Verification of the Origins of Rotation in Tornadoes Experiment

VORTEX2

Experimental Design Overview

VORTEX2 Steering Committee

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1. Executive Summary

The Verification of the Origins of Rotation in Tornadoes Experiment (VORTEX) is a multi-agency field program proposed to investigate tornadogenesis, tornado structure, and the relationships between tornadoes, their parent thunderstorms, and the larger-scale environment. The second experiment of VORTEX (VORTEX2) is proposed to take place in the United States Great Plains region during the months of April-June, 2009 and 2010. It will be conducted as a two-phase experiment. A “tethered phase”, utilizing an adaptable observation network tethered to fixed observing facilities in central Oklahoma and conducted in April and early May, will address foci having to do with storm-environment and storm-storm interactions, as well as numerical predictability. A fully mobile phase will take place in mid-May through June in a prescribed domain in the central United States, with a focus on tornadogenesis and tornado wind fields.

The first phase of VORTEX (VORTEX1), conducted in 1994–1995, resulted in well-documented advances in our understanding of the kinematic similarities between tornadic and nontornadic supercell thunderstorms and the implied sensitivity of supercells and tornadogenesis to fine-scale heterogeneity, both pre-storm and storm-induced. Recent improvements in National Weather Service warning statistics may be attributable in part to the application of VORTEX1 findings pertaining to the important role of the near-storm environment in determining potential for tornado formation.

Despite (and because of) the broad successes of VORTEX1, many new questions have emerged regarding the circulation sources for tornadoes, the role of downdrafts and thermodynamics in tornadogenesis, the dynamics of the tornado itself, and the relationship between tornadoes and larger scales of motion**.** These questions are described in the accompanying VORTEX2 Scientific Program Overview (SPO). Significant technological advances have occurred since VORTEX1, including notable advances in ground-based mobile Doppler radars and our ability to obtain thermodynamic observations using ground-based and near-ground platforms. These advances permit investigators to explore aspects of tornadoes and tornadogenesis that they could not pursue in VORTEX1. These advances have increased not only the ability to resolve small spatial and temporal scales within thunderstorms, but also the mobility of data-collecting fleets and the ability to target storms.

VORTEX2 will take full advantage of cutting-edge remote and in situ observing systems, including radar data collection from moving ground-based platforms, in situ tornado probes for profiling wind and state data, and in situ observations obtained from remotely-piloted aircraft. Furthermore, VORTEX2 includes the application of data assimilation techniques to determine better the atmospheric state.

This document provides an overview of the experimental design of VORTEX2. The scientific objectives, presented in the separate SPO document, are reviewed briefly in section 2. Section 3 describes the generic observing capabilities, as well as examples of specific instruments with these capabilities, needed to answer questions about processes occurring on multiple scales. In section 4, scientific questions are grouped according to the foci they address. Sections 5 addresses the topic of damage surveys. Experiment coordination, logistics, data management, and personnel are discussed in the final four sections.

2. Scientific Objectives

The scientific objectives of VORTEX2 are discussed in detail in the separate Scientific Program Overview (SPO) document. There are four foci: tornadogenesis, near-ground winds in tornadoes, the relationship between tornadic storms and their environments, and the numerical prediction of tornadic storms. From the experiment design perspective, these foci can be further grouped into two classes: foci that are best addressed via fully mobile storm-scale observations, and those that can be most efficiently addressed using a fixed mesoscale network of observations. Hence, the VORTEX2 Steering Committee has designed a two-phase experiment incorporating adaptable mesoscale observation and fully mobile storm-scale observation components. The first phase will be referred to as the "tethered phase" because the adaptable observing network will be anchored by certain important fixed facilities in central Oklahoma. The second phase will be referred to as the "fully mobile phase" because it will be conducted using only mobile facilities, without a "home base" per se, anywhere in the central United States. The scientific foci are described broadly in this section, along with the experimental observing strategies that will be applied.

The VORTEX2 **tornadogenesis focus** encompasses scientific objectives regarding processes of vorticity generation, redistribution, and amplification. Vorticity with a quasi-horizontal orientation is generated through the action of buoyancy gradients and synoptic-scale processes (environmental vorticity). In the tethered phase, VORTEX2 will observe vorticity generation by buoyancy gradients associated with mesoscale boundaries independent of the supercell and produce comprehensive documentation of the distribution of vorticity in the boundary layer over time periods encompassing the pre-storm and storm stages. The vorticity will be characterized through observations obtained by a network of at least eight mobile and fixed Doppler radars operating in central Oklahoma (the mesoscale experiment observing strategies and network are described in detail in a later section). Buoyancy gradients will be quantified using targeted mobile soundings, mobile mesonet and UAV traverses, and fixed mesonet observations.

Much larger buoyancy gradients typify supercell storms, where updraft cores can sometimes be more than 10 C warmer than the storm environment, and cool and hydrometeor-laden downdrafts can have effective negative buoyancy just as large. The buoyancy contrasts are associated with localized shading by the thunderstorm anvil, storm-generated boundaries in and near clouds and precipitation owing to precipitation loading, warming by condensation/freezing, and cooling by evaporation/sublimation. These intra-storm buoyancy gradients will be studied in the fully mobile phase of VORTEX2 using targeted soundings and mobile mesonet and UAV transects, and a rapidly-deployable surface sensor network. Microphysical observations, which are necessary to estimate variations in buoyancy owing to precipitation loading and phase change, will be obtained by certain UAV and mobile mesonet platforms, as well as inferred through mobile dual-polarization radar. Dual-polarization radar also will be useful for studying rear-flank descending precipitation cores, which in some cases appear to serve as catalysts in the tornadogenesis process.

Vertical-velocity gradients and convergence are responsible for reorienting horizontal vorticity into the vertical and for amplifying vertical vorticity, respectively. Both updrafts and downdrafts are involved in the reorientation and amplification of vorticity, and rear-flank downdrafts, gust fronts, and updrafts near the ground are believed to be particularly important. VORTEX2 will observe the wind field throughout the depth of the target storm, with particular emphasis near the ground at spatial intervals of O[100 m] and temporal intervals of O[1 min]. Such resolution was not attainable during VORTEX1 due to the lack of mobile, ground-based radars. As described in the next section, the critical wind measurements will be obtained with nested ground-based radars: Storm-Surveillance Doppler radars and Mesocyclone-Studies Doppler radars. Since some VORTEX2 hypotheses concerning why tornadoes do or do not develop within the mesocyclone involve relative buoyancy in the low-level mesocyclone, these radar observations will be complemented with thermodynamic observations obtained by in situ probes deployed directly in the path of mesocyclones and tornadoes.

The second VORTEX2 focus, on **near-ground winds in tornadoes**, concerns profiles of radial, tangential, and vertical motion in a variety of tornadoes (strong vs. weak, wide vs. narrow, single-vortex vs. multiple-vortex) and relationships between damage and wind speed, acceleration, and duration. The challenge of obtaining wind measurements in the lowest few tens of m AGL will be met through "targets of opportunity", in which tornadoes cross or pass near roads where narrow-beam and rapidly-scanning radars, tornado in situ probes, and photogrammetry cameras are deployed. When tornadoes are well observed by these instruments, detailed ground and aerial damage surveys will be conducted soon after tornado occurrence.

The VORTEX2 focus on **supercells and their environments** concerns environmental heterogeneity and its impact on supercell evolution, and impacts of interactions among multiple storms on tornado formation and dissipation. Although this focus could possibly be addressed through the utilization of a mobile observing system, the Steering Committee has determined that the higher quality, more scientifically valuable data sets can be obtained by observing storms as they pass through a fixed mesoscale observing system. Hence, this focus will be addressed in the tethered phase of the experiment. The scientific questions will be evaluated using wind analyses from a multiple-Doppler radar network (nine or more radars), surface fixed and deployable mesonetwork, targeted mobile mesonet and UAV observations, and targeted mobile sounding observations. These adaptable network observations will also provide the base data to be used in extensive experiments designed to **assess and improve the numerical prediction of supercells and tornadoes**, which is the fourth VORTEX2 focus. This focus also will include the assessment of parameterization errors for storm-scale models and data assimilation at the storm scale. Additional topics of interest are optimal use of observations and analysis and prediction of the pre-storm environment.

3. Description of Instruments

In this section, we describe classes of instruments that will be utilized in VORTEX2. The classes correspond to the observing systems shown in the tables and figures of Section 4 (Experiment Scenarios) and to Section I of the SPO. Each class of instruments will consist of specific observing platforms and systems that will be available in VORTEX2. Most of these systems are presently available for research applications. A few of the systems are still under development, but critical concepts and components have been demonstrated already.

It is likely that, in some instrument categories, more instruments will be available than will be required by VORTEX2 to achieve its core goals. Further, the Steering Committee has prioritized the instrument systems based on their criticality to the core scientific program. Some individual PIs have proposals that overlap in their technical capabilities (Section J of the SPO). These include multiple X-band ground-based radars, multiple dual-polarization ground-based radars, different techniques for obtaining in situ near-ground wind measurements, various sources for mobile mesonet systems, and various mobile balloon-sounding systems. At this stage of project planning, it is not known which particular systems will be supported and available. Therefore, where multiple choices exist, we describe generic system capabilities, rather than naming particular instruments.

The information below is arranged into these broad categories: Radars, airborne instruments, in situ instruments, and the field coordination system. In each category, the observing capabilities are then categorized using the same designations as are applied in the next section of this EDO.

a. Mobile radars

Several ground-based mobile radars will be used to obtain storm-scale, mesocyclone-scale, and tornado-scale observations, and to estimate microphysical properties. The Radar Coordinator (Sec. 6), who will have access to real-time mobile and fixed-based Doppler data and satellite imagery, will supervise the ground-based radar systems. These systems are described in detail elsewhere, including radar conference papers, so only overviews are provided here.

Storm Surveillance Doppler

For the VORTEX2 storm-environment focus, as well as to provide supercell context information for the tornadogenesis and near-ground wind field foci, wind analyses must be produced at a scale containing most of or the entire supercell and nearby cells (if present), with updates every 3 minutes or less. These radar observations must be resistant to attenuation, so that the wind analyses can be completed over the entire supercell. This can best be accomplished through the deployment of two or more mobile C-band Doppler radars (SMART-Radars). These offer the needed coverage, beamwidth, and attenuation characteristics for storm surveillance, and at least one of the SMART-Radars will have dual-polarization capability. In the fully mobile experiment phase, there will be occasional gaps in dual-Doppler coverage, as radars must be relocated owing to storm motion. These gaps are mitigated through the use of mesocyclone-studies and dual-polarization Doppler radars, and possibly through four-dimensional data assimilation (4DDA) techniques that do not require coordinated dual-Doppler coverage.

Mesocyclone-Studies Doppler

For the VORTEX2 tornadogenesis focus, wind analyses must be produced at the 100 m scale, with analyses extending to within 100 m AGL and updates every 60 sec or better. To obtain the data for these analyses, two or more X-band mobile radars will be used (DOW radars). During mesocyclone studies, these will be deployed near and ahead of the mesocyclone. At other times, they will assist the C-band storm-scale network to obtain continuous dual-Doppler coverage during redeployments. During tornado studies, they will be deployed in coordination with the W-band radar (below) and a rapidly-scanning radar (below) to provide dual-Doppler coverage of the tornado circulation.

Tornado Fine-scale Doppler

For the VORTEX2 near-ground tornadic winds focus, observations at very high resolution very near the ground are desired. A W-band radar (UMASS W-band), with 0.2 degree beamwidth, can measure single-Doppler winds with O[20] m resolution in tornado circulations. During tornadoes, it will be deployed in safe, close proximity to the tornado.

Dual-Polarization Doppler

Dual-polarization radar data are required primarily for two objectives. First, inferences about microphysical species and concentrations will be made for precipitation features in the rear of the supercell. Second, dual-polarization data will be combined with observations from other radars at different wavelengths to try to estimate the sizes and concentrations of scatterers in tornado debris. A Dual-Polarization Radar (NOXP) will be directed to observe these phenomena on a target-of-opportunity basis. At other times, it will be utilized to augment the general multiple-Doppler radar coverage of other storm features.

Rapidly-Scanning Doppler

Since the wind fields of tornadoes evolve very quickly, even the 50-60 sec volumetric updates typically observed by Mesocyclone-Studies Dopplers miss the details of this rapid evolution. VORTEX2 objectives related to rapid evolution of the wind field during tornadogenesis and the quantification of low level winds will use data from a rapidly-scanning mobile radar (Rapid-Scan DOW). The Rapidly-Scanning Doppler will also collect data in coordination with mesocyclone-scale and storm-scale radars to produce continuous multiple-Doppler coverage of the storm. One of the proposed Rapid-Scan radars can fully serve as a mesoscale studies radar as a multiple-Doppler node.

b. Fixed-site radars

Phased array radar

Electronically formed and steered radar beams allow for rapid scan data collection and adaptive scan strategies to maximize data collection for features of interest (e.g. tornado signatures). With the Phased Array Radar, 3-D volumetric data around the radar can be collected at 1 minute intervals and data on localized signature areas can be collected every few seconds. These data will be useful (along with other rapidly-scanning Doppler data) in quantifying rapid storm evolution during tornadogenesis. Since Phased Array Radar is a candidate system for next-generation operational radar use, better understanding of the use of the data in storm-scale numerical modeling and real-time warning applications will provide scientific results that will benefit future technology transfer to operations. The Phased Array Radar is located in Norman, OK.

WSR-88D

WSR-88D radars will have two primary roles in VORTEX2. In the tethered phase, the data from the KOUN and KTLX WSR-88D radars will be utilized in the multiple-Doppler wind syntheses. In addition, it is expected that the KTLX radar will be retrofitted with dual-polarization capabilities by 2009, augmenting those already present in KOUN. In the fully mobile phase, network WSR-88D radars will provide contextual information about supercell structure and evolution. Note that several radars in the central U.S. may be augmented with dual-polarization capability by 2009-10.

CASA

The use of large numbers of low-powered, inexpensive, X-band radars allows for rapid and coordinated scanning of storm low levels. Thunderstorm low-level wind fields (both traditional multi-Doppler processing and data assimilation processing) can be produced at 30 second intervals. These data are comparable to data produced by Mesocyclone-Studies Doppler radars and can be used for tornadogenesis focus studies. Since CASA radars are a candidate system for next-generation operational radar use, better understanding of the use of the data in storm-scale numerical modeling and real-time warning applications will provide scientific results that will benefit future technology transfer to operations. The Center for Collaborative Adaptive Sensing of the Atmosphere (CASA) radar system in Oklahoma presently consists of four X-band Doppler radars that are mounted on communication towers. This network provides multiple-Doppler wind determination capability over an area of ~70,000 km2. If possible, VORTEX2 scientists will be able to access these data, augmenting the tethered array of mobile and fixed Doppler radars.

Other

VORTEX2 will investigate the incorporation of data from various broadcast media Doppler radars located in central Oklahoma.

c. Airborne Instruments

Lower Troposphere Thermodynamics Systems

A number of hypotheses critical to VORTEX2 require in situ state observations throughout the lowest ~1 km AGL. The technology that is most suited to obtaining the needed state observations is UAV aircraft (Fig. 3.1). These aircraft have been under development for the past few years at the Research Center for Unmanned Vehicles (RECUV) at the University of Colorado (http://recuv.colorado.edu). The aircraft to be used in VORTEX2 is a long-available off-the-shelf remote control hobbyist design called the Telemaster. However, only the airframe design has been copied for the research UAVs. To better suit research purposes, the airframe is structurally hardened (to survive turbulence and hail), a much more powerful engine is used than is typical (to allow for adequate power in areas of large wind shear), an engine-driven generator will be used to supply power, and meteorological sensors are added. At least one airframe will be equipped with a next-generation microphysics imager, developed in collaboration with Andy Heymsfield (NCAR/ MMM), suitable to image cloud droplets and hydrometeors.

Figure 3.1. RECUV UAV being ready for flight at the test field.

Safety to other aircraft, as well as people and structures on the ground, is of paramount importance in this UAV design and in planned VORTEX2 operations. The aircraft will have several safety enhancements. First, it will be equipped with strobes to make it clearly visible from the ground or air. Second, it will be electronically tethered to a beacon on a ground vehicle dedicated to monitoring the aircraft visually, in the same fashion as hobbyist aircraft are operated. This point deserves repeating: VORTEX2 will use UAVs in "hobbyist" mode, under visual control, requiring no special regulation other than that applies to hobbyist UAVs (unless/until other arrangements have been made with the Federal Aviation Administration). The potential risk to manned aircraft will be less than occurs from existing hobbyist UAVs due to extra safety procedures described briefly below. The beacon tethering has been demonstrated in winter/spring 2005 under a non-meteorological contract to RECUV, and will be further tested and demonstrated in meteorological sampling deployments in a small experiment planned for 2007. The tethering will ensure that each aircraft is continuously "attached" to, and visible from, a dedicated ground vehicle. The vehicle personnel will have sampling missions that never include regions in which manned research aircraft are operating; the situational awareness display will show the positions of all aircraft including UAVs. If a UAV becomes untethered (either loss of the radio beacon tether or loss of visual contact), one of two strategies will be employed. Either the aircraft will return to the takeoff/landing site to be manually landed via radio control, or it will ballistically deploy a parachute and return to the ground unpowered. The same safety measures will be employed if the ground team loses sight of the aircraft, and/or they see any manned aircraft that could possibly enter the same airspace as the UAV. These strategies take safety beyond the typical operating modes of radio-controlled, hobbyist, aircraft.

The UAVs will be transported, launched, and landed by an experienced dedicated team from the University of Colorado Aerospace Engineering department. The ground team to which each UAV is beacon-tethered will be led by an experienced storm chaser who has been trained in the safety issues of UAV/manned aircraft operation. The Aircraft Coordinator will monitor UAV position and data.

Lower Troposphere Microphysical Systems

It is desirable to obtain particle shape and size distribution measurements in certain key areas of supercells in the lowest ~1 km. The particles of interest are raindrops. Collaboration has been initiated with Andy Heymsfield of NCAR in order to develop a particle video imager that is suitable for installation on the UAV aircraft described above. This imager is feasible with current, COTS video and laser illumination technology. There will be no requirement for telemetry of particle information during missions; target acquisition will be apparent in real time through comparison of radar reflectivity data and aircraft location.

d. Ground-based in situ observations

Targeted Soundings

A number of VORTEX2 research objectives require thermodynamic observations in specific storm-relative or boundary-relative locations. This level of targeting requires four ground-based mobile sounding systems. For example, targeted soundings are needed to sample on both sides of a mesoscale boundary or an anvil edge shadow with a spatial separation of 10-20 km, and to obtain several soundings at locations successively deeper in the forward-flank cold pool of supercells. Mobile sounding systems from several organizations have been suggested for VORTEX2.

Mobile Mesonet

Vehicle-based mobile mesonet systems were used productively in VORTEX1 (Straka et al 1996), and in more recent experiments (e.g., Lee et al. 2004, Grzych et al. 2006). Improvements in technology since VORTEX1 have enabled additional channels for additional instruments. Standard variables that are measured by these systems, while rolling or stationary, are horizontal wind direction and speed, temperature, relative humidity, pressure, and position (GPS). The temperature and relative humidity sensors are aspirated while shielded from radiation and precipitation. The pressure and wind sensors are positioned outside the vehicle slipstream. VORTEX2 will utilize 8-10 of these platforms. Observations will be broadcast across the ad hoc mobile digital network at certain fixed intervals, as well as at unscheduled intervals based on pre-specified changes in conservative variables or wind vectors.

Each mobile mesonet will have access to the situational awareness display (Sec. 7) so that individual navigators in the vehicles can position themselves according to their specific missions. The Probe Coordinator (Sec. 6) will monitor overall mobile mesonet routes and observations in order to advise teams, when necessary, of safety issues or the need to modify sampling strategies. In this way, mobile mesonet operation will be semi-autonomous.

Optical disdrometers are lightweight, durable, and relatively inexpensive, and have been shown to be accurate in several past studies (e.g. Goddard et al 1982; Bringi et al. 2003; Löffler-Mang and Joss 2000). Five of the mobile mesonet vehicles will be equipped with a disdrometer capable of measuring the raindrop sizes, amounts, and intensity. This will allow for a large number of opportunities to take measurements in a rapidly evolving environment in storms with translational speeds up to ~18 ms^{-1}. The situational awareness data (Sec. 8) that are received in the mobile mesonet vehicles will contain radar reflectivity data, allowing the vehicles to target the most interesting portions of the storm. Further, if mobile dual-polarization data depict especially interesting targets, this will be conveyed as an annotation to the situational awareness graphic. If practical and affordable, small particle imaging devices may be utilized on certain mobile mesonet vehicles as well.

Stick Net

The rapidly deployed sensor network, dubbed "Stick Net", is an array of surface sensors that is being designed to complement the vehicle-based surface-data collection. The instruments will be mounted on tripods approximately 1 m tall that can be anchored to the ground. Three to four teams in vans will work in parallel to deploy instruments in a swath ~20 km wide in the projected path of the target storm's main updraft, rear-flank downdraft and gust front, etc. Ideally, the instruments would be deployed along several consecutive roads that run mainly perpendicular to storm motion. The spacing between instrument packages will be 1-5 km, depending on such factors as storm motion, the road network, and the particular days mission. Approximately 30-50 instrument packages will be needed to allow sampling for periods of a few hours. The instruments will be retrieved while the target storm moves out of the sensor array. Owing to the time required to retrieve instruments, only one or two deployments of the Stick Net are anticipated per mission day. During the tethered phase, some of the devices will be held in reserve in case special targeted observations are required (Sec. 4). Likewise, during the mobile phase, some of the devices will be held in reserve in case tornado cyclone or near-tornado observations become possible.

The Stick Net will collect observations of pressure, temperature, humidity, wind, time, and location; the observations will be recorded by dataloggers. The Stick Net has many advantages that make it complementary to mobile data collection from vehicles: a large number and regular spacing of observations collected over a broad region, the reliability of pressure measurements obtained from stationary instruments (which will be helpful in detecting such features as low-level outflows that interact with the main updraft), and the ability to collect measurements in regions that are too dangerous for personnel (e.g., in low-level mesocyclones of high-precipitation supercells, and in and near the path of tornadoes).

In situ Tornado Instruments

In VORTEX1, in situ observations of tornadoes were attempted many times, with only one successful result (Winn et al. 1999). However, recent advances in tornado sampling (Samaras 2004; Lee and Samaras 2004) have demonstrated that in situ measurements of pressure are possible and reliable and compare well with simultaneously observed radar data (Wurman and Samaras 2004). The more recent designs have been calibrated using wind tunnels, and will be capable of sampling at 1 kHz. At least eight of these systems exist and can be deployed ahead of tornadoes. The incorporation of accurate temperature and relative humidity sensors is under development and will likely be available by the start of VORTEX2.

Alternate designs of smaller, more rapidly deployable, in situ probes may be available by the start of VORTEX2. If available, the new probes would permit the dense deployment of O[30] instruments at O[20] m spacing, ahead of tornadoes in order to further increase the probability of obtaining data within the tornado core, and to result in quasi-2D fields of near-surface T, RH, and wind inside and outside of the core flow regions, rather than the 1D sections that result from tornadoes crossing single instruments.

Another in situ device has six mini-DV format video cameras mounted to observe 60-degree sectors of the sky through glass windows. This device has successfully obtained in situ video from inside a tornado. Several improvements are required to enhance the capability of this device to obtain photogrammetry-ready images. Various technological approaches are presently under consideration, including low cost strobe photography methods. There are proposals to deploy as many as O[30] of these devices at a spacing of O[20] m in advance of a tornado in order to obtain photogrammetry-ready imagery from which vertical wind profiles and/or single-level horizontal wind vector estimates can be obtained.

Photogrammetry

Dedicated photography teams will use mini-DV format cameras to obtain images suitable for cloud-mapping photogrammetry. It is anticipated that in the fully mobile phase, two camera teams will operate in the inflow region, documenting the overall 3D cloud morphology of the low-level updraft region. These cameras may be incorporated with the mesocyclone studies mobile Doppler radars. Two will operate behind the storm, capturing the rear cumulonimbus structure so that rear-flank precipitation features derived from radar can be compared to cloud locations. Two teams will be available for close-range high-resolution videography of tornado debris motion. All cameras will be mounted on special tripod mounts that have integrated digital compasses and GPS systems. This will provide the camera location and orientation data needed for photogrammetry, reducing or eliminating the need for costly pre-photogrammetry survey work. During the tethered experiment phase, the cameras will be used on a targeted basis to provide cloud-mapping data at time and space scales smaller than generally available via satellite data.

e. Mobile Field Coordination

NSSL has developed a new class of mobile laboratory. These are ambulance-class vehicles with sufficient space, lighting, air conditioning, etc., to house 3-4 scientists, computers, and communications equipment, comfortably in the rear. The Field Coordination vehicle will be equipped with redundant communication and computer gear. It has a 10-m telescoping communication mast to significantly improve the range of radio communications. Further, it has a deployable dish for satellite broadband internet that can be deployed whenever the vehicle stops. While rolling, internet connectivity is maintained over terrestrial channels. It is possible that by 2009 the FCC will allow satellite broadband through tracking-while-rolling dish systems.

It is anticipated that the Field Coordination team will consist of a driver (and perhaps a technician), and 3 coordinators/scientists: the Information Coordinator (IC), the Aircraft Coordinator (AC), and the Mesoscale Coordinator (MC) (details in Sec. 6). Radar coordination will be conducted from one of the mobile radar platforms, and mobile mesonet coordination will be conducted from a probe-type vehicle. For convenience and economy, it is likely that the same field coordination center will be utilized in both phases of the experiment (fixed and fully mobile).

4. Experiment Scenarios

As described previously in Sec. 2, VORTEX2 data collection will consist of two phases which have been designed to optimally address the experiment foci. The first phase, to be conducted between 1 April and 10 May in both years of the experiment, is referred to as the "tethered phase". In this phase, data appropriate to the storm-environment and NWP foci will be collected. An adaptable observing network more-or-less tethered to fixed facilities in central Oklahoma will be utilized. The second phase, to be conducted from 10 May to 30 June in both years, will be fully mobile and address the tornadogenesis and tornado wind field foci.

The two phases are described in detail in this section. The research objectives are presented in terms of tightly constrained scientific questions that can be answered through the proposed experiment scenarios. The diagrams in this section include sensing systems that are essential to address the specific scientific questions. Additional sensors may be available in VORTEX2 depending on the success of research proposals from individual investigators. For more details on the sensing systems shown in the figures, see Section 3 (Description of Instruments) as well as the accompanying SPO.

NSF document length requirements do not allow space, for an experiment of this scope, to provide more than very cursory information regarding scientific questions, hypotheses, and rationale. In this EDO, we simply list the questions to be addressed, focusing instead on the required experimental design to demonstrate the feasibility of the experiment. We refer the reader to the SPO for the detailed scientific discussion.

Because this overview has been developed well in advance of the proposed field experiment, it should be expected that technologies, as well as scientific questions and hypotheses, will advance during the intervening period. Hence, in several parts of this document, we will describe baseline technological approaches and capabilities that exist today, and technologies that are expected to be available for VORTEX2 (as well as brief comments regarding the path to those technologies). To the extent that unforeseen scientific and technological developments occur between this writing and the field experiment, certain aspects of the experimental design should be expected to evolve positively. A parallel proposal to test and integrate core technologies that are critical to VORTEX2, prior to the major field campaign in 2009-10, is being submitted concurrently with this proposal.

a. Tethered phase: storm-environment focus

The scientific issues to be investigated in this focus are detailed in Sec. 5.3 of the accompanying SPO, and include both storm-environment and storm-storm interaction questions. The following is a set of focused scientific questions that investigators have posed in this focus:

a1. *Do kinematic, thermodynamic, and microphysical changes occur in storms as they cross low-level boundaries that are different than the evolution observed in storms away from boundaries?*

a2. *Is horizontal and vertical vorticity along pre-existing boundaries a significant source of storm rotation?*

a3. *Do low-level boundaries favor tornadic supercells through a combination of increased CAPE, lowered LCLs, and horizontal vorticity?*

a4. *Do low-level updraft strength and rotation decrease as mature storms encounter increasing CIN after crossing boundaries?*

It should be noted that VORTEX2 is interested in all of the observable boundary layer inhomogeneity that might be influential in supercell evolution, because at this point it is not entirely clear what kinematic structures constitute what is conventionally called a mesoscale "boundary".

In the tethered phase of VORTEX2, observations will be obtained on every day deemed to have the potential for supercell convection in the domain (Figure 4.1). This will include both the

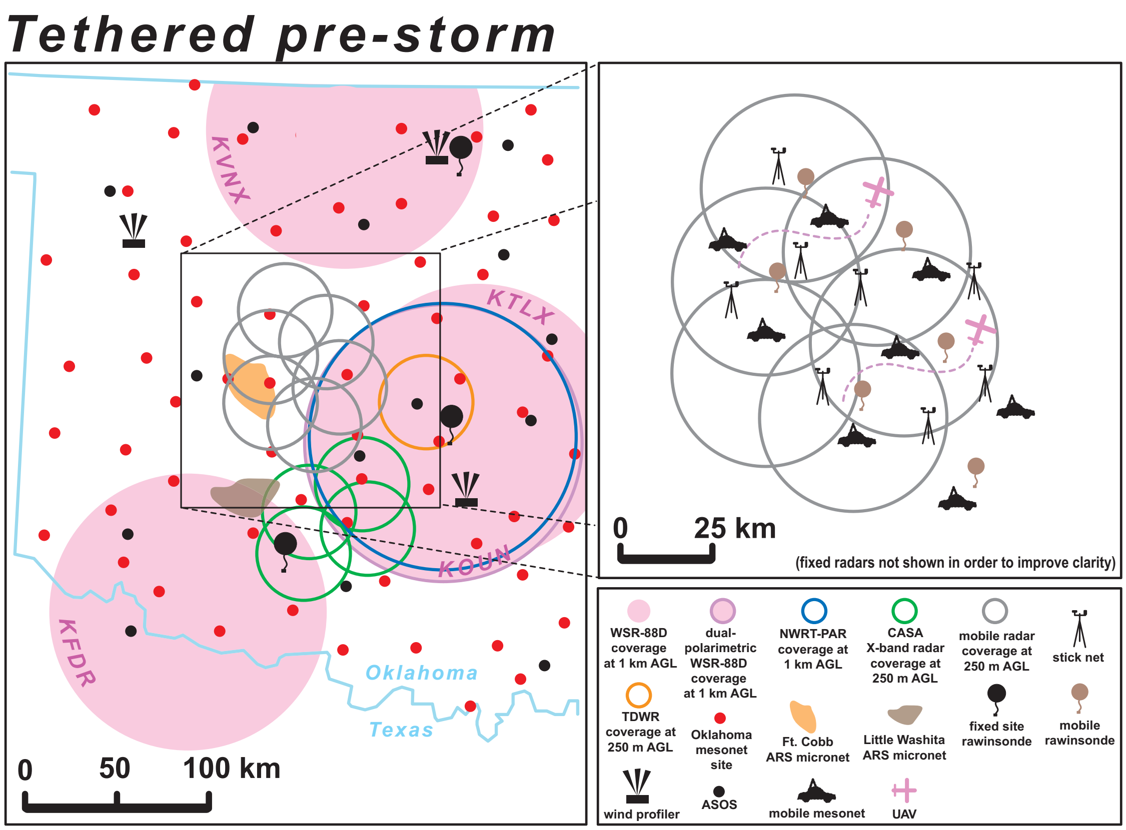

Figure 4.1. Example deployment during the tethered phase prior to storm formation. Symbols as shown in the legend.

possibility of initiation within the domain, as well as storms moving into the domain. On every operation day, a radar network will be constructed by positioning all available mobile Doppler radars at pre-surveyed sites suitable to provide baselines of about 20-30 km. Data collection will commence at least two hours prior to the forecasted time of storm initiation or arrival of storms in the tethered domain. This is necessary to document the evolution of boundaries and other boundary layer phenomena in relation to the forcing of those features, as well as ensuring that the network is fully operational by the time convection commences. The constraints on the locations of mobile Dopplers will include the degree of beam obstruction, as well as the necessity to provide the maximum amount of dual-Doppler (or multi-Doppler) wind synthesis data in the lower boundary layer. In all cases, we seek to obtain wind data down to at least 250 m above ground level. The network will be adaptable in the sense that the surveillance emphasis can be shifted in any direction from the anchoring fixed-site radars in central Oklahoma. In most cases, the network will remain in the same configuration throughout an observing day. Hence the radar network will be utilized to obtain high-resolution 3D wind mappings of the scatterer-filled boundary layer, as well as troposphere-deep observations of precipitation, with update periods of around 3 min. during clear-air periods, and 5 min during precipitation. The Doppler network observations will provide complete quantification of the boundary layer vorticity structure and its variability. Scans will be coordinated to the degree possible. The likely strategy is to attempt to have all radars start scans at the same time based on the start time of (e.g.) the KTLX WSR-88D. Radars that have shorter volumetric scan times will attempt to obtain integer multiples of volumes during the 88D volume period.

The radar network will be configured after careful consideration of the desired total coverage area, minimum acceptable spatial resolution, and maximum acceptable lowest coverage height (probably around 250 m AGL) given the scientific objectives.

In addition to the Doppler network wind observations, other useful observations will be routinely collected on operations days. These include serial sounding releases from four-six mobile sounding units, surface observations from roughly 30 mesonet sites, and six-minute wind profiles from the Purcell 405 MHz wind profiler. Any gaps in surface mesonet data that are deemed to be problematic on a given operations day may be filled using mobile mesonets and Stick Net systems that are deployed to fixed, well-exposed sites. The surface mesonet observations will be useful for quantifying the degree of near-ground baroclinity across the tethered domain, and the sounding releases will help quantify the mesoscale variability and conventionally understood supercell potential of the troposphere above the boundary layer.

When mesoscale boundaries or other potentially significant low-level features are identified in real-time via the mobile Doppler network, satellite, or surface mesonet data, certain sensing systems will be targeted to those features. An example of a deployment scenario that will be utilized is shown below (Fig. 4.2). In this example, a boundary is present and targetable. Mobile mesonet vehicles will be deployed to obtain transects of the boundary. Logistics permitting, UAV aircraft will also be utilized to obtain thermodynamic cross-sections of the boundary by utilizing a "flying tower" formation where aircraft are flown one above the other at heights of (e.g.) 150, 300, and 500 m. Mobile sounding systems will be redeployed to sites straddling the boundary and continue serial sounding launches.

The following additional questions pertain to the role of anvils and forward-flank processes. Some of these questions could perhaps be classified as belonging to both the tornadogenesis focus as well as the storm-environment focus, but all can be readily addressed with tethered-phase observations:

> *b1 Are baroclinic zones associated with daytime anvil shadows, but not observed at night in the same storm-relative locations?*

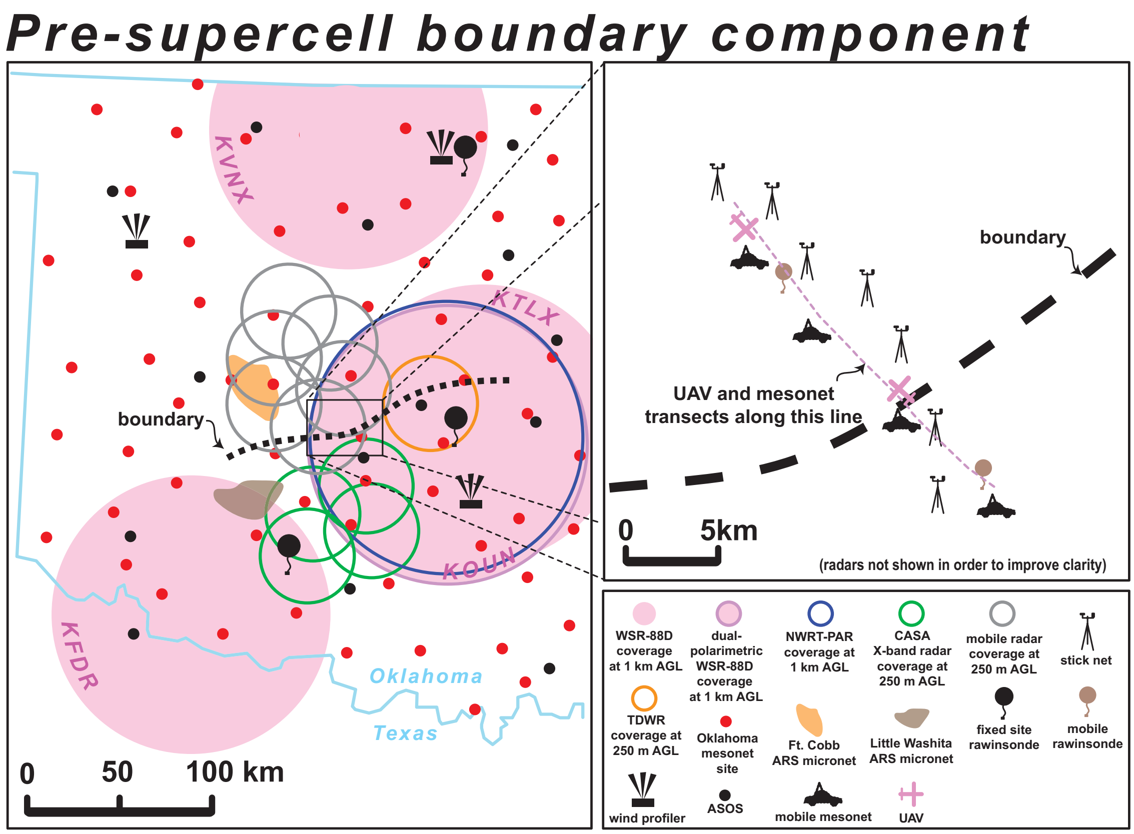

Figure 4.2. Example of a deployment to observe a boundary that is detected in satellite, radar network, or surface network data prior to deep convection. Stick Net symbols denote a general deployment area; more instruments will be utilized than can be shown here.

b2 Does baroclinity associated with anvil shadows generate enough horizontal vorticity to affect low-level updraft rotation?

b3 Does the anvil-shaded boundary layer have eddy character that is significantly different from the nearby sunlit boundary layer?

b4 Does the low-level vertical shear of the horizontal wind vary across the inflow region, and is it larger than that of the storm environment?

b5 What is the typical magnitude of forward-flank baroclinity, and does the generated horizontal vorticity contribute significantly to mesocyclone strength?

b6) Is updraft and mesocyclone intensification in a supercell associated with a mature cell merging into the forward flank? Is storm demise associated with a merger into the rear flank? Are these different behaviors related partially to microphysical interactions?

These questions focus on the conditions and processes of the forward-flank region of supercell storms. As detailed above, the observing network will be in place and operating well in advance of the time of the onset of moist convection in the domain. Troposphere-deep observations by the Doppler network will continue until convection ends. However, as storms develop or move into the domain, some of the sensing systems will be relocated to obtain focused observations related to questions b1-b6 above.

As storms develop or move into the domain, the coordination team may choose one storm as a target for more intensive forward-flank observations (Fig. 4.3). Both storm/anvil structure and

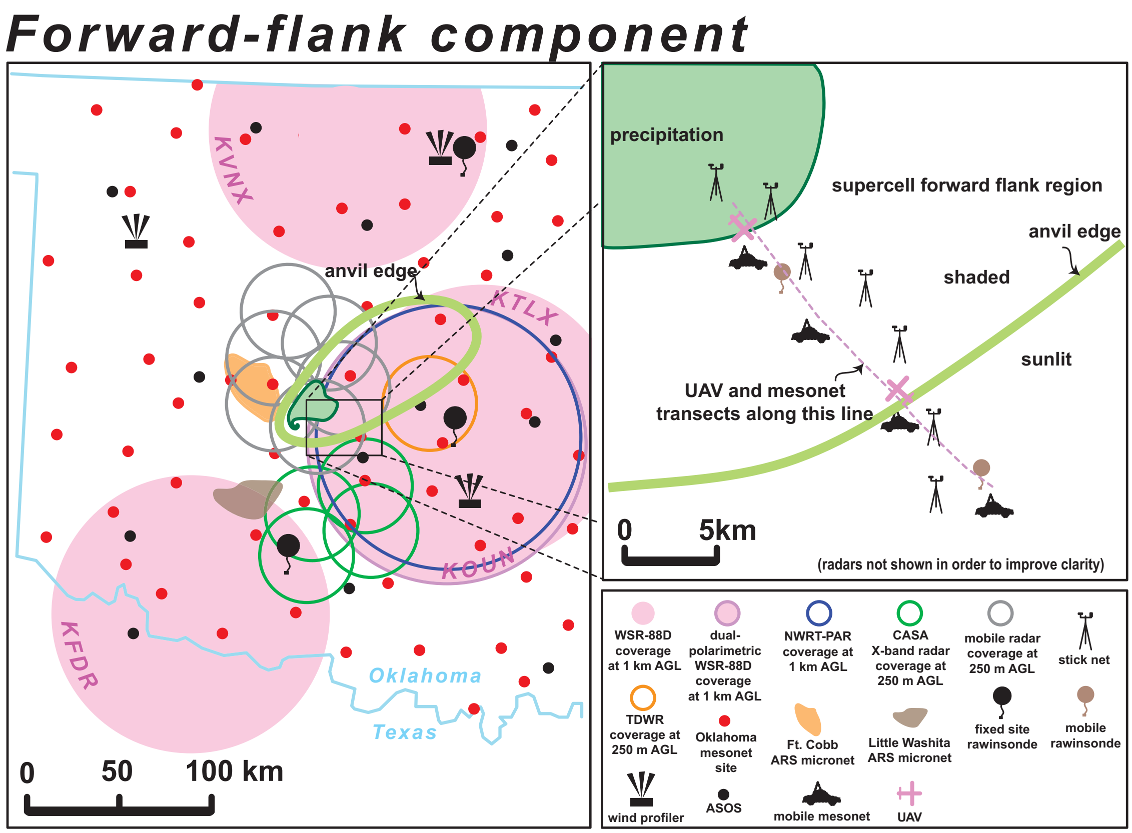

Figure 4.3. This figure illustrates the forward-flank focused observations that occasionally will be conducted during the tethered phase. The small-scale inset illustrates the forward-flank region of a supercell. UAV, Stick Net, and mobile mesonet observations will be obtained in the same cross-section. The exact positioning will depend on road availability.

evolution, as well as road/accessibility issues will be considered. The questions concerning forward-flank baroclinity will be addressed using surface observations collected with targeted mobile mesonet transects, the Stick Net, and mobile sounding systems obtaining targeted ~simultaneous soundings. In addition, UAVs will be used when feasible to obtain thermodynamic data in the above-ground boundary layer. In general, all of these systems will be utilized to obtain data in the same forward-flank cross-section as shown in Fig. 4.3. The cross-section will generally extend from the sunlit area immediately outside the anvil-shaded region into the forward flank precipitation.

On certain occasions, the targeted forward-flank strategy shown in Fig. 4.3 may be superseded by observations targeted at question B6 related to storm mergers. In general, the process of storm merger will be fairly well observed using the Doppler network. However, it is of interest to document how the cold pools (if they exist) of the two storms interact or influence the evolution of the cells. Hence, if the coordination team believes that a merger is likely, it will direct mobile mesonets, UAV teams, and mobile sounding teams to certain locations to perform data collection (Fig. 4.4). This will necessarily be a fairly *ad hoc* deployment based on observed and projected

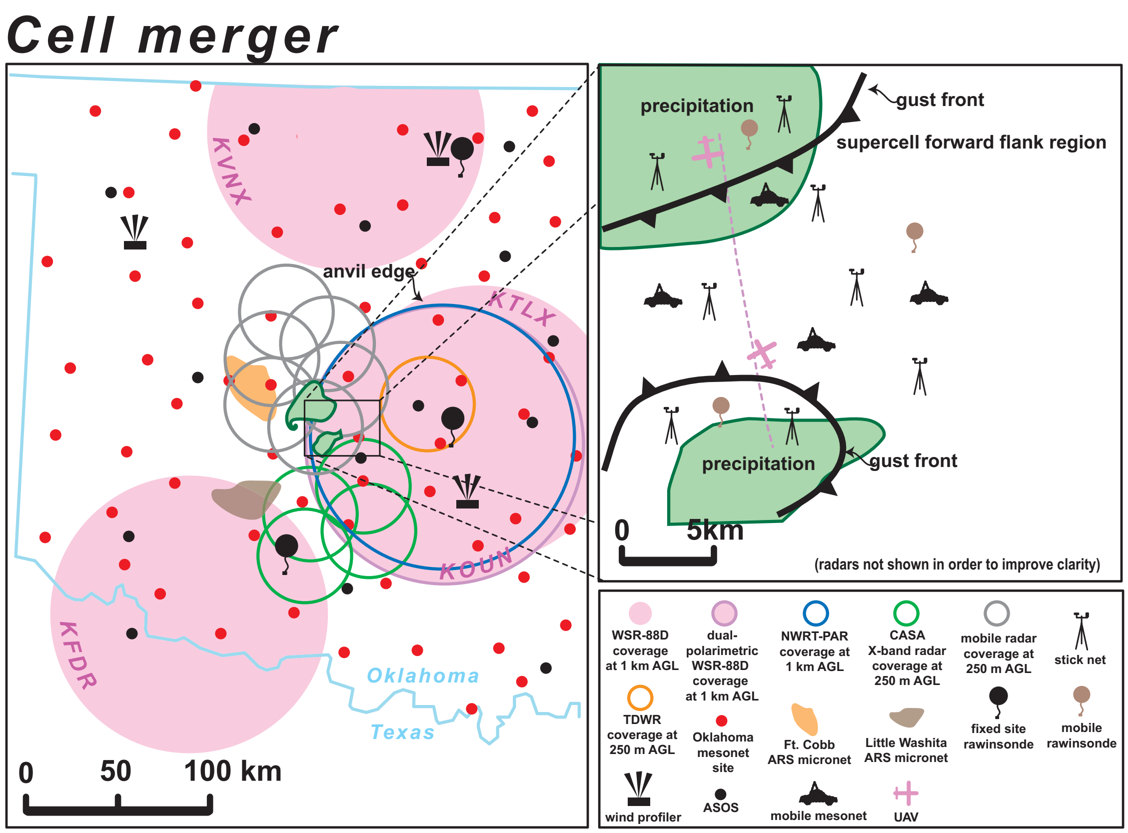

Figure 4.4. Example focused deployment of observing systems when cell merger is expected. The inset shows various instruments in the region where merger is expected to occur, including three mobile sounding systems to sample the cold pools of the two cells as well as the ambient airmass.

cell motions. The objective will be to obtain as much low-level thermodynamic data as possible in the vicinity of the cold pools and gust fronts near and below the merging updrafts. Coordination of this strategy will rely heavily on real-time Doppler depictions of low-level precipitation and gust fronts (Fig. 4.4).

b. Tethered phase: NWP focus

The reader is referred to Sec. 5.4 of the SPO for detailed information regarding the NWP focus. In general, the observations required to provide data for various NWP experiments are those collected for the storm-environment focus described above. At this time, no unique observing strategies have been specified for the objectives of this focus beyond those already described for the storm-environment focus. However, certain parts of the observing system can be adapted to particular NWP experiments, such as the placement of the mobile sounding systems, the frequency of soundings, etc. Some PIs have proposed augmenting the tethered network with dropsondes to investigate mesoscale features such as boundaries and to support the NWP experiments. The current experiment design and coordination plan readily supports the incorporation of dropsondes.

c. Mobile phase: tornadogenesis focus

The fully mobile phase of VORTEX2 will be conducted in both years of the experiment during the period 10 May to 30 June. It will operate wherever supercells are expected in the domain shown in Fig. 4.5. There will be no "home base" per se, but three equipment

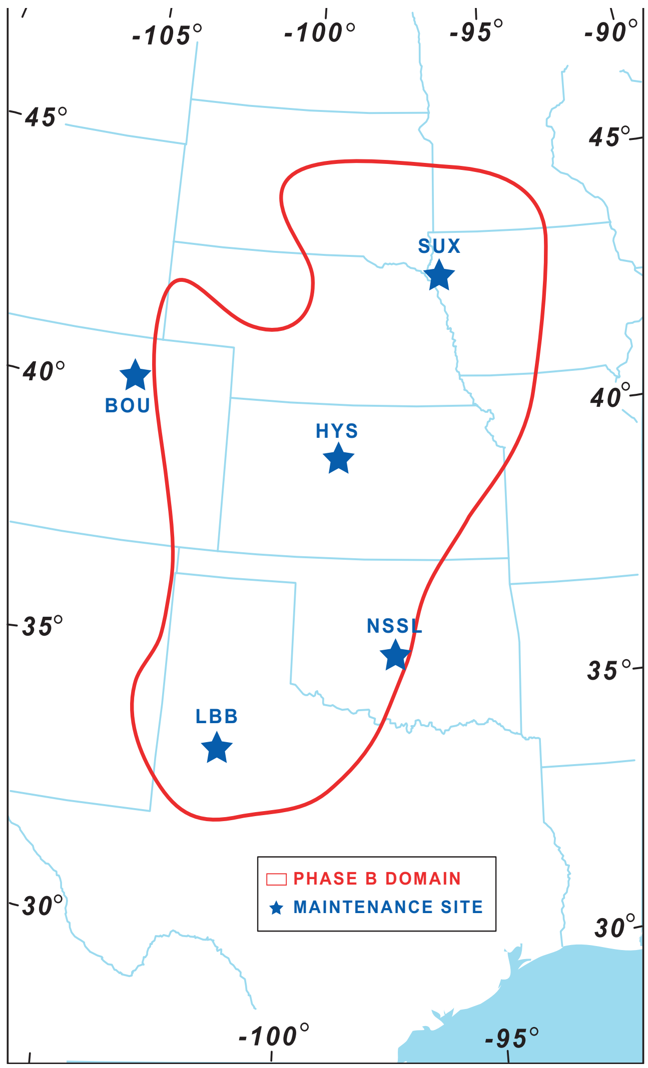

Figure 4.5. Domain of the fully mobile experiment showing potential maintenance depot sites.

maintenance sites will be rented that will serve as shops to make minor repairs on vehicles or instruments. Normally, supercells occur in the same region for several successive days depending on the presence of the dryline, stalled fronts, etc. Once a severe weather regime ends in a certain region, the mobile observing systems will ferry to the next region forecasted to have supercell activity. Logistics of coordinating the mobile observing are detailed in Sec. 6.

On a given operations day, the coordination team will make an early-morning targeting decision, and all mobile sensing systems will proceed toward the target region (~100 km diameter area). As deep convection begins to form, the mobile systems will be targeted to a particular developing storm, and will then proceed to collect observations until a new target is selected or operations cease.

The operational philosophy is fairly simple and relies largely on field teams carrying out their missions based upon the information assimilated and distributed by the coordination team. During the duration of observations, the mobile C-band Doppler radars will collect observations of the entire storm to provide contextual dual-Doppler wind syntheses and precipitation observations. To the extent possible (allowing for redeployment, setup, takedown) coordinated dual-Doppler scanning will be done with these radars. The aim will be to maximize the duration of the dual-Doppler observation periods. All other mobile observing assets will be focused on the updraft/rear-flank region of the supercell, with a few specialized teams on standby beneath the updraft for tornado observations (see below). The intent will be to observe the supercell updraft, mesocyclone, and rear-flank processes from about the time of the onset of the mesocyclone and/or weak echo region until the storm is no longer observable because of safety or logistical considerations.

The tornadogenesis focus is designed to address these questions:

c1. Is the local lifting (arching) of vortex lines near the rear-flank gust front a necessary and/or sufficient condition for tornadogenesis? Is the tilting of inflow streamwise vorticity a necessary and/or sufficient condition for tornadogenesis?

c2. Does negative buoyancy exist in the rear-flank downdraft aloft, but weaken or become positive near the ground?

c3. What is the orientation and magnitude of baroclinity above the ground near typical mesocyclones?

c4. How are RFDs related to vortex-line distributions? How do the patterns vary from storm to storm?

c5. Are small-scale (~ 2 km) descending precipitation cores at the supercell rear flank a forcing mechanism for RFDs?

c6. What are the dominant forcings for RFDs, as a function of location within the RFD, stage in storm evolution, and supercell type (e.g., tornadic vs. nontornadic, LP vs. HP)?

c7. What role does entrainment of environmental air play in tornadic supercell RFDs? How significant are microphysical variations?

c8. Is vorticity generation during the vortex-maintenance stage different than during the genesis and demise stages?

c9. What are the differences in vorticity generation processes between short-lived and long-lived tornadoes, and between strong and weak tornadoes?

c10. Does tornadogenesis require a balance between low-level buoyancy and angular momentum in the incipient vortex?

c11. What is the role of vortices along the rear-flank gust front in tornadogenesis?

An example of a deployment strategy to gather data to address these questions is shown in Fig. 4.6. Each mobile observing team will have specific science-related goals, and will

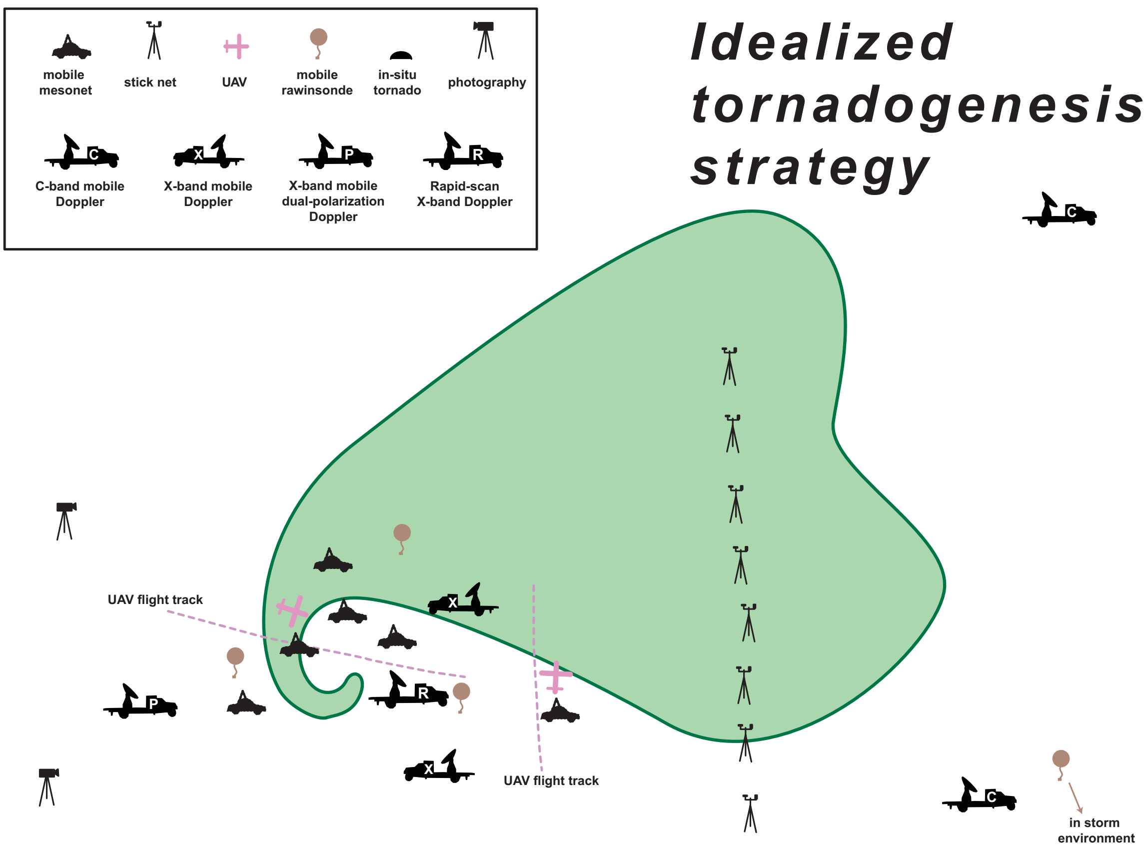

Figure 4.6. Idealized schematic of a deployment to gather data for the tornadogenesis focus. Stick nets will be deployed at a smaller spatial interval than shown (more sites than in the schematic), and likely along several north-south roads. The considerations for various deployment sites are discussed in the text.

choose their optimum deployment strategies based on those goals, the available road network, storm evolution, and safety. The mobile radars require a significant amount of collaborative communication to ensure adequate baselines and coordinated scans, and this activity will be managed by a Radar Coordinator in the field.

In the idealized deployment and in a general sense, the two X-band mobile Dopplers (DOWs) will be deployed to document the 3D wind field in the region of the low-level mesocyclone, encompassing the base of the storm updraft, the rear-flank downdraft and attendant gust front, and the region of significant rotation. As with all of the sensors, the actual deployment sites will vary greatly in part because the storm will be moving with respect to the radars as they collect data, and in part because of limitations in the road network, clutter considerations, and safety concerns.

The mobile C-band Dopplers (SMART-Radars) will be deployed on a much longer baseline to document as much of the supercell as possible, for the longest dual-Doppler observing periods as possible. Often, the baseline may be parallel to the storm motion with the radars observing from the inflow side. But the actual deployment positions will be determined based on real-time considerations.

The X-band dual-polarization Doppler radar (NOXP) will typically follow the storm from behind to minimize attenuation through the rear-flank precipitation, which often occurs in a band of a few kilometers thickness. In storms that tend toward the high-precipitation end of the supercell spectrum, this radar will be deployed ahead of the mesocyclone, again to minimize attenuation. The goal of this system is to obtain data which can be used to infer the hydrometeor species and concentrations in the rear-flank region to produce new knowledge of the role of thermodynamics in forcing the rear-flank downdraft.

The rapidly scanning mobile Doppler (Rapid-Scan DOW), as well as the W-band mobile Doppler (UMASS W-band; not shown in Fig. 4.6 for clarity) will be kept in proximity to the strongest low-level rotation in order to be ready to collect tornado wind field data should a tornado form.

The mobile mesonets will each have a storm-relative area that they will sample. For example, one will sample the hook echo and most intense outflow to the right of the low-level mesocyclone, another will collect data in the precipitation immediately trailing the mesocyclone, and yet another will seek regions of large temperature contrast in the core immediately to the left of the mesocyclone. To the extent feasible, mobile mesonet vehicles will be equipped with disdrometers and/or other means to document precipitation location and intensity.

Complementing the mobile mesonet observations which are highly targeted and phenomena-specific, the Stick Net will be deployed to obtain observations on the 1-10 km scale as the storm passes over the deployment lines along multiple roads. This ~linear deployment will provide a set of time-series of near-ground state information which can then be converted into a two-dimensional spatial analysis using time-to-space conversion, subject to the constraints of storm steadiness. Note that a portion of the Stick Net instruments will be held in reserve for smaller-scale deployment near developing tornado cyclones and/or tornadoes, and that the symbols in the diagram represent a general area for deployment, not all of the individual systems.

In the fully mobile phase of VORTEX2, UAV aircraft will be operated whenever feasible. In all cases, the aircraft will be electronically/digitally tethered to a surface vehicle, and will fly generally above the vehicle and within visual range of a UAV specialist in the vehicle. Several deployment scenarios are being considered. In one, 2-3 UAVs will fly in a “mobile tower” formation above a surface vehicle to obtain thermodynamic cross-sections in regions of interest as shown in the diagram. In another plausible scenario, individual UAVs are tethered to separate vehicles to sample larger regions. It is hoped that in addition to thermodynamic observations on scales < 100 m, one or more UAVs will be equipped with particle imaging systems for assessment of low-level hydrometeor character.

Stereo photogrammetry will be utilized to produce maps of important cloud features. In particular, cameras near the sites of the mobile X-band radars will provide data suitable for mapping the general low-level updraft cloud base, dust whirls or outflow dust, etc. Two cameras will also be situated behind the storm to photograph the main updraft cumulonimbus column when feasible. These cloud mappings will be compared to radar reflectivity information to determine the relative spatial positions of rear-flank precipitation and cloud. All camera systems will be equipped with digital compass tripods and GPS units to record camera orientation and location, precluding the necessity of pre-photogrammetry field survey work.

The purpose of the mobile sounding systems will be to obtain soundings in regions that might be representative of extremes in the temperature distribution around the storm. One sounding will be in the storm environment to assess the usual thermodynamic environment contextual information for the supercell. Another sounding system will focus on updraft soundings to represent the warmest vertical profile of the storm. A third will attempt to obtain soundings in the coolest part of the storm cold pool to the north of the mesocyclone. And a fourth will obtain soundings in the area of the forward flank precipitation to address research questions related to forward flank baroclinity.

d. Mobile phase: tornado wind field focus

All of the observing strategies described above will continue when a tornado develops. However, certain additional observing systems will be deployed once a tornado cyclone forms and tornadogenesis appears likely. These finer-scale observation strategies, mainly aimed at addressing questions regarding the tornado wind field, are illustrated in Fig. 4.7. These scientific research questions are to be addressed:

d1. Are the broad aspects of the corner-region conceptual model correct? Is the corner-flow swirl ratio related to tornado-core structure?

d2. What is the relationship between observed winds and structural damage?

d3. What is the vertical wind profile in the corner region?

d4. What are typical temporal and spatial variations of flow within tornadoes?

d5. What is the distribution of radar scatterers in tornadoes, and can this information be used to derive Doppler velocity corrections?

All of these research questions can only be addressed by close-range deployment of in situ sensors, W-band and rapidly-scanning mobile Doppler radars, and high-resolution video cameras for photogrammetry. The deployment illustrated in Fig. 4.7 is completely hypothetical, because to a very great degree the actual deployment positions will depend on operator safety, the road network, and the very large time constraints involved with collecting data on a developing, moving tornado.

There are general principles which will guide the sensor deployment decisions by various teams. The W-band radar will require a reasonably unobstructed view of the tornado in the lowest few

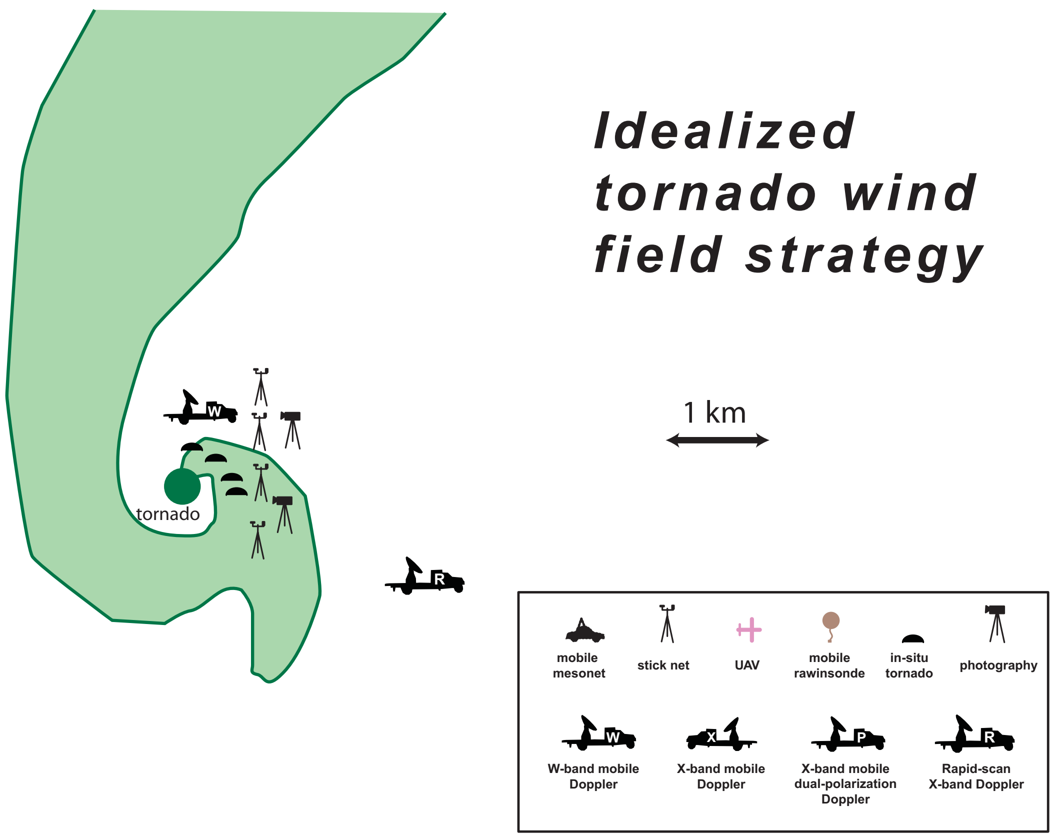

Figure 4.7. Idealized deployment of sensors to collect observations for the tornado wind field focus. More Stick Net systems will be deployed than space permits in this illustration.

meters above the ground. Similarly, the rapidly-scanning radar will be deployed based on safety and clutter considerations.

In-situ tornado sensors are always deployed wherever the operators can safely stop a vehicle and deposit a sensor. The aim is to try to get the sensors in the path of the tornado so that they take a direct hit, and larger numbers of sensors ensure that at least the tornado cyclone is sampled if not the tornado itself. As many stick net instruments will be deployed as can be safely deployed, and this means that the deployments will likely be along paved roads where the team can move quickly from site to site. The stick net instruments should provide good documentation of the near-ground tornado cyclone wind field and thermodynamic fields, also important for research questions c2 and c10 in the previous section.

When a tornado forms or appears imminent, two photography teams with digital-compass tripods and GPS will be deployed to near the vortex to obtain high-resolution video of the low-level vortex. Photogrammetry can be used to determine the windfields in parts of the vortex that are observed simultaneously from two angles, with the assumption that tracers like dust and puffs of condensation are moving with the wind and not being centrifuged strongly.

Again, the deployment illustrated in Fig. 4.7 concerns the near-tornado instruments. The other mobile platforms continue to gather the same larger-scale data during the tornado stage as illustrated in Fig. 4.

5. Damage Surveys

Several VORTEX2 investigators require detailed damage surveys. It is expected that these investigators will lead and coordinate the damage survey work. If at all possible, all other field personnel will be made available to these investigators the day after a damaging event to participate in damage documentation. However, in many cases, this will not be possible owing to field operations. The VORTEX2 Logistics Coordinator will work with the damage survey leaders during the first ~12 hours after an event in order to coordinate access to the damaged area with local emergency managers and law enforcement. If possible, aerial photography will be arranged to help map the damage path.

6. Experiment Coordination

a. Forecasting and operational decisions

During periods of active weather and field operations, a small team of expert severe weather forecasters will develop VORTEX2 forecasts. In the tethered phase, the main forecasting issue will be the probability of supercells in the tethered domain. In the fully mobile phase, the forecasting problem becomes considerably more complex with areal probabilities required throughout the central United States, for several forecast periods. The individual forecasters will develop independent opinions concerning general target areas and probabilities. Then, the forecasters will meet to develop a consensus forecast which will be discussed with a small group of field leaders in order to decide the day's operational plan and target area, if any. It is anticipated that most decisions will be reached by consensus, but a daily "PI-in-charge" determined by a rotating schedule will be responsible for breaking deadlocks when timely decisions are needed. The mobile VORTEX2 experiment will move with the active weather regimes across the domain in the central U.S. Typical examples might include an active regime on the southern High Plains dryline or a stationary front in the northern Plains. Hence, the mobile experiment should generally not be far from the target region at the start of the day. This concept is discussed more in Section 7 under the heading "Logistics of Full Mobility". The daily general operational decision will be made by 0900 LT to allow for travel to a new target region if needed (see the timeline, Fig. 6.1).

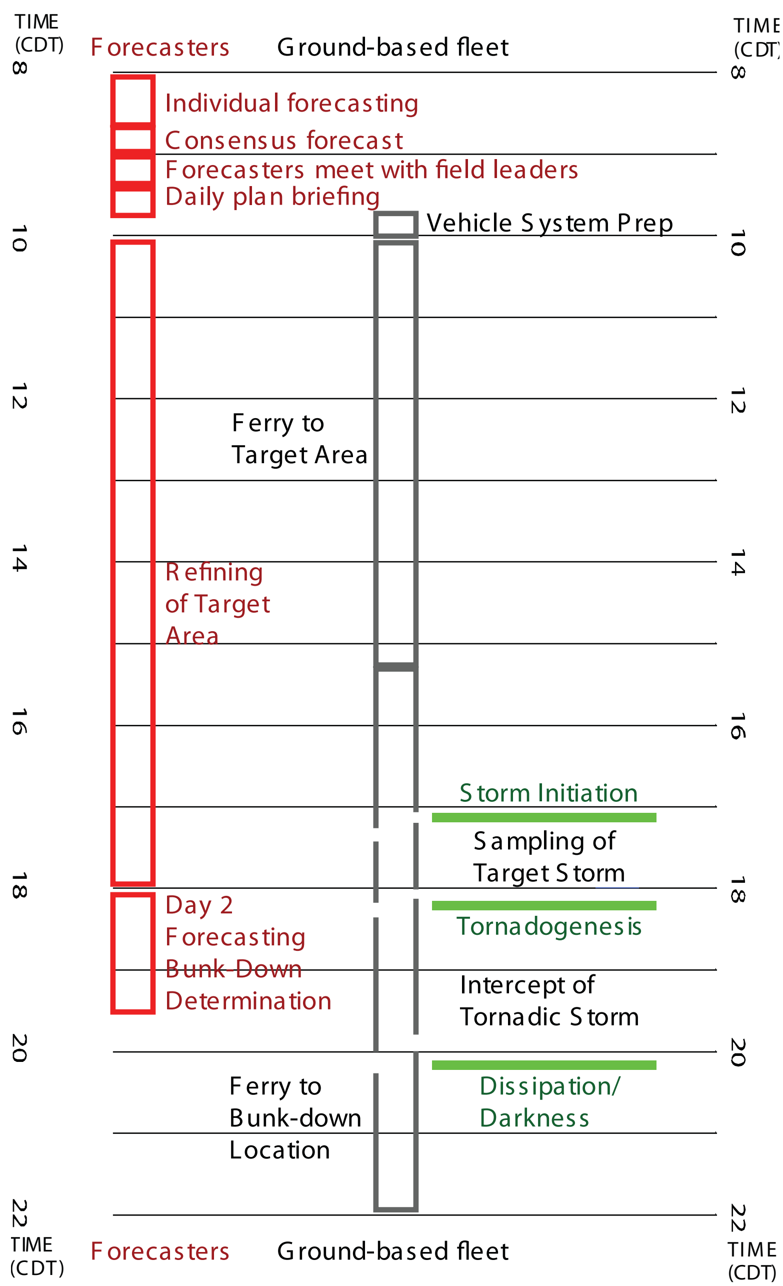

Figure 6.1. Timeline for daily operations during the fully mobile phase.

In the tethered phase, the timeline will be more relaxed, with a daily operational decision made by roughly 1000-1030 LT to allow for time for equipment preparation. If early convection is expected the next day, an announcement will be made so that participants can anticipate an earlier operational decision. These overall forecasting and decision-making strategies are modeled after the successful VORTEX1, IHOP, and other recent supercell experiments.

Certain non-meteorological factors will be incorporated into the choice of general target in the fully mobile phase. In some areas, fixed-site observing systems are available that would augment the mobile observations (e.g. the NSSL dual-polarization and phased-array radars and CASA network in Oklahoma, the Oklahoma and West Texas Mesonets, and the CHILL and S-POL in eastern Colorado). VORTEX2 will endeavor to operate near these fixed site systems, and collect data in coordination with these systems, when favorable weather is forecast near these locations. Crew rest, road network availability, and terrain quality will always be important factors determining mobile observation targeting.

b. Target refinement in the fully mobile phase

A home-based nowcaster (NC) will monitor the evolving situation and communicate with the field team through the Mesoscale Coordinator (MC). When convection initiates, it is likely that mobile radar data will be available to the field teams, as described below. These data will be combined with mesoscale analyses in an effort to choose the cell most likely to become a tornadic supercell. Some of the mesoscale meteorological factors to be considered include the likelihood of interaction with a mesoscale boundary, local enhancement of storm-relative helicity, etc.

Some hypotheses address events and processes that occur up to 30 minutes prior to low-level vortex intensification (and the usual visual manifestations). Hence, the experiment will attempt to target young cells that appear to have the potential for tornadogenesis. This is somewhat in contrast to the more traditional mobile observation strategy in which mature supercells are targeted, with an emphasis on observing only those stages of evolution immediately preceding tornado formation, through tornado demise.

Observations will be collected on the target cell until such time that it appears certain to dissipate, storm interactions reduce the apparent tornado potential, the target cell is failing to evolve toward tornadogenesis while a nearby, easily targeted storm has obvious tornado potential, or the mobile fleet has fallen too far behind the storm to attempt further intercepts. Because of the inertia of a large array of mobile instruments, the decision to leave one storm and target another will be based on fairly compelling observations.

c. Active sampling and coordination

The VORTEX2 fleet will be the most extensive array of mobile instrumentation ever fielded, possibly comprising O[30] vehicles, and it will be deployed in a difficult to predict, potentially hazardous, and rapidly evolving environment. Coordination of the complex, heterogeneous, and extensive VORTEX2 fleet of airborne and ground based platforms will be conducted by a tightly collaborative team consisting of several senior personnel with extensive experience in scientific severe weather intercepts. A home-based nowcaster (NC) with access to high speed internet landlines will have the lead responsibility for tracking the evolution of the broad target area prior to intercept missions, and the evolution of the larger scale pattern during intercepts to evaluate whether target changes are necessary (Sec. 6b above). The NC will communicate primarily with the field-based Mesoscale Coordinator (MC), located in the FC vehicle. The MC has the lead responsibility in the field for tracking the larger scale environment outside the currently targeted storm, including potential storm mergers, other initiations, etc. The field-based Information Coordinator (IC) will maintain the situational awareness display in the FC vehicle and generate predictions of the future location of the target portions of the storms. These forecasts will be made in close coordination with the Radar Coordinator (RC) and Probe Coordinator (PC), described below, who will have unique visual and raw real-time radar observations available. The situational awareness graphic will be disseminated to all platforms using ad-hoc digital network technology and standards such as WiFi or WiMax. During the afternoon and early evening, while other senior personnel are coordinating intercepts, the NC will work with the MC and the fixed-based Logistics Coordinator (LC) to develop plans for overnighting and the next day's target. (Note that even seemingly mundane logistics such as finding lodging for O[100] personnel in remote areas on short notice, are complex.)

The extensive array of VORTEX2 instrumentation can be divided into semi-homogeneous groups with somewhat similar logistical concerns. Each group will have a lead coordinator who is in charge of maintaining awareness of all team locations and potential hazards to the team, and providing guidance to ensure that individual instruments are deployed optimally. The Probe Coordinator (PC) will occupy a mobile mesonet vehicle and guide instrumented cars, in situ instrument deployment team(s), and mobile balloon launchers. The PC is likely to frequent positions with excellent proximate visibility to tornadoes and their near-environment and will maintain close contact with the IC and RC in order to develop short-term forecasts to be provided to the full fleet by the IC. (In contrast, the FC vehicle and radars may be a few to several kilometers away from the tornadic region of the storm due to various logistical factors.) The Radar Coordinator (RC) will guide the fleet of radars, which have to maintain a particularly tight choreography in order to obtain synchronized multiple-Doppler coverage and continuous single-Doppler coverage of various portions of the target storm. The RC, stationed in a radar, will have real-time access to raw radar data, can quickly program customized sweeps if needed, and will maintain close contact with the IC and PC to develop short term forecasts to be communicated to the full fleet in the situational display by the IC. The Aircraft Coordinator (AC) will supervise the deployment of UAVs that will be virtually tethered to cars, and monitor the local airspace for the unlikely possible conflicts with manned aircraft. Decisions concerning the general movement of the fleet will be made by consensus by coordinators, with a rotating tiebreaker.

VORTEX2 observations will be obtained by platforms that are operated semi-autonomously. Semi-autonomous operation will permit the coordinators to focus on providing short term forecast information, making overall targeting decisions, and maintaining a safety watch on the many vehicles in the fleet, while only minimally monitoring the locations and movements of individual observing platforms. Special attention will be given to situations in which it appears that platforms could be more effectively targeted, or when it appears that personnel may not be aware of imminent danger.

Principal investigators and/or students trained by them, will operate many platforms. Rigorous training will be provided to all participants so that they may safely and effectively obtain the needed observations.

As a minimal capability, the coordination team will provide nowcasts of important storm features, movement, and predicted positions via VHF voice channels as were done in VORTEX1. A much-augmented capability is planned for VORTEX2, however. Using an ad-hoc mobile digital network (see Communication Infrastructure in the Logistical Support section), the IC will gather data in real-time from most mobile platforms. These data will be combined into a situational awareness graphic that includes radar reflectivity data, two levels of Doppler velocity data shown as stippled simplified overlays, platform locations (including manned and UAV aircraft), and selected in situ observations. Annotations will be made of critical storm features such as low-level vortex and gust front locations, as well as annotations of historical and predicted locations. This situational awareness graphic will be compatible with an off-the-shelf GIS system so that the graphic can be overlain with the users' platform position and road/navigation data.

d. Coordination of the tethered phase

The coordination of the tethered phase will not differ substantially from the fully mobile phase. This will allow participants to be accustomed to one paradigm of coordination and eliminate the expense and planning problems associated with developing two separate coordination strategies. In the tethered phase, it is anticipated that the mobile coordination facility will be stationed at or near the National Weather Center in Norman, allowing the PIs and coordinators to interact with personnel of the National Weather Service and NSSL at that site. It is possible, if desired, that mobile field data will be fed directly to the NWS via the internet capabilities of the Field Coordination vehicle. In general, the radar deployment sites will be pre-selected based on site surveys, and the surface network gaps identified, so the major operational decision during the morning hours will be the orientation of the tethered radar network and locations for gap-filling mobile mesonet and stick net instruments. As information (such as real-time reflectivity display data) begins to flow from that network, and targetable boundary layer features are identified, the coordination team will then direct certain mobile observing assets to target locations.

7. Logistics

a. Communication Infrastructure

The VORTEX2 fleet will be the largest and most complex mobile scientific array of its type ever fielded, and it will be fielded in and near hostile environments. Effective communication and exchange of critical safety and logistics information among the O[30] fleet vehicles is of paramount importance. The minimum capability for field coordination during active sampling is based on the IHOP-2002 mobile digital network (Ziegler et al. 2004). This capability includes VHF voice and mobile digital radio modems capable of communication over a 20 km radius from the Field Coordination vehicle. In the tethered phase, much communication with field teams will be via cell phone.

However, VORTEX2 anticipates the development of a new level of communication capability relying on commercial off-the-shelf digital communication technology. This capability is based on prototype systems such as AUGNet (http://augnet.colorado.edu). In this system, 802.11b protocol radio modems are placed in ground vehicles as well as a UAV. The network automatically configures the best routes for message passing between the various platforms in real-time. The implementation of this design, or a successor, in VORTEX2 will be inexpensive since it relies on commercial off-the-shelf technology (e.g., the 802.11 protocol is implemented in "WiFi" cards in many notebook computers such as those likely to be used in VORTEX2). The AUGNet-type ad hoc network would supply the situational awareness graphic to the platform operators, and supply platform observations and positions to the IC. It is possible that it could even be used for voice-over-IP applications. It should be noted here that 802.11 inter-vehicle digital communications has already been implemented in some mobile platforms such as the DOW radars. An effort to field-test communications and the situational display prior to VORTEX2 has been proposed simultaneously with this submission. Obviously, rapidly-evolving technologies such as WiMax may be advantageous to VORTEX2, especially in the tethered phase because it is being conducted in a more populated region than many of the mobile phase deployments.

Vehicles used by experiment coordinators will be equipped with satellite internet links to obtain real-time meteorological data. The satellite capability will also allow email or instant messaging exchange of graphical and text information needed for coordination. Most vehicles will have cell phone capability. Several VHF channels also will be available, with specific roles for various categories of teams (e.g. one channel may be dedicated to mobile mesonet use, another to mobile radar use, etc.).

b. Logistics of full mobility

The domain for the fully mobile phase of VORTEX2 (see Fig 4.5) has been selected based on density of the road network (largely a function of agricultural land use), terrain and vegetation conducive to mobile radar operations, and frequency of supercell storms.

This phase of VORTEX2 will be a fully mobile experiment without a long-term home base. The advantages of this are both logistic and financial. Supercell outbreaks suitable for VORTEX2 study can occur over a large region of the High Plains and many cannot be reached in a single day from a fixed base. Experience has shown that the number of useful supercell and tornado data sets increases significantly when a platform's range can span the entire middle portion of the U.S. Since the distribution of supercell outbreaks in any given year is unpredictable and varies greatly, no ideal home base location can be chosen *a priori*. Furthermore, since the domain is large, no home base, particularly those at the meteorological centers in Norman and Boulder, which are at the extreme southeast and northwest corners of the VORTEX2 domain, provides single-day accessibility to the full domain.

In the fully mobile concept to be implemented in VORTEX2, all platforms generally remain in remote regions where the weather is active, and only return to a fixed base when no active weather is anticipated for an extended period across the entire domain. By remaining in the field, daily ferrying trips will be reduced, which are fatiguing for both vehicles and crews. Ferrying of large vehicles, particularly mobile radars, is more expensive than finding lodging for their occupants. Overnight lodging will usually be found near to the end point of that day's mission, with a bias towards the next day's anticipated mission location.

In a large experiment such as VORTEX2, a majority of participants will come from diverse locations instead of meteorological research centers such as Norman or Boulder. Thus, travel costs are likely lower compared to a semi-fixed-base strategy, which would result in some double lodging charges.

In a fleet of O[30] vehicles, many with complex radar or other instrumentation, efficiency of maintenance will be critical. Due to the sheer number of platforms, it is likely that repairs will be necessary on at least some of these 30 vehicles after many missions. VORTEX2 will obtain three remote depots, likely in garages or hangars, at locations in the southwest, center, and northeast of the operational domain (Shown schematically in Fig. 4.5). These depots will be equipped with minimal tools and infrastructure and will provide dry, lighted, locations for vehicle and instrument maintenance. An example of this type of remote maintenance facility is the garage that was used by the DOWs, XPOL, MIPS, and other systems in Liberal, Kansas during IHOP. No special communications infrastructure will be needed at these locations because several of the platforms, including the FC, DOW3, and the DOW-SCOUT vehicle have satellite internet capabilities.

During prolonged lulls in the weather pattern, participants will find temporary lodging near the location where their platform is being stored/parked. For many groups, a logical location will be Norman, but for others it will be Boulder, etc. Efforts will be made to encourage all investigators to have the same down-time base in order to facilitate interactions and communications. However, from a purely logistical viewpoint, the platforms could be based at other places in the experiment domain and rendezvous when operations resumed.

8. Data Management

The development and maintenance of a comprehensive and accurate data archive is a critical step in meeting the scientific objectives of VORTEX2. The overall guiding philosophy for the VORTEX2 data management is to make the completed data set available to the scientific community as soon as possible following the field project in order to better accomplish the scientific objectives of VORTEX2 as well as to incorporate these results into improved operational forecast and precipitation prediction models. The VORTEX2 data management archive activities will be coordinated by the NCAR/EOL/FPS (Field Project Services). FPS will determine the needs of the VORTEX2 community, implement a real-time web-based field data catalog, and establish a data archive center for post-project data dissemination. ***VORTEX2 will follow standard NSF practice for data sharing including requiring the prompt submission of data, full sharing of data after an initial analysis period, and proper attribution of data sources***.

9. Personnel, Training, and Education

The roles of Information Coordinator, Aircraft Coordinator, Radar Coordinator, Probe Coordinator, and Mesoscale Coordinator are likely to be filled by scientists from the VORTEX2 Steering Committee (Don Burgess, David Dowell, Paul Markowski, Erik Rasmussen, Yvette Richardson, Lou Wicker, and Josh Wurman) and other researchers with extensive intercept experience. These positions may be filled on a rotating basis.

The managers of the instruments, in conjunction with the PIs who will be using data from each platform, will designate leaders of various mobile teams. In general, these team leaders will be experiment PIs or their graduate students. Support positions such as drivers and technicians require less understanding of the scientific mission, and will be filled by temporary staff, students and volunteers.

Forecasters, including the Nowcaster, will be drawn from a pool of volunteers who have demonstrated expertise in forecasting for storm intercepts. During the five-day work week, special products used for the second-day outlook will be developed by the NOAA/NCEP Storm Prediction Center. The SPC will make space available to VORTEX2 on a continuous basis for the use of the Nowcaster. The Nowcaster will have access to the entire data stream used at SPC, as well as custom numerical forecast guidance and public internet data sources.

A non-field-based Logistics Coordinator will provide logistical support for the very large mobile crew and fleet. The Logistics Coordinator will work with the field-based Mesoscale Coordinator and the Nowcaster to determine overnighting locations, coordinate overnight deliveries of parts, repairs, arrange for seminar rooms in the field for the Mobile Seminar Series (described below), and swap personnel to/from the mobile fleet. Individual PI's and instrument managers will be encouraged strongly to have the Logistics Coordinator arrange for their teams' lodging since the VORTEX2 teams may require upwards of 60 hotel rooms every night. The Logistics Coordinator also will coordinate administrative matters during the period leading up to and through VORTEX2, including contacts with law enforcement, logistically-related databases, personnel lists, frequency licensing, and coordination of pre- and post- VORTEX2 meetings.

Depending on the success of proposals from individual PIs, there will be numerous mobile ground-based radars and balloon launching systems, and rawinsondes used for electrification studies, so it will be critical to ensure minimal electromagnetic interference among systems. This is particularly true in the 9 GHz band used by DOW2, DOW3, Rapid-DOW (6 frequencies), NOXP, XPOL, UMASS-X, and UMASS-Phased Array, as well as near 400 MHz, used by many if not all of the balloon sounding systems and rocketsondes. A Frequency Coordinator will work with all instrument managers to resolve conflicts. It will be mandatory that all instrument managers work through the Frequency Coordinator to ensure that their instruments produce the minimal possible interference to other instruments. It is likely that some pairs or groups of instruments that share frequencies will have to operate at staggered times and locations. It is anticipated that more than one VHF frequency will be used in order to divide voice and/or data traffic.

Training will be critical to the success of VORTEX2 because of the semi-autonomous operation of many of the data collection platforms. It is anticipated that the PIs will attend a 1-2 day training session before or at the time the experiment commences. The training will involve the experiment scenarios, scientific objectives, safety and regulations, and the use of the situational awareness information to customize data gathering strategies. All participants must be familiar with the operating procedures and safety issues involving their platforms before participating in the field.

VORTEX2 will include a novel educational program for all participants. Portable projection and computer equipment will be used to present a Mobile Seminar Series. These talks will be presented by experiment PIs at motels or other convenient locations to discuss research topics relevant to the experiment. All students will be encouraged strongly to attend. Some seminars may feature a review of recent VORTEX2 cases, focusing on scientific issues and methods to improve sampling to address emerging ideas and experiment goals. Others will discuss ongoing data analyses, computer modeling, and conceptual studies of tornadoes and supercells. A rotating Seminar Coordinator will work with the Logistics Coordinator to arrange for meeting rooms and other issues.

10. References

Refer to the complete reference list contained in the VORTEX2 SPO.