

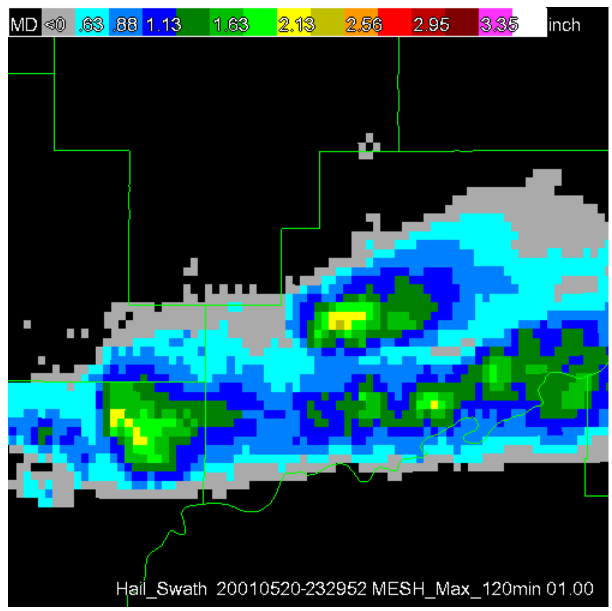

Fig. 3: 2-hour maximum expected hail size ("Hail Swath") derived from a gridded Severe Hail Index (SHI; Witt et al. 1998) product. The gridded SHI is derived from a multiple-radar 3D grid of reflectivity, and mesoscale model data for 222453 UTC 20 May 2001. Radar data are from KTLX, KINX, and KSRX.

Also for consideration for operational implementation is a scalar azimuthal shear product derived from single-radar radial velocity data and combined from multiple-radars. The technique, known as Linear Least Square Derivatives (LLSD, Smith et al. 2003) has the capability of integrating maximum azimuthal shear across a vertical depth (typically 0-4 km AGL) and across a multi-hour time period, providing a "Rotation Track" product (Fig. 4). This one image has the advantage of providing important tornado warning guidance information on both movement of rotating storm signatures and the trends of intensity over time, without solely relying on sometimes-unstable centroid-based algorithms and multiple displays. The new product has also played an important role in some post-event tornado damage verification [at Jackson MS, Norman OK, and Wichita KS WFOs, where the software was tested (Stumpf et al. 2003b, Scharfenberg et al. 2004)], and greatly lessens the time for forecasters to manually replay old radar data and track individual mesocyclones and tornado vortex signatures by hand. By overlaying street-level map data, damage surveyors can pinpoint nearly exact locations where to survey for damage, rather than hunting for the proverbial "needle-in-a-haystack" when events go unreported or underreported.

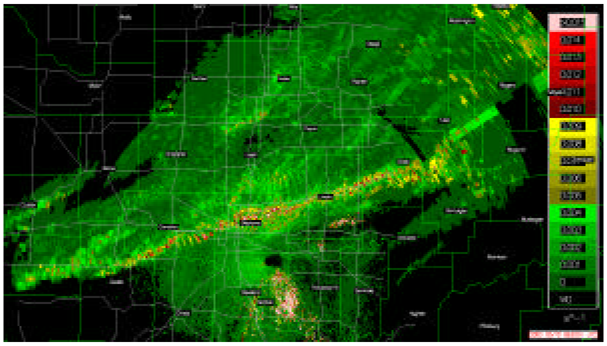

Fig. 4. Six-hour Rotation Tracks product for the 10 May 2003 Central Oklahoma tornado event.

Work is also underway at NSSL to develop a multi-sensor cloud-to-ground (CG) lightning warning application which fuses multiple-radar data, NSE data from mesoscale models (at regions of graupel growth in storms), and real-time CG lightning data (Lakshman and Stumpf, 2005). This application uses a real-time training function that compares actual real-time lightning reports to past multi-sensor data to predict the initiation and motion of future CG lightning locations. This application will be further developed and evaluated and may play a role in a future new NWS lightning warning product.

Finally, there has been a long history at NSSL to develop, evaluate, and test in real-time a Quantitative Precipitation Estimation and Segregation algorithm Using Multiple Sensors (QPESUMS; Gourley et al. 2002). This application combines data from multiple radars, NSE data from mesoscale models, lightning data, and terrain information to determine locations of optimal rain rate estimation. In "radar hostile" regimes (terrain blockage, brightband contamination in stratiform echo, mixed phase precipitation), infrared satellite precipitation estimates, adapting "on-the-fly" by comparing satellite data to "good" precipitation estimates (outside the "hostile" regions), are used. These satellite estimates are then optimally merged with the good radar-based rain rate estimates. A QPESUMS testbed will be initiated in the spring of 2005, with the eventual goal of possibly implementing QPESUMS rain rates into the Flash Flood Monitoring and Prediction system (FFMP, Smith et al. 2000).

3. NEW DECISION ASSISTANCE TOOLS

3.1 Proposed near-term upgrades to the System for Convection Analysis and Nowcasting (SCAN)

While leading-edge research and development is being conducted at NSSL, the NWS is beginning to consider some of these applications for more near-term upgrades to existing AWIPS applications. These include several VIL Density products to aid in hail diagnosis (Amburn and Wolf 1997). There will be a cell-based VIL Density product to be made available in the System for Convection Analysis and Nowcast table (SCAN; Smith et al. 1999). And there will be two VIL Density products available as gridded products. The first will be a straight vertical integration of the VIL and Echo Tops products (most likely, the "digital" high-resolution versions of these products). The second will be an enhanced VIL Density that will be derived by first applying image dilation to the VIL and Echo Tops fields (see Stumpf et al. 2004). This will aid in situations where storm cores are vertically tilted due to fast motion or high shear.

Work is presently being done to incorporate the "Digital Mesocyclone Display" (DMD) product into SCAN. The DMD product is tied to the "rapid-update" version of the Mesocyclone Detection Algorithm (MDA; Stumpf et al. 1998), and includes 2D elevation scan feature output issued at the end of each elevation scan. Time-height trends, first developed and tested using the legacy NSSL Warning Decision Support System (WDSS; Eilts et al. 1996), are being implemented in SCAN using DMD 2D feature products. This rapid-update product will allow for the display of live updates in the time-height trends, such that users will not have to wait until the end of the volume scans to populate the time-height trend plots. Alternative ways to display multiple-attribute time-height trend data (e.g., rotational velocity <u>and</u> diameter) are also being considered for implementation.

The work to incorporate rapidly-updating intermediate output from the MDA has led to a proposed idea for a "Rapid SCAN" extension to AWIPS, in which all the SCAN tables, icons, trends, and time-height trends will update in rapid fashion, after each elevation scan instead of at the end of each volume scan. The first step includes the development of a requirement to output elevation scan 2D features from the SCIT algorithm (similar to the DMD product for MDA). The new SCIT 2D feature product will include, in addition to feature centroids, the feature's areal extent. Cell areas can be used for new cell tracking icons depicting areas and cell leading and trailing edges, rather than cell centroids which typically *trail* the onset of severe weather. Cell areas can be combined in the vertical to provide storm volume information, which then can be combined with other sensor data, such as total (CG and intra-cloud) lightning data in order to trend these data in the storm volume. This new SCIT 2D product will also pave the way for the operational implementation of the multiple-radar SCIT using virtual volumes.

3.2 Four-Dimensional Stormcell Investigator (FSI)

Historically, the tools to analyze base WSR-88D radar data within the NWS Weather Forecast Office (WFO) severe weather warning decision-making environment have limited users to two-dimensional (2D) representations of the data. This is primarily because most meteorologists have been trained in the paradigm of 2D weather analysis, including radar data. Conceptual models of severe storms (e.g., supercell thunderstorms) are frequently portrayed with 2D dimensional representations and with 2D vertical cross-sections.

A multi-agency effort is underway to adapt the NSSL Warning Decision Support System – Integrated Information (WDSSII; Hondl 2002) display system as a 3D and four-dimensional (animate in three dimensions), base radar data analysis tool for NWS severe weather warning decision operations (Stumpf et al. 2004). The WDSS-II display system is designed to accurately and precisely represent radar data on spherical coordinates in three dimensions. Agencies represented in the project include NWS/MDL, NWS/Systems Engineering Center (SEC), NSSL, and the Forecast Systems Laboratory (FSL).

The *Four-Dimensional Stormcell Investigator (FSI)* will be designed to augment existing NWS 2D display. It will reduce the amount of 2D data needed for analysis and to relieve meteorologists from having to do mental two-dimensional to three-dimensional calculations. It is hoped that operational 3D visualization of radar data will allow meteorologists to discover new clues and new 3D signatures useful in the diagnosis of severe storms, including wind, hail, and tornado signatures from supercell and non-supercell storms. 3D (and 4D) visualization in meteorology is expected to produce revolutionary public benefits through increased warning skill and warning service.

The FSI will provide quick and easy access to the data, such that the decision maker can move quickly from storm to storm and extract information as the radar data volumes rapidly update (e.g., be able to choose a cross-section, and dynamically interact with one storm on the order of 15 to 30 seconds). The FSI interface will have a look and feel similar to the AWIPS Display Two Dimensions (D2D), with comparable features for animation control, product labels, keyboard shortcuts for product selection and "all-tilt" control, and colormap configuration. The radar data will be represented in its native spherical coordinate system, with no resampling to other coordinate systems or to lower resolutions. In other words, the native "8-bit" spatial resolution and data precision will be retained.

The WDSSII Graphical User Interface ('wg') is a powerful 4D data analysis tool that is used extensively by NSSL and other researchers in academia for multi-sensor severe weather application development and applied research activities. The 'wg' display functionality is built using fast and interactive 3D visualization tools available in OpenGL (www.opengl.org). For the radar data from a spherical grid, each elevation scan is mapped to a 2D cone surface OpenGL "texture" situated in 3D earth-centered coordinates. For radar cross-sections, the spherical radar data is remapped to a 2D plane surface. The 2D plane and 2D conical surfaces are then represented in 3D space, such that on-the-fly 3D navigation (zoom, pan, pitch, and yaw) about the surfaces from any viewing angle can be performed. All of these 3D view controls can be executed in a continuous fashion, allowing a user to smoothly and quickly analyze and scan threat areas faster than with point-and-click and stepwise zoom and re-center functions.

The initial layout configuration of the FSI will include four linked panels of base radar data (see display mockup in Figure 5 at the end of this manuscript). These linked panels include both 2D and 3D representations of the same data, to facilitate the migration to 3D data analysis for users who are not yet comfortable with it. The four panels will include: a) a *Plan-Position Indicator* (PPI; elevation scan data at fixed zenith view), b) a *Constant Altitude PPI* (CAPPI; user choice of altitude above radar level at fixed zenith view), c) a *Vertical Dynamic Cross-Section* (VDX; view locked perpendicular to cross-section plane), and d) a *3D Flier* (3DF).

The 3DF view depicts radar data plotted in true 3D earth coordinates. Shown will be the selected elevation angle of data in the PPI panel plotted on a conical surface, as well as any vertical or horizontal cross-section planes that are being displayed in the VDX and CAPPI panels respectively. These three data surfaces can be independently toggled off or on, and all the surfaces will be represented in 3D space with full 3D navigation controllability.

Although the atmosphere is three-dimensional, it is still difficult for many forecasters to overcome the tendency to want to view fields in the traditional 2D manner. Thus, the FSI will provide a linkage between 2D and 3D representations of the radar data through the use of interactive and dynamic cross-sections. After launching a cross section of any length or angle on the PPI or CAPPI, the user can then interact with the placement of the drawn cross section on the fly while the cross-section data displays dynamically change. Users can manipulate either end point of the cross-section reference line (on the PPI or CAPPI panel), or drag the entire reference line through the radar data while the cross-section views in the VDX and 3DF will update dynamically. The FSI will also have the capability to provide an "enhanced all-tilt", or *virtual volume* scan capability (Lynn and Lakshmanan 2002). Elevation scans from individual radars will update and replace the previous elevation scan in the virtual volume such that there is always a complete volume scan of tilts at all times. This also means that the cross sections will always contain the latest elevation scans of data and always be complete.

In order to make quick and effective decisions, the meteorologist will also have to be well versed in the understanding of the meteorological signatures associated with severe weather from a non-traditional 3D perspective. *The development and prototype testing of the FSI should be introduced concurrently with an effective training program.* Although proper training on the knobology of the FSI is required, training should more-strongly focus on the science and decision-making aspects of understanding and viewing storms in 3D, a new paradigm that can be challenging for many operational meteorologists. This training should include innovative ways to compare storm features using only traditional 2D methods (e.g., via "all-tilts"), aside the FSI methods that link 2D and 3D representations together.

The FSI will be implemented in AWIPS by running two processes. The first will be a persistent background notification server process that will populate a radar index file for the FSI display. The second will be a script to launch the display from either D2D or from the SCAN cell table. The alpha version is expected to be ready by AWIPS Operational Build 7 (OB7), which is scheduled to be fielded in the spring of 2006.

4. AWIPS EXPERIMENTAL WARNING TESTBED

The development of a testbed for experimental warning decision applications such as the FSI and new multiple-radar and multiple-sensor algorithms is underway at the MDL and NSSL. This includes the installation of the first-ever AWIPS development workstation at the NSSL in Norman OK. This AWIPS workstation machine retains the same system specifications of a LX workstation for the WFOs. The MDL scientist at NSSL will be able to work with NSSL scientists to aid the incorporation new warning application displays and products within the D2D, SCAN, FFMP, and other operational decision assistance displays.

Eventually, the MDL-NSSL AWIPS workstation will pave the way for experimental warning decision application testbed locations at several WFOs. Ideally, we propose that there should be at least one WFO testbed site per region. These sites will be used to test new multi-sensor products and displays in a proof-of-concept test setting, with the prospect of including application developers in actual warning operations so that they better understand operational warning requirements. Feedback on new products and displays can be acquired in similar fashion to the FSL real-time D3D exercises (McCaslin et al. 1999; Szoke et al. 2001; Szoke et al. 2002), and NSSL WDSS and WDSSII proof-of-concept test exercises (Stumpf and Foster 1996, Stumpf et al. 2003b, Scharfenberg et al. 2004), utilizing usage logs and user surveys.

5. CONCLUSIONS

The NWS faces enormous challenges in determining how to best utilize and integrate multi-sensor information into warning operations. The amount of data available to forecasters is increasing exponentially and will continue to do so. Concurrently, advances in information technology are driving new concepts of operations for NWS. To keep pace with these rapid shifts in paradigm and in the face of restricted budgets, this new partnership will facilitate the leveraging of federal research (and university research via the National Oceanic and Atmospheric Administration Joint Institutes) and expertise to quickly and successfully transfer science and technology into operations.

With the addition of an MDL scientist in the Norman weather community (along with two MDL scientists co-located with FSL in Boulder), we anticipate a strengthened collaboration between NSSL and MDL (and FSL) to infuse cutting edge severe weather warning research and decision support system development into NWS warning operations. We foresee that this will naturally improve NWS warning services for the public with increased detection accuracy, longer lead times, and fewer false alarms for tornadoes, flash floods, and other forms of severe convective weather.

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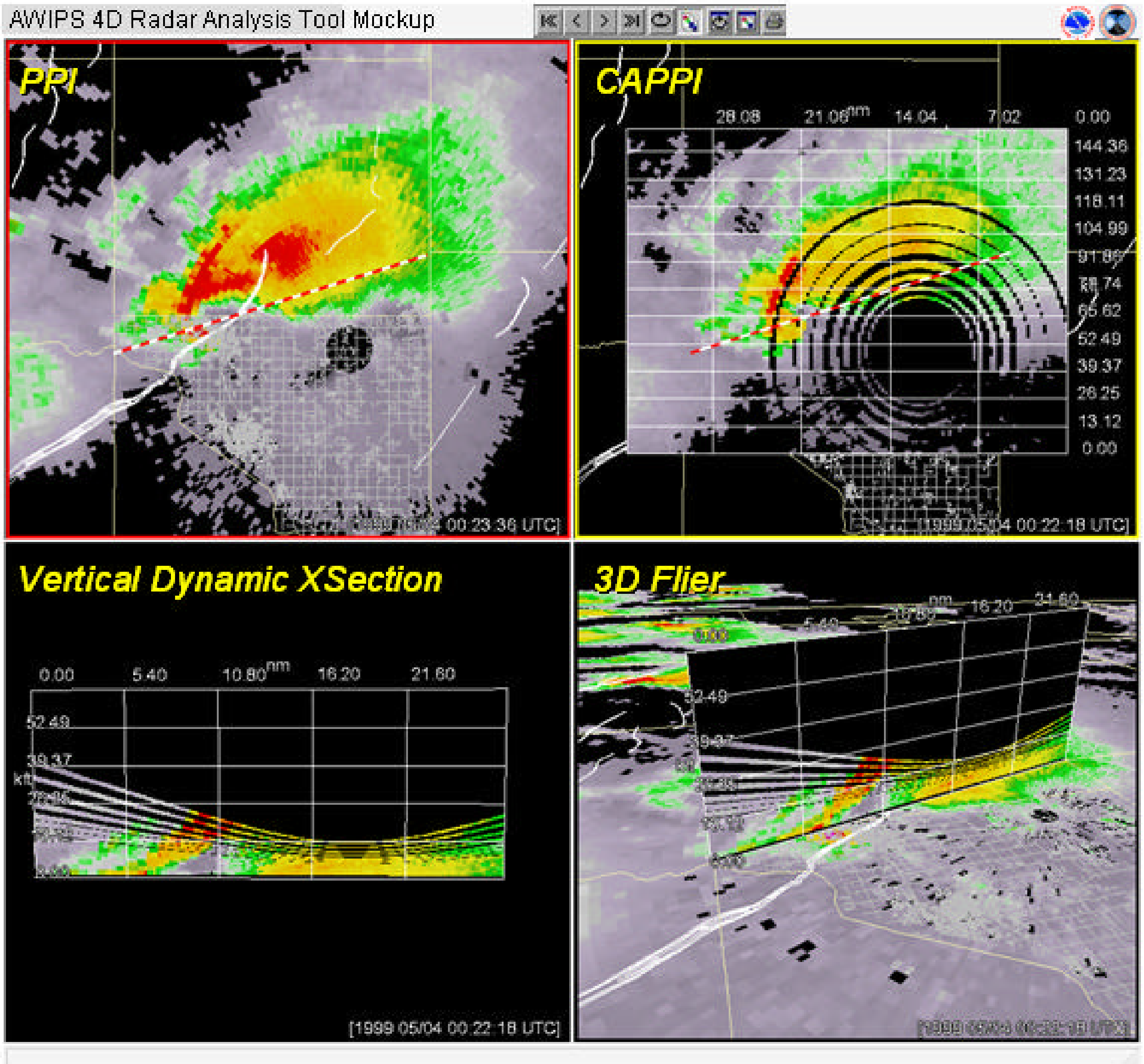

Figure 5: FSI 4-panel Display Mockup. Radar data are from 02218 UTC 4 May 1999, Oklahoma City, OK (KTLX).