A Science Overview for the NSF Component of the Joint Polarization Experiment
(JPOLE)

Submitted to the National Science Foundation, Division of Atmospheric Sciences and Division of Earth Sciences

Prepared by

Terry Schuur
Co-chair, JPOLE Steering Committee
Cooperative Institute for Mesoscale Meteorological Studies
University of Oklahoma
Norman, OK 73019

V. Chandrasekar
Co-chair, JPOLE Steering Committee
Colorado State University
Fort Collins, CO 80523

With contributions from:
M. Askelson, L. Carey, J. Gourley, D. MacGorman, J. Straka, B. Vieux, and D. Zrnić

15 March 2002

Program Summary

The Joint Polarization Experiment (JPOLE) field campaign is a multi-agency project designed to investigate the use of polarimetric radar signatures of precipitation to advance numerous NSF-related meteorological and hydrological objectives. Broadly, the objectives include improving physical understanding of polarimetric data interpretation, improving rainfall estimation and hydrometeor classification and quantification techniques, and investigating the use of polarimetric radar data in distributed hydrologic and storm-scale prediction models. It will be held during a much longer NOAA-sponsored JPOLE operational demonstration, which seeks to demonstrate the utility of the first polarimetric WSR-88D radar to operational meteorologists, hydrologists, and aviation users. The JPOLE field campaign builds upon a significant program infrastructure provided by a NOAA-sponsored project.

The JPOLE field campaign is planned for central Oklahoma for 15 March 2003 through 15 June 2003. This time period is ideal to address the NSF-related objectives presented in this document. In addition to being a transitional period wherein central Oklahoma experiences precipitation events that span a wide variety of regimes (suitable for investigating a broad range of objectives), it is also a time period wherein central Oklahoma experiences a climatological maximum in heavy precipitation events that commonly lead to flooding.

Given the potential of a future network of polarimetric radars, the implications of this research promises to have a much broader and far reaching impact at a national scale for the research community.

1. Introduction

The Joint Polarization Experiment (JPOLE) field campaign is a coordinated, multi-agency effort to investigate numerous objectives related to the physical retrievals, interpretation, and meteorological/hydrological application of polarimetric radar observations. It will be held during a much longer NOAA-sponsored JPOLE operational demonstration, which seeks to examine the feasibility of an operational polarimetric WSR-88D radar. The JPOLE operational demonstration will benefit the field campaign by providing a broad array of field observing facilities, significant program infrastructure, and logistical support that will greatly enhance NSF-funded science. In short, JPOLE will provide NSF-funded PIs a unique, opportunity to investigate a number of basic meteorological and hydrological science objectives.

In this overview document, we propose the deployment of the Colorado State University CHILL radar and the South Dakota School of Mines and Technology T-28 aircraft to the JPOLE field campaign. The CSU-CHILL radar, combined with the KOUN WSR-88D polarimetric radar (currently being developed at the National Severe Storms Laboratory (NSSL)), will be used to conduct investigations of polarimetric radar data observations, cloud microphysical properties and processes, and the use of polarimetric radar data to develop improved rainfall estimation and hydrometeor classification/quantification techniques. Investigations of the use of polarimetric radar data in the initialization of storm-resolving cloud models will also be conducted. More importantly, we propose a first-ever coupling of meteorological and hydrological objectives through the use of improved polarimetric radar Quantitative Precipitation Estimation (QPE) in distributed hydrologic models. These objectives, along with several adjunct science objectives, are addressed in detail in this overview document.

Field operations during JPOLE will focus upon data collection by the CSU-CHILL and KOUN WSR-88D polarimetric radars. Initial KOUN radar data collection will begin in the Spring of 2002. Simultaneous data collection by both radars will provide widespread coverage of multiple watershed basins for use in hydrologic distributed model investigations. The KOUN radar will employ a transmission scheme in which horizontal and vertical signals are transmitted simultaneously (also referred to as hybrid mode). This simultaneous transmission mode has several advantages over the more traditional alternate mode of transmission. For example, it will provide a more direct estimation of the differential phase and copolar correlation magnitude, a decoupling of differential phase estimation from Doppler velocity estimation, and less error in polarimetric variables for the same scan rates (Doviak et al. 2000). However, cross polar observations are not measured in this mode. This mode is equivalent to the switched mode if the propagation and backscatter matrices of precipitation medium are diagonal. Otherwise, coupling can bias polarimetric estimates. Except for limited tests with the CSU-CHILL radar, the simultaneous mode remains relatively untested. Therefore, JPOLE provides the first opportunity to cross validate the two measurement techniques.

Since the KOUN radar is a prototype polarimetric WSR-88D radar, it represents a significant advance in that it will be the first in a possible future national network of polarimetric WSR-88D radars. The meteorological and hydrological objectives listed in this overview document will therefore have far reaching implications. In addition to the KOUN radar, a wide array of field observing facilities are in place in central Oklahoma and available for use by NSF researchers at no cost as part of this experiment. These include four conventional National Weather Service (NWS) WSR-88D radars, limited use of the NSSL Cimarron polarimetric radar, three rain gauge networks, a 2D-video-disdrometer, and a 3-D lightning mapping network (cloud electrification is listed as an adjunct objective in this overview document). The rain gauge networks cover a variety of spatial scales. They include the Oklahoma Climatological Survey (OCS) mesonet, the Agricultural Research Service (ARS) micronet, and the Environmental Verification and Analysis Center (EVAC) piconet (average gauge spacing of 30 km, 5 km, and 0.65 km, respectively). For the hydrologic measurements, the U.S. Geological Survey (USGS) operates and maintains 174 surface water gauges in the proposed study region. These gauges report gage height and streamflow conditions every 15 minutes. Specifications and locations of all instrumentation are discussed in more detail in the experimental design section of this overview document.

The JPOLE field campaign is planned from 15 March 2003 through 15 June 2003. It will therefore fall during the much longer operational demonstration, which will extend from the Spring of 2002 through the Spring of 2004. The JPOLE field campaign will be the first dual-polarimetric field project to have a goal of coupling meteorological/hydrological observations to improve QPE and to use polarimetric radar data in distributed hydrologic models. It will also be the first project where the alternate polarization mode and hybrid mode will be used simultaneously. During the project, concurrent radar data collection by the CSU-CHILL and KOUN polarimetric radars will be used to understand the basic assumptions of microphysical retrievals of the simultaneous transmission mode, provide widespread coverage of several watershed basins, and collect data that can be used to address the other science objectives. The T-28 aircraft (proposed for a 4-6 week subset of the CSU-CHILL deployment) will collect important in-situ data sets that can be used in investigations of raindrop size distribution parameter retrievals as well as other cloud microphysical properties/processes, hydrometeor classification/quantification techniques, and storm-scale model initialization. The combined NSF and NOAA facilities deployed for this experiment will provide a unique project infrastructure upon which many NSF-related objectives can be addressed at low cost.

This experiment provides a unique opportunity to leverage the NSF and NOAA assets to advance the cloud microphysical understanding through polarimetry, and the joint operation with a prototype WSR-88D radar will set the stage for extending the retrieval and interpretation throughout the country. Given the potential of a future network of polarimetric radars, the implications of this research promises to have a far reaching impact at a national scale for the research community.

The CSU-CHILL radar has been a magnet for undergraduate and graduate research students for the past 10 years. All the students who are selected to participate in these programs in the year 2003 will have the opportunity to work on the JPOLE field project. JPOLE will also provide numerous field experience and research opportunities for undergraduate and graduate students at the University of Oklahoma.

2. Meteorological and Hydrological Overview

The mid March through mid June time frame proposed for the field campaign represents a period during which southern great plains precipitation typically transitions through a variety of regimes. These include late cold-season synoptic-scale events, early warm-season synoptic-scale events, frequent weak to moderate intensity systems that produce widespread showers, intense convective storms that often contain large hail, and late spring Mesoscale Convective Systems (MCSs) that often produce heavy rainfall. This broad range of precipitation events makes the study time and location well-suited to address the NSF-related objectives listed in this overview document (see Section 3).

Due to the significant portion of the annual precipitation that falls during this time period, there are also numerous hydrologic reasons for the time and location of this project. Average annual precipitation in central Oklahoma is approximately 85 cm, with nearly 50% typically falling during the proposed study period. Furthermore, the frequency of heavy precipitation events that lead to flash flooding reaches a maximum during the month of June. During this month, the average number of days with reported thunder and the peak monthly precipitation reach their maximum (9 days and 37 cm, respectively).

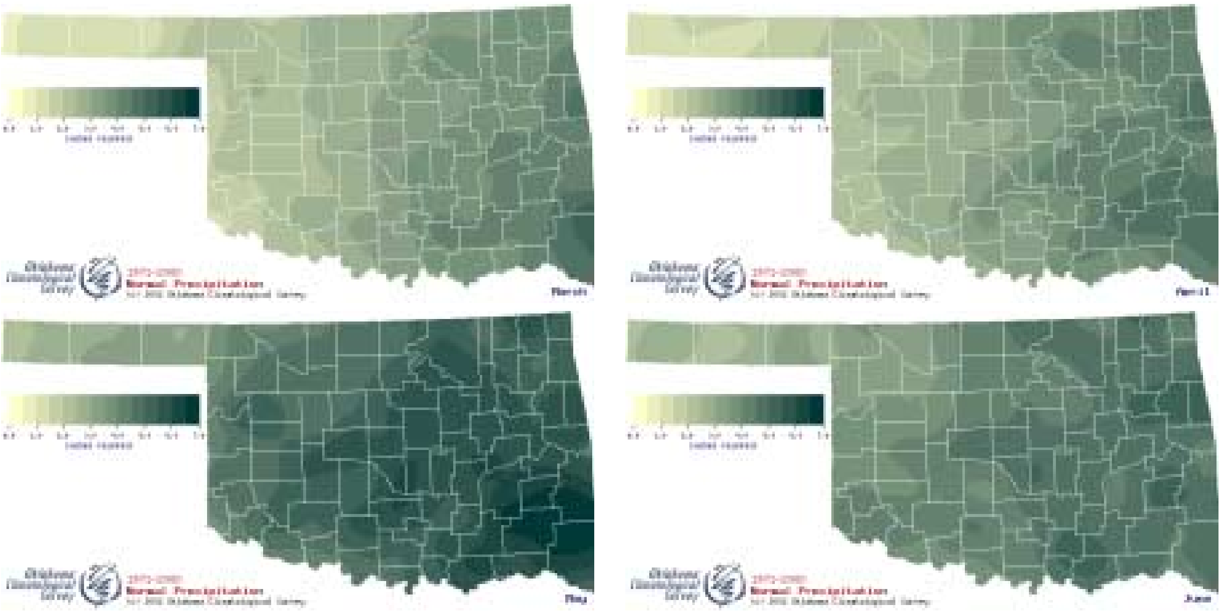

Figure 1. Average monthly precipitation for Oklahoma for the months of March through June. Averages are computed for the 30-year period of 1971-2000. Color scale runs from 0.0 to 7.0 inches (0.0 to 17.8 cm) of precipitation. (Figures courtesy of the Oklahoma Climatological Survey.)

Fig. 1 shows the average monthly rainfall for Oklahoma computed over a 30-year period from 1971 to 2000. From April into May, precipitation in Oklahoma typically evolves from fast-moving convective storms to more slow-moving MCSs that produce heavy rainfall. This is clearly reflected in Fig. 1, which shows a dramatic increase in rainfall over much of Oklahoma in the month of May (with a rainfall maximum of approximately 15 cm located in central Oklahoma). Though total rainfall amounts are somewhat smaller in June, the central Oklahoma rainfall maximum is still evident. This overall decrease in rainfall from May to June is likely due to a climatological dropoff in MCS frequency during the last two weeks of the month (as an intense upper-level ridge builds over the central U.S. in the late Spring and early Summer).

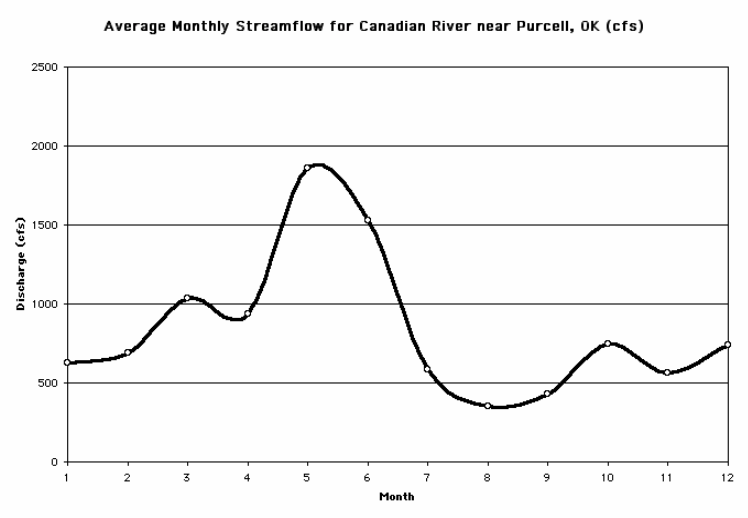

Figure 2. Average monthly streamflow for the Canadian River near Purcell in central Oklahoma. Streamflow is in cubic feet per second (cfs). Streamflow reflects a 30-year average.

This spring-time precipitation pattern is also depicted well by hydrologic records. Fig. 2 shows a 30-year average annual streamflow for the Canadian River near the city of Purcell, in central Oklahoma; it also indicates a springtime maximum in precipitation. A sharp increase in streamflow is seen in the latter half of April, a peak in early to mid May, followed by a gradual decrease throughout the month of June. A secondary streamflow maximum in October is less than half the intensity of that seen in mid May. Combined, Figs. 1 and 2 clearly show that the mid March through mid June time period proposed for the JPOLE field campaign is optimal for capturing the period of peak precipitation in central Oklahoma.

3. NSF Objectives in JPOLE

A recent report of the Ninth Prospectus Development Team of the U.S. Weather Research Program noted that coupled efforts in meteorology and hydrology could lead to major advances in heavy precipitation estimation and flood prediction (Droegemeier et al. 2000). They also emphasized the possible future importance of a polarimetric WSR-88D radar network towards achieving those goals. In JPOLE, we attempt to take a first step in that direction by combining NSF- and NOAA-related objectives into a collaborative field project that emphasizes both basic meteorological and hydrological research as well as the development and testing of the first polarimetric WSR-88D radar.

The science objectives presented in this section are a collection of meteorological and hydrological objectives related to the interpretation of polarimetric signatures, use of polarimetric radar observations to develop improved hydrometeor classification and quantification techniques, drop size distribution retrievals, and use of polarimetric radar data to initialize storm-scale prediction and distributed hydrologic models. The primary source of data for these investigations will come from the CSU-CHILL and KOUN WSR-88D polarimetric radars. With its simultaneous transmission mode, the KOUN WSR-88D radar is capable of measuring reflectivity (Z_h), the polarimetric variables differential reflectivity (Z_{dr}), specific differential phase (K_{dp}), and correlation coefficient (ρ_{hv}). With its added ability to transmit in either alternate or simultaneous mode, the CSU-CHILL radar is capable of collecting the above listed polarimetric variables, but also LDR and other cross-polar variables. Combined, these radars will provide widespread coverage of numerous river basins, as well as data that can be used to investigate the sensitivity of hydrometeor classification and quantification techniques to input variables and their use in storm-scale model simulations.

The science objectives listed here will be addressed by science proposals to be submitted by the JPOLE PIs listed in Appendices A and B. These objectives are to:

i. *Improve physical understanding of polarimetric signatures.*
   Some of the difficulties in developing procedures to deduce dominant hydrometeor types and bulk amounts from polarimetric radar data are caused by a lack of a thorough understanding of polarimetric radar signatures. For example, there is a need for information about drop size distributions (DSDs), hydrometeor characteristics, and ambiguities associated with hydrometeor identification. (e.g., whether several or no hydrometeor types are identified). In order to complete rigorous validation studies, complete sets of quantitative and qualitative observations and information on the occurrence of artifacts in the data and uncertainties in radar calibration are also required. While significant insights have already been obtained, it is evident that much work remains. The future significance of this need is further magnified by the prospects for a polarimetric upgrade to existing WSR-88Ds radars in the coming decade, which promises to expose many in the community to this type of information. Research carried out under this objective will provide valuable information that will be used to understand the evidence and limitations to polarimetric radar data and products.

ii. *Investigate the effect of natural drop size distribution variability, drop oscillations, and canting angles on conventional and polarimetric rainfall estimators*.

Natural variations in DSDs impact radar-derived rainfall estimates. Rain rate estimates are also impacted by variability in drop shape (frequently caused by oscillations) and canting angles. Though less susceptible than conventional radar methods, even polarimetric methods of rainfall estimation are affected by variability in raindrop spectra. For example, DSDs with an anomalously large number of small (large) raindrops will commonly result in an underestimation (overestimation) of rainfall (Schuur et al. 2001). These known dependencies underscore a need to better understand natural DSD variations in precipitation events. Indeed, observations indicate that significant DSD variability exists not only from one event to the next, but even within individual precipitation events. Under this objective, high-quality DSD measurements from multiple 2D-video-disdrometers will be combined with measurements from the CSU-CHILL and KOUN WSR-88D polarimetric radars to understand the impact of DSD variability on polarimetric rainfall estimation. The data will be used to improve rainfall estimation techniques. In turn, the improved polarimetric rainfall estimates will be used as input to distributed hydrologic models, which will be used to predict the runoff associated with heavy precipitation events.

iii. *Develop and test robust precipitation identification and quantification algorithms at long ranges. Investigate methods to account for bright band contamination in rainfall measurements.*

Since DSDs evolve significantly as they fall from cloud base, DSDs illuminated by the radar beam at long ranges (locations well above the ground) can bear little resemblance to those encountered at the surface. This can make rainfall estimation at long ranges difficult. This problem is compounded further for shallow stratiform systems, where “bright band” contamination at long ranges results in an increase in reflectivity that makes rainfall estimation by conventional methods (such as Z-R relations) almost impossible. In the past, most polarimetric radar analyses have used data collected in the 30 to 60 km range. Recent polarimetric radar and aircraft studies, however, have shown that important hydrometeor information can be obtained at distances of 90 to 120 km. Similar research needs to be conducted for rainfall estimation at long ranges, possibly out to 150 km. Two advantages of polarimetric radar measurements are their abilities to discern information about DSD characteristics and to clearly identify regions of “bright band” contamination. Under this objective, data from the CSU-CHILL and KOUN WSR-88D polarimetric radars will be compared against data from the Oklahoma mesonet. By studying rainfall estimation over large domains (the coverage area of the two radars encompasses most of the state of Oklahoma), techniques will be developed to estimate rain rate at long ranges. In addition to serving as input to hydrologic models, this information will have valuable applications in both climatological and storm-scale model validation studies.

iv. *Investigate how improved precipitation estimates from polarimetric rainfall measurements can be used to initialize hydrologic models*.

Recent advances in hydrologic modeling provide the capability to capitalize on improved precipitation estimates made possible by polarimetric radar. Specifically, these models are beginning to utilize spatially distributed parameters as opposed to basin-averaged, or lumped parameters. These distributed hydrologic models also take full advantage of high-resolution, gridded inputs from polarimetric radar. The quantitative precipitation estimates are transformed to runoff on a grid cell-by-grid cell basis using physics instead of empiricism. The work proposed here will incorporate the polarimetric rainfall estimates in a physics-based, fully distributed hydrologic model called r.water.fea that was developed at the University of

Oklahoma. Model-predicted stream flow will be compared to observed stream flow at USGS gauging stations. Results from this study will be used to assess the operational use of hydrologic modeling at the scales at which flash flooding occurs.

v. *Investigate how input data uncertainties influence flood prediction, the maximum time/space scales required to accurately simulate a flash flood, and the basin characteristics that are most important in transforming rainfall into runoff.*

With improved precipitation estimates from polarimetric radar, many advances in the understanding of hydrologic processes can proceed. Specifically, basin characteristics are parameterized in the hydrologic model using proxy data sources, such as infiltration derived from soil types and Manning's roughness coefficient from land use/land cover maps. A limited sensitivity test will be conducted with these parameter sets to determine the influence of the sampled information content on stream flow predictions. These tests will improve our understanding of basin characteristics and their impacts on runoff. In addition, sensitivity tests can begin to comparatively assess how much uncertainty exists in the parameter sets, the input polarimetric rainfall estimates, within the context of the hydrologic model structure. The aim of these tests is to ascertain the amount of uncertainty associated with model-predicted stream flow. Lastly, simulations of river flow will be performed at varying frequencies and spatial resolutions to determine the maximum scales at which flash floods can be adequately modeled.

vi. *Examine the accuracy of hydrometeor classification schemes through detailed comparisons with verification data sets. Use verification data sets to develop hydrometeor quantification schemes.*

Polarimetric-radar-based hydrometeor classification schemes are in a dire need of comprehensive verification data sets. This is especially true for widespread cold- and warm-season stratiform precipitation events that, unlike hailstorms, have received only scant attention. In-situ information from a variety of precipitation systems is therefore critical to both the refinement of current qualification/quantification techniques and to the development of new techniques. Particular emphasis will be placed on the delineation of the error modes in which classification and quantification techniques tend to fail, and the quantification of expected errors. Under this objective, T-28 aircraft data will be compared with data from the CSU-CHILL and KOUN WSR-88D polarimetric radars to improve understanding of the strengths and weaknesses of classification and quantification techniques, estimate expected errors for microphysical parameters (e.g., distribution slopes, ice-water content) that are derived from polarimetric-radar data, and identify classification/quantification failure modes and possible methods for dealing with them. They will also be used to investigate new classification/quantification techniques and provide feedback to other objectives (e.g., objectives ii, iii, vii, xi, and xii). The principal method for accomplishing these goals will be the comparison of algorithm-estimated qualitative and quantitative information (derived from polarimetric radar data) to the qualitative and quantitative hydrometeor-field properties determined by in-situ observation (derived principally from T-28 data).

vii. *Investigate how microphysical information derived from polarimetric radar measurements can be used in cloud resolving models.*

For several years, modelers have been noting a need for improved microphysical initialization data for storm-scale models. Hydrometeor classification and quantification information derived from polarimetric radar data promises to be provide valuable information that can be used to produce short-term model predictions. Under this objective, the variational technique will be used to fit cloud models to microphysical observations for both basic scientific investigations and operational meteorological applications. Owing to the complexity of the problem, initial attention will be given deep, moist convection that includes both the liquid and ice phase and a simple ice/liquid microphysics parameterization. These data and tools also will be used to improve understanding of long-standing problems with quantitative precipitation forecasts, such as the so called moisture spin-up, microphysical/kinematical interactions, and validation of numerical models with varying microphysical representation complexities. The variational approach to this problem has several strengths. They include an ability to create complete data sets with physical conditions, assimilate observations over short periods of time, assimilate data from a variety of observation platforms even if the observed variable is missing from a model equation, and allow for ingest of inhomogeneous data in time and space. Some of the challenges of the approach include defining weights in the cost function, dealing with discontinuities or step-function processes, finding the right amount of data to ingest, and representing physical processes correctly.

viii. *Investigate the retrieval of drop size distributions from polarimetric radar measurements.*
A long-standing goal of radar polarimetry has been the retrieval of DSD parameters using measurements of Z_h, Z_{dr} and K_{dp}. To do so requires knowledge of the relation between the axis ratio and equivalent volume diameter, which is non-linear. Nonetheless it is possible to define an equivalent linear model with slope of β_{eff} such that a correct relation between K_{dp}/N_w and D_o is preserved on average. Gorgucci et al. (2001) developed algorithms for retrieving rain rate (R) as well as D_o, N_w and μ using β_{eff} in combination with the pair ($Z_{h,}$ Z_{dr}). The "effective" slope (β_{eff}) of the mean axis ratio versus D relation captures the effects of both drop oscillations and canting which vary considerably in different precipitation regimes. We will investigate thoroughly β_{eff} and reasons behind its variability. Because β_{eff} is estimated from the measurement set ($Z_{h,}$ $Z_{dr,}$ K_{dp}), and K_{dp} at long wavelengths (such as S-band) is known to be very noisy (at low rain rates), it follows that the retrieval of the DSD parameters is only practical if the radar reflectivity is sufficiently high. At low rain rates the Z_{dr} also tends to be noisy therefore a large areal average is necessary to reduce the measurement fluctuations and retrieve DSD parameters (Bringi et al. 2001). In addition to the variability of β_{eff} (particularly in updraft/downdraft regions), an important goals of this research is to study the space-time variability of the drop size distribution over life cycles of storms. Finally, the last goal is to compare radar-derived rain rates against a network of gages to demonstrate the benefits from β_{eff} in reducing the rainfall accumulation bias.

ix. *Examine the microphysical basis for drop size distribution variability in both cold and warm season precipitation events with particular emphasis on extreme "cold-processes" and "warm-processes".*
The adjective "extreme" is a rather subjective qualifier because it usually refers to destructive effects of rain which, depending on spatial and temporal scales, are not uniquely related to rain rate. To quantify these, accurate precipitation measurements are needed over scales ranging from those at which urban flash floods are produced to those at which major river flooding occurs. Often, it is not the extreme precipitation itself, but the associated hydrologic response at the land surface (such as flash floods, land slides, debris flow, etc.) that cause the greatest damage (e.g. Smith et al. 2000). The impact of extreme precipitation can be particularly severe over urban areas. Under this objective, warm and cold rain processes will be observed (and differentiated) by the polarimetric radar and aircraft measurements. It is anticipated that warm rain processes would dominate the storms earlier in their lifetime, but that gradually cold rain processes would take over. The differences in DSDs (as measured by aircraft and disdrometers at the ground) from the two types of processes will be compared. Besides enhancing understanding of rain processes, the knowledge gained will tell if polarimetric rainfall estimators should adaptively adjust to the rain type. Furthermore, it will help explain the

source of typical overestimation of extreme "cold-process" rain and underestimation of extreme "warm-process" rain estimated from fixed R(Z) relations.

x. *Conduct X-band and S-band polarimetric radar intercomparison studies.*
The majority of polarimetric research has been conducted at S-band frequencies. The primary reason for using S-band is to minimize the effect of attenuation. However, it is also known that some of the signatures are more pronounced at higher frequencies. For example, in rain, K_{dp} scales directly with frequency (Bringi and Chandrasekar 2001). Chandrasekar et al. (1990) evaluated the error structure of rainfall rate estimates at S-band and determined regions where polarimetric algorithms perform better than other algorithms. This error structure consists of measurement error and dynamic range of S-band radar observation of precipitation. X-band, while affected by attenuation, offers a larger dynamic range of polarimetric radar observations at low and moderate rain rates (5 to 15 mm h^{-1}). This has important implications for drop size distribution retrievals at X-band, and the corresponding error structure. In addition, combined operation of X-band and S-band polarimetric radars will provide a unique opportunity to explicitly evaluate attenuation correction techniques. The attenuation correction currently proposed for X-band apply to rain. However, it has not been explored for mixed and ice phase precipitation. The joint operation of X-band and S-band radars provides a unique opportunity to validate theoretical models of attenuation connection at X-band for a variety of hydrometeor types, which is one of the components of JPOLE research. Comparisons of results from X-band and S-band radars will also be valuable for investigating the accuracy of hydrometeor classification and quantification techniques.

xi. *Investigate the microphysical processes responsible for rapid changes in polarimetric signatures.*
Enhanced signatures of polarimetric variables (i.e., regions where a polarimetric variable has a distinctly different value than in its surroundings) are widely believed to be tied to specific microphysical processes. So far, several types of signatures have been observed. For example structures of K_{dp} and Z_{dr} columnar fields displaced from each other have been reported in Colorado (Hubbert et al. 1998) and Oklahoma supercell storms (Loney et al. 2002). In ordinary storm, the Z_{dr} and K_{dp} have been collocated (Zrnić et al. 2001). Further the process of upward drop advection and subsequent freezing has been documented for ordinary storms. Very little is known about the evolution and advection of polarimetric signatures in supercell storms and squall lines. These are, of course, caused by the bulk hydrometeors; frequent observation of the signatures could help explain the processes that lead to these changes. To fully capitalize on polarimetric measurements, fast volume scans (< 1 min) to provide observations with a resolution of a few hundred meters are needed. This can be achieved with conventional radar by probing small sectors and utilizing recently proposed techniques to greatly reduce statistical errors in polarimetric radar signals (Torres and Zrnić 2001). Although tested, the technique has not and will not be implemented in time for the experiment. Nonetheless, the CSU-CHILL radar can oversample (in range) the time series and record such data. JPOLE will provide an opportunity to obtain polarimetric signatures at unprecedented updates rates and with superior accuracy for several events. This information will be useful for understanding rapid microphysical changes in clouds, conducting trajectory analysis studies, and providing valuable insight that can improve model parameterizations.

xii. *Investigate the effects of electric fields on the orientation of ice crystals using polarimetric radar measurements.*
Both plate and needle like crystals naturally fall with their long axis oriented horizontally. However, vertically oriented crystals have been observed in-situ and hints appeared in polarimetric signatures. The polarimetric radar observations indicate negative K_{dp}'s of many

small vertically oriented crystals. However, the orientation for the small crystals in the strong electric fields is primarily in the vertical (Caylor and Chandrasekar, 1996). These electric fields are not strong enough to reorient the larger needle or plate like crystals. As the small pristine needle crystals occur in much larger numbers they produce the negative K_{dp} signature. The signature is not indicated by Z_{dr}, which is dominated by the fewer, though much larger small crystals. Observations would require polarimetric radar and field mill measurements from equipment on board the T-28 at temperatures of around -5 °C and perhaps at temperatures colder than -17.5 °C.

4. NOAA Objectives in JPOLE

The polarimetric upgrade to the KOUN WSR-88D radar has been a tri-agency effort sponsored by the National Weather Service (NWS), Federal Aviation Administration (FAA), and Air Force Weather Agency (AFWA). NOAA objectives and requirements during JPOLE can be broken down into two broad categories: 1) evaluating the engineering design and data quality of a polarimetric WSR-88D radar, and 2) examining the benefits of polarimetric radar data to operational meteorologist, hydrologists, and aviation users.

4.1 Engineering Design and Data Quality

The JPOLE operational demonstration will provide an opportunity to evaluate critical engineering and data quality issues. For example, radar data quality must be assessed through a detailed comparison with verification data sets, the radar scanning strategy evaluated to assess compatibility with requirements of the existing WSR-88D radar system, and the simultaneous transmission mode (Doviak et al. 2000) examined to calibrate polarimetric radar measurements, establish and verify engineering specifications, and investigate short and long term stability. More specifically, the engineering design and data quality objectives of the operational demonstration are to

- Demonstrate the accuracy of KOUN reflectivity, velocity, and spectrum width measurements through comparisons with conventional WSR-88D radar data.
- Demonstrate the accuracy of KOUN polarimetric measurements through comparisons with high-quality research polarimetric radar data.
- Demonstrate that polarimetric precipitation estimation and hydrometeor classification products can be collected with volume updates compatible with NWS requirements (all previous research results were obtained with relatively slow scan strategies).
- Perform tests to ensure minimal degradation in Volume Coverage Pattern times, and no degradation in ground clutter filtering, anomalous propagation filtering, and velocity dealiasing.
- Evaluate the value of alternate scans at horizontal polarization to obtain ρ_{xh} and LDR.

4.2 Benefits to Operational Users

In addition to addressing engineering and data quality issues, the JPOLE operational demonstration seeks to examine the benefits of polarimetric radar data to operational meteorologist, hydrologists, and aviation users. This will be accomplished by conducting an evaluation of the performance of polarimetric radar rainfall and hydrometeor products. As such, operations during both field phases (covering both warm and cold season precipitation) will focus on the collection of data sets that can be used for a detailed comparison of conventional and polarimetric radar products. This evaluation will be completed both in 1) real-time with the collaboration of operational forecasters, and 2) postanalysis where a more detail analysis of polarimetric algorithm performance can be made. More specifically, the product performance evaluation objectives are to

- Improve Quantitative Precipitation Estimation (QPE).
- Use QPE to improve operational hydrologic forecasts (especially for flash flood events).
- Discriminate hail from rain and gauge hail size.
- Identify precipitation type in winter storms (dry/wet snow, sleet, rain).
- Identify biological scatterers (and their effects on the wind measurements).
- Identify the presence of chaff (and its effect on precipitation measurements).
- Identify areas of ground clutter and anomalous propagation.
- Provide improved initial conditions and constraints to numerical models for short term forecasts.
- Investigate the feasibility of identifying aircraft icing conditions.

Product comparisons will be of fundamental importance to the test and evaluation of the polarimetric KOUN WSR-88D radar's capabilities. As such, real-time data collection will be conducted in collaboration with operational hydrologists, meteorologists, and aviation users, whose insight will be of vital importance to the evaluation of WSR-88D radar products.

4.3 NSF Benefits to the JPOLE Operational Demonstration

During JPOLE, NSF-funded facilities will benefit the operational demonstration in many ways. First, they will provide critical verification data sets that can be used in the evaluation of the KOUN WSR-88D radar data quality. Data from the CSU-CHILL radar, which is capable of transmitting in both alternate and simultaneous mode, will provide a valuable comparison data set that will be used to ascertain data quality of the KOUN WSR-88D radar. Data from the T-28 aircraft will be processed and used to evaluate the accuracy of a polarimetric Hydrometeor Classification Algorithm (HCA), which will be delivered to forecasters at the Norman, Oklahoma NWS Forecast Office in real-time. Accurate, real-time hydrometeor classification is of fundamental importance to the tri-agency sponsors of the polarimetric upgrade of the KOUN WSR-88D radar.

The KOUN WSR-88D radar represents the first in a potential future network of polarimetric WSR-88D radars. Therefore, just as important as the collection of verification data sets, NSF-funded research will also have a significant impact on the availability and quality of future polarimetric radar data and products to operational meteorological, hydrological, and aviation users. NSF-funded research will help clarify outstanding questions in polarimetric radar data interpretation, improve polarimetric rainfall estimation and hydrometeor classification and quantification techniques, and investigate the use of polarimetric radar data in storm-scale prediction and distributed hydrologic models. It therefore promises to have a far reaching impact on the operational meteorological and hydrological communities for years to come.

5. Adjunct Objectives

The observing facilities and organizational infrastructure required to investigate the primary objectives (listed in Section 3) will also provide an extraordinary, low cost opportunity to conduct research on several adjunct NSF-related objectives. These objectives include:

5.1 Storm Electrification

Considerable evidence indicates that knowledge of storm kinematics and ice microphysics is key to the study of storm electrification processes. Negative and positive cloud-to-ground lightning observations necessary for storm electrification studies also are already being acquired by the National Lightning Detection Network. Furthermore, a three-dimensional total lightning mapping system built by New Mexico Institute of Mining and Technology is to be permanently installed in central Oklahoma by the summer of 2002. Given the significant observing facility infrastructure already provided by JPOLE, the only other observations missing for a comprehensive study of storm electrification are in-situ balloon-borne electric field measurements (necessary to examine the relationships among the electrical, kinematic, and microphysical structures of storms and their effect on lightning production).

Data collected during the JPOLE field campaign will serve to investigate several storm electrification objectives. First, they can be used to evaluate the hypothesis that large hail and tornadoes tend to be preceded by large increases in cloud flash rates caused by large updraft surges and also that positive cloud-to-ground lightning production is related systematically to severe weather. To understand the reasons for these behaviors, it would also be necessary to examine the electrical structures that cause the lightning activity. The period and region of JPOLE typically would have 10-15 severe storm days, and the range of storm would be much broader than observed in the few published lightning mapping studies. Second, they can be used to investigate various means of using cloud and cloud-to-ground lightning data to improve precipitation estimates in regions with poor or no radar coverage and to improve forecasts through assimilation of lightning data into forecast models. These are relatively new topics of lightning research. Some aspects of the topics are already being studied, but the comprehensive data sets these studies need are very sparse. JPOLE would be expected to provide several data sets much superior to any existing ones for this research. Finally, the data can be used to examine how seasonal variations and specific mesoscale features of the environment (such as the horizontal distribution of low-altitude moisture) systematically affect lightning production, particularly their hypothesized effect on cloud-to-ground lightning polarity and on lightning relationships with severe storms and MCSs. Adding aerosol measurements would provide the data needed to test a published hypothesis that unusual aerosol populations can enhance production of positive cloud-to-ground lightning.

5.2 Precipitation Trajectory Analysis

The development of polarimetric radars has enabled an unprecedented look at precipitation processes. As these studies have progressed, several important questions have become prominent. Included in these important questions are: 1) What are the principal precipitation trajectories associated with Z_{dr} and K_{dp} columns (columns of enhanced Z_{dr} and K_{dp} values that extend above the environmental freezing level and are thought to be important suppliers of hailstone embryos)?, 2) Which microphysical processes dominate in the production of Z_{dr} and K_{dp} columns?, 3) Does accumulation, by influencing hailstone embryos, play an important role in hail processes (especially in supercells), and 4) Do precipitation particle trajectories indicate a relatively rapid evacuation of the updraft region in LP supercells, as suggested by Rasmussen and Straka (1998)? To answer these questions, all of which have direct relevance to hail production and precipitation efficiency (and indirect relevance to issues like tornado formation), comprehensive observational data sets concerning the concurrent kinematic and microphysical fields of storms are needed.

The data collected in JPOLE will assist in further answering these questions. Highly relevant data were recently obtained in the Severe Thunderstorm Electrification and Precipitation Study (STEPS) field campaign. These data, however, were obtained in the high great plains region of eastern Colorado and western Kansas, where cloud bases tend to be relatively cool. Because of the warmer (on average) bases of Oklahoma storms, more pronounced polarimetric signatures (including Z_{dr} and K_{dp} columns) tend to arise in these storms. The stronger signals associated with these storms should assist in the identification of important trajectories and microphysical processes. In addition, JPOLE offers, from an observational-platform standpoint, a tremendous opportunity for addressing the above questions. The proposed dual S-band polarimetric radar deployment and consequential opportunity for multiple-Doppler analyses (dual, triple, and possibly more) will produce a unique set of data to which trajectory calculations and microphysical models/analyses can aptly be applied. Furthermore, the possible utilization of the SMART-R radars, by providing fine-scale details and additional Doppler data sets, would help refine the information and would enhance the analyses of microphysical processes. Using JPOLE data sets, multiple-Doppler analyses, precipitation and air trajectory calculations, and microphysical models, answers to the above questions will be pursued.

5.3 Modeling Investigations of Soil Moisture and Vegetation on Convective Initiation

In addition to the primary objectives, JPOLE measurements can also be used to understand the role of the three-dimensional soil moisture anomalies and the coupling between the surface vegetation and subsurface soil moisture in controlling the deep convective processes. They can also be used to assess soil moisture feedback on the regional climatic circulation and precipitation patterns of the JPOLE region. We propose to use a flux-adjusting surface data assimilation system (FASDAS) to improve the diagnosis of the coupling between surface and subsurface processes, and cumulus convection and precipitation. Oklahoma mesonet and OASIS flux data would also be used in this effort. Validation of convective initiation will be simply accomplished with radar reflectivity data over the large domain supplied by the KOUN WSR-88D and CSU-CHILL radar coverage area, supplemented by GOES operational visible satellite data. Rainfall patterns that strongly affect soil moisture conditions will be provided by advanced polarimetric radar methods using data from the KOUN WSR-88D and CSU-CHILL radars with validation from surface rain gauges.

6. How JPOLE Differs From Previous Projects

In approximately the past five years, several field campaigns have received either full or partial NSF support for the deployment of an S-band polarimetric radar. These projects include the Cooperative Atmosphere-Surface Exchange Study (CASES; Wichita, Kansas in 1997), the Texas and Florida Underflights Experiment (TEFLUN-B; Melbourne, Florida in 1998), the Tropical Rainfall Measuring Mission/Large Scale Biosphere-Atmosphere Experiment (TRMM-LBA; Rondonia, Brazil in 1999), the Mesoscale Alpine Experiment (MAP; Vergiate, Italy in 1999), the Severe Thunderstorm Electrification and Precipitation Study (STEPS; Goodland, Kansas in 2000), and the Improvement of Microphysical Parameterizations through Observational Verification Experiment (IMPROVE I and II; Washington and Oregon coastlines in 2001). All of these field campaigns requested deployment of the National Center for Atmospheric Research (NCAR) S-POL radar. STEPS also requested partial deployment costs for the CSU-CHILL radar. It remains the only experiment with two S-band polarimetric radars to date.

The JPOLE field campaign differs from these projects in many respects. First, the JPOLE science objectives differ significantly from those of previous projects. Many of the above projects were either conducted outside of the continental U.S., in coastal regions, or in climatic regimes that were unfavorable for the study of hydrologic response to heavy rainfall. Others had primary objectives that emphasized study of mesoscale dynamics over orographic terrain. *The JPOLE field campaign is a* *coupled meteorological/hydrological experiment with a goal of using polarimetric radar rainfall estimates to initialize distributed hydrologic models. It also seeks to improve polarimetric hydrometeor classification and quantification techniques and investigate the use of polarimetrically derived hydrometeor information in storm-scale prediction models.*

Second, JPOLE will be only the second study to combine observations from two S-band polarimetric radars (but the first with two polarimetric radars operating in alternating and hybrid modes). STEPS deployed two S-band polarimetric radars, but it was conducted in the semi-arid high great plains region of eastern Colorado and western Kansas and had scientific objectives that primarily emphasized the study of cloud electrification processes. *The JPOLE field campaign leverages significant NOAA assets to provide an infrastructure upon which a dual S-band polarimetric radar experiment can be conducted at relatively low cost.*

Finally, JPOLE provides the first opportunity to cross validate the alternate and simultaneous transmission techniques. Since the KOUN radar is a prototype polarimetric WSR-88D radar, it represents the first in a possible future national network of polarimetric WSR-88D radars. *The JPOLE field campaign will therefore have a significant impact at a national scale for both the meteorological and hydrological research communities.*

7. Experimental Design

JPOLE will field a comprehensive array of observing facilities in central Oklahoma for the Spring of 2003. In addition to the polarimetric CSU-CHILL radar and T-28 aircraft (requested by the JPOLE field campaign), these facilities include the polarimetric KOUN WSR-88D radar, the polarimetric NSSL Cimarron radar, four conventional WSR-88D radars, three rain gauge networks, a 2D-video-disdrometer, and a 3-D lightning mapping network. Stream flow information will be provided by the 174 USGS surface water gauges that are located in the proposed study region. In addition to these facilities, several auxiliary instruments are being sought from collaborating institutions. These instruments include the NOAA/Environmental Technology Laboratory (ETL) scanning X-band polarimetric radar, and the University of Iowa/Iowa Institute for Hydraulic Research (IIHR) vertically pointing X-band radar and 2D-video-disdrometer. These instruments are summarized in Table 1.

Table 1: Primary instrumentation available for JPOLE field campaign

Radars:	
Polarimetric CSU-CHILL radar	S-band polarimetric radar. Transmits in alternate and simultaneous mode.
Polarimetric KOUN WSR-88D radar	S-band polarimetric radar. Transmits in simultaneous mode.
Non-polarimetric KTLX, KINX, KVNX, KFDR WSR-88D radars	S-band non-polarimetric WSR-88D radars. Available as auxiliary instruments.
Aircraft:	
SDSMT T-28 aircraft	Measurements include 2D-C, HVPS, hail spectrometer, FSSP, liquid water, vertical wind, and temperature probes, and GPS position.
Rain gauge networks:	
Oklahoma Climatological Survey (OCS) mesonet	107 station mesonet (average gauge spacing of 30km).
Agricultural Research Services (ARS) micronet	42 tipping bucket gauges in an instrumented basin (average gauge spacing of 5 km).
Environmental Verification and Analysis Center (EVAC) piconet	25 duplicated rain gauges (average gauge spacing of 0.65 km).
Disdrometers:	
NSSL 2D-video-disdrometer	Video disdrometer capable of providing accurate DSD and drop shape data. Comes with an accompanying weighing rain gauge.
Stream flow measurements:	
USGS surface water gauges	174 gauges maintained in the proposed study region. Reports gauge height and streamflow.
Lightning Mapping:	
3D total lightning mapping system	Provides a 3D map of lightning flashes over central OK, 2D map over entire JPOLE region.
Auxiliary instrumentation (collaborating institutions):	
polarimetric ETL X-band radar	X-band radar for multifrequency comparison studies.
Non-polarimetric, vertically pointing IIHR radar	Vertically pointing X-band radar for studies of drop size distributions.
IIHR 2D-video-disdrometer	Video disdrometer capable of providing accurate DSD and drop shape data.

The JPOLE field campaign will focus upon data collection by the polarimetric CSU-CHILL and KOUN WSR-88D radars. Fig. 3 depicts proposed JPOLE observing facility deployment locations. As shown in Fig. 3, the proposed location for the CSU-CHILL radar would be to the southwest of the KOUN WSR-88D radar (with a baseline of approximately 50 km). In addition to providing widespread coverage of numerous river basins, this location and baseline should prove ideal for alternate/simultaneous transmission mode data quality comparisons with the KOUN WSR-88D radar, and rain rate estimation comparisons with nearby rain gauge networks (on a variety of spatial scales). The polarimetric NSSL Cimarron radar is also expected to be available for data collection. However, since Cimarron is an old radar with numerous mechanical and real-time data quality problems, it can only be considered reliable for the collection of occasional complementary data sets. It is therefore not listed in Table 2. With multiple radars, several dual-Doppler options will be available during JPOLE. The CSU-CHILL and KOUN WSR-88D radar pair, however, is considered the primary option. Dual-Doppler data will be important for studying drop size distribution retrievals as a function of storm structure and evolution.

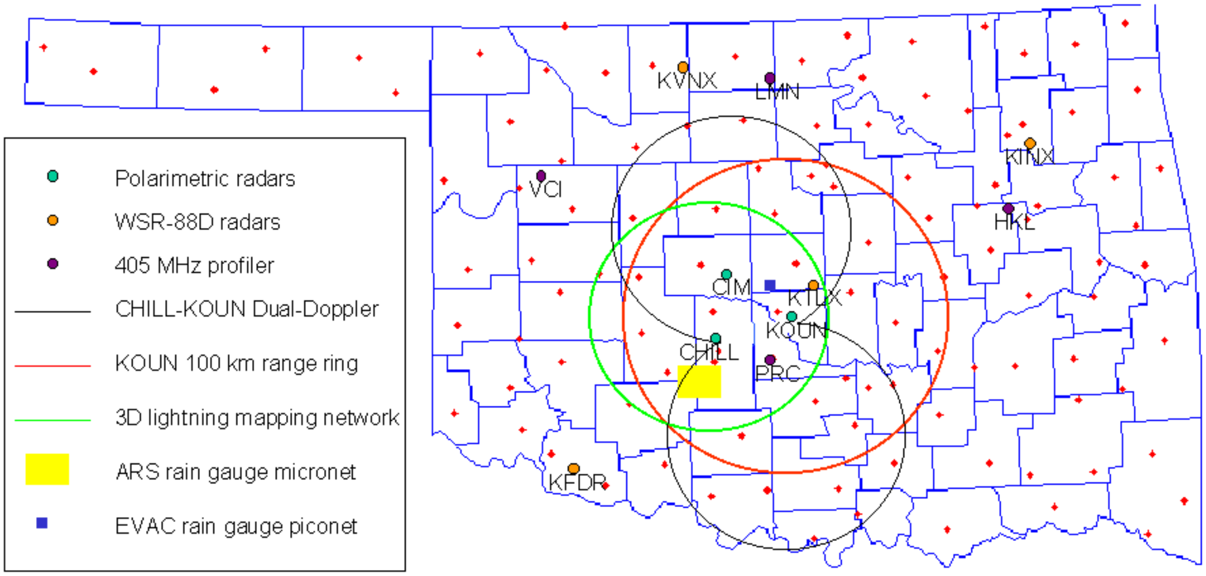

Figure 3. JPOLE observational facilities for the Spring of 2003. Green dots depict locations of the polarimetric KOUN WSR-88D, NSSL Cimarron, and CSU-CHILL (proposed deployment location) radars. Orange dots depict locations of conventional KTLX, KINX, KVNX, and KFDR WSR-88D radars. Purple dots depict locations of PRC, HKL, LMN, and VCI 403 MHz profilers. Red dots indicate locations of the 107 Oklahoma mesonet rain gauges, yellow box the location of 42 gauge ARS micronet, and blue box the location of the 25 gauge EVAC piconet. Red circle shows 100 km range ring for the KOUN radar. Green circle shows 3D total lightning mapping system coverage. Black circles depict approximate KOUN-CHILL dual-Doppler lobes locations.

Fig. 3 also shows the locations for the OCS mesonet, the ARS micronet, and the EVAC piconet rain gauge networks. With average gauge spacings of 30 km, 5 km, and 0.65 km, respectively, these three networks provide an opportunity to investigate polarimetric rainfall estimation accuracy on a variety of spatial scales. A 2D-video-disdrometer, which is owned and operated by NSSL, is located at the Norman, mesonet site. The 2D-video-disdrometer provides detailed, orthogonal side image views of all raindrops that fall through the sensing area. It comes with an accompanying, weighing rain gauge that can be used for comparisons. This information is valuable for investigating the sensitivity of polarimetric radar rainfall estimators to natural drop size distribution variability and drop shape. Expected collaborations with other institutions may result in the deployment of additional 2D-video-disdrometers, as well as possibly two Joss impact-type disdrometers (with accompanying rain gauges for rain rate verification). Optimal deployment locations for those facilities will be determined at a later date. Locations of these ground-based facilities, along with river basins and USGS surface water gauges available for the hydrologic portion of the JPOLE field campaign, are shown in Fig. 4.

Finally, Fig. 3 depicts the location of the 3D total lightning mapping system coverage. The green circle indicates the region where a three dimensional map of total lightning flashes is possible; a two dimensional map is possible out to a range that approximately extends to the Oklahoma-Kansas border to the north, the Oklahoma-Texas panhandle border to the west, and just into northern Texas to the south.

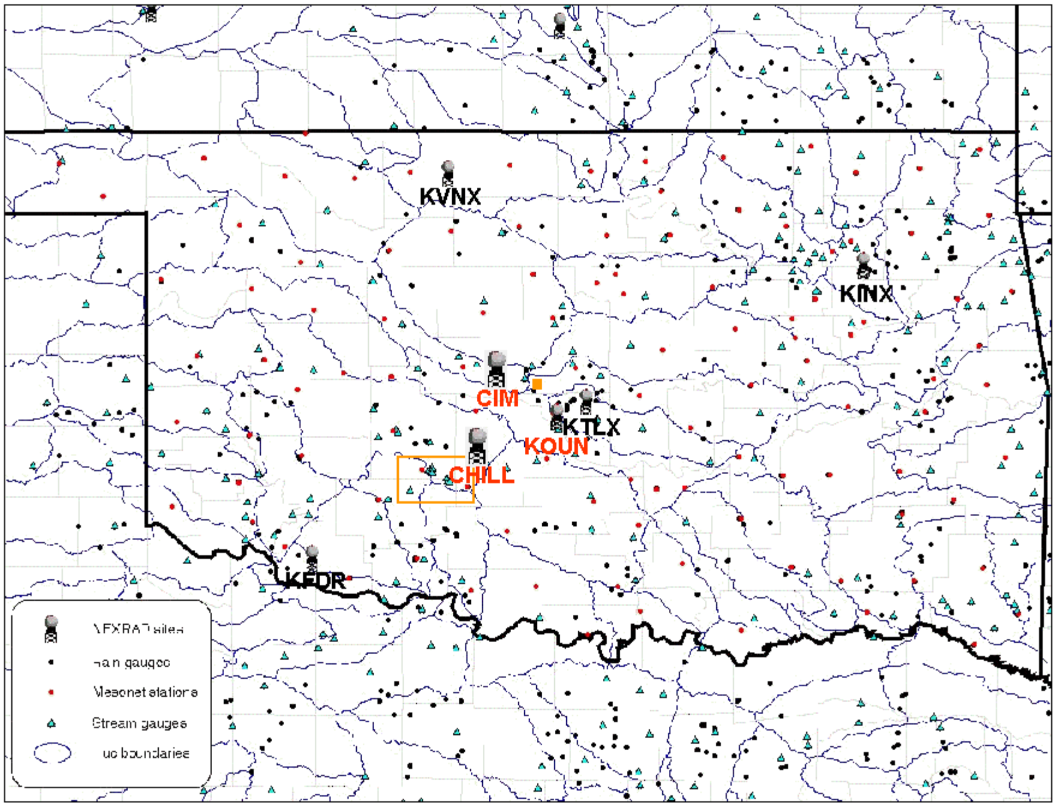

Figure 4: JPOLE observational facilities for the Spring of 2003. River basins indicated by blue lines with location of USGS stream gauges depicted by green triangles. Locations of polarimetric KOUN WSR-88D, NSSL Cimarron, and CSU-CHILL (proposed deployment location) radars are depicted by radar icons with red labels; locations of conventional KTLX, KINX, KVNX, and KFDR WSR-88D radars are depicted by radar icons with black labels. The locations of the Oklahoma mesonet rain gauges (red dots), ARS micronet (orange box boundary), and EVAC piconet (orange box) are also shown.

The T-28 aircraft is also being requested by the JPOLE field campaign. During JPOLE, the T-28 aircraft will operate out of the Norman airport (Westheimer Field) and fly storm penetrations at all ranges covered by the polarimetric CSU-CHILL and KOUN WSR-88D radars. It will be equipped with a suite of instruments that include the 2D-C, HVPS, hail spectrometer, FSSP, and DMT liquid water probe. Additional instrumentation include GPS position, vertical wind, two temperature probes, and a small video camera in the pylon (accompanied by an audio recording of both the cockpit audio and the windscreen impact microphone). These data will be important for identifying microphysical processes associated with polarimetric radar observations, in-situ validation of hydrometeor identification and quantification techniques, and as verification data sets for the JPOLE operational demonstration requirements. They will also provide useful information that can be used in adjunct cloud electrification investigations.

As noted earlier, several auxiliary instruments are being sought from collaborating institutions. If secured, the polarimetric ETL X-band polarimetric radar will likely be deployed to a location between the ARS micronet and EVAC piconet where it would collect data that could be used for investigations of X-band rainfall estimation accuracy (on the various spatial scales covered by the three rain gauge networks, see Fig. 3), and for multifrequency comparisons with the nearby S-band polarimetric radars. The IIHR vertically pointing X-band radar and 2D-video-disdrometer would likely be deployed to the Purcell, Oklahoma (PRC in Fig. 3) 403 MHz profiler site to investigate drop size distribution retrievals.

Finally, an expected collaboration with the NASA Global Precipitation Measurement (GPM) pilot ground validation experiment will likely make additional facilities available, including a 2D-video-disdrometer and several Joss disdrometers and accompanying rain gauges. Additional GPM satellite-like instrumentation proposed for ground-based deployment as part of the pilot ground validation experiment include a Ka-band (35.6 GHz) and Ku-band (13.6 GHz) dual-frequency radar and multichannel (10.65 GHz HV, 19.35 GHz HV, 21.3 GHz H, 37.0 GHz HV, 85.5 GHz HV) radiometer. Possible NASA instrumentation to be deployed to the JPOLE field campaign are listed in Table 2.

Table 2: Proposed NASA instrumentation available for JPOLE field campaign

Proposed NASA instrumentation:	
Dual frequency radar	Ka-band and Ku-band vertically pointing, dual-frequency radar (35.6 GHz, 13.6 GHz).
Multi-Channel Radiometer	Vertically pointing, multi-channel radiometer (10.65 GHz HV, 19.35 GHz HV, 21.3 GHz H, 37.0 GHz HV, 85.5 GHz HV).
NASA 2D-video-disdrometer	Video disdrometer capable of providing accurate DSD and drop shape data.
Joss disdrometers	Impact-type disdrometer. Comes with accompanying tipping bucket rain gauges.

Deployment locations for these facilities will be determined upon final completion of the GPM Pilot ground validation experiment operational plan.

8. Field Operations and Logistics

The JPOLE field campaign will be managed by the JPOLE Steering Committee, which is composed of the following University and Government researchers.

Terry Schuur (Co-chair)	*University of Oklahoma/CIMMS* Norman, OK
V. Chandrasekar (Co-chair)	*Colorado State University* Fort Collins, CO
Mark Askelson	*University of North Dakota/AS* Grand Forks, ND
Ed Brandes	*National Center for Atmospheric Research/RAP* Boulder, CO
Larry Carey	*North Carolina State University/MEAS* Raleigh, NC
Rich Fulton	*National Weather Service/OHD* Silver Spring, MD
Brooks Martner	*NOAA/Environmental Technology Laboratory* Boulder, CO
Jerry Straka	*University of Oklahoma/SOM* Norman, OK
Baxter Vieux	*University of Oklahoma/CEES* Norman, OK
Andy White	*National Weather Service/ROC* Norman, OK

Upon acceptance of the science objectives, the JPOLE Steering Committee will prepare a JPOLE Operations Plan to govern daily JPOLE operations. It will include a detailed list of the project organizational structure, radar scanning strategies required to achieve the primary objectives, and an outline of data management procedures. The Joint Office for Science Support will support project planning and data management.

A preliminary site survey for the CSU-CHILL radar has already been completed, with a tentative deployment location set for an airport site located just north of Chickasha, Oklahoma. As noted earlier in the document, this site will give a radar baseline of approximately 50 km with the KOUN WSR-88D radar. All field operations during JPOLE will be coordinated out of NSSL, with T-28 aircraft operations run out the CSU-CHILL radar site. Each PI will be responsible for performing quality control, archiving, and making data from their facilities available to other JPOLE scientists accessed through a common website. The CSU team and the NSSL team will assume joint responsibility in ensuring overall coordination and distribution of data sets. This will also be addressed in the JPOLE Operations Plan.

9. **References**

Bringi, V.N., and V. Chandrasekar, 2001: Polarimetric Doppler Weather Radar, Principles and Applications. Cambridge University Press.

Bringi, V.N., Gwo-Jong Huang, V. Chandrasekar, and T. D. Keenan, 2001: An Areal Rainfall Estimator Using Differential Propagation Phase: Evaluation Using a C-Band Radar and a Dense Gauge Network in the Tropics. *J. Atmos. Ocean. Tech.,***18**, 1810-1818.

Caylor, I. J., and V. Chandrasekar, 1996: Time-varying ice crystal orientation in thunderstorms observed with multiparameter radar. *IEEE Trans. GRSS*., Vol 34, No 4, 1996.

Chandrasekar, V., V.N. Bringi, N. Balakrishnan, and D.S. Zrnić, 1990: Error structure of multiparameter radar and surface measurements of rainfall. Part III: specific differential phase. *J. Atmos. Ocean. Tech.,***7**, 621-629.

Doviak, R. J., V. Bringi, A. Ryzhkov, A, Zaharai, and D. Zrnić, 2000: Considerations for Polarimetric Upgrades to Operational WSR-88D Radars. *J. Atmos. Oceanic Tech*., **17**, 257-278.

Droegemeier, K. K., J. D. Smith, S. Businger, C. Doswell III, J. Doyle, C. Duffy, E. Foufoula-Georgiou, T. Graziano, L. D. James, V. Krawjewski, M. LeMone, D. Lettenmaier, C. Mass, R. Pielke, Sr., P. Ray, S. Rutledge, J. Schaake, and E. Zipser, 2000: Hydrological Aspects of Weather Prediction and Flood Warnings: Report of the Ninth Prospectus Development Team of the U.S. Weather Research Program. *Bull. Amer. Meteor. Soc*., **81**, 2665-2680.

Gorgucci, E., G.Scarchilli, V. Chandrasekar, and V.N., Bringi, 2001: Rainfall Estimation from Polarimetric Radar Measurements: Composite Algorithms Immune to Variability in Raindrop Shape–Size Relation. *J. Atmos. Ocean. Tech.,***18**, 1773-1786.

Hubbert, J., V.N. Bringi and L.D. Carey, 1998: CSU-CHILL polarimetric measurements from a severe hailstorm in eastern Colorado. *J. Appl. Meteor.,* **37,** 749-775.

Loney, M.L., D.S. Zrnić, J. M. Straka, and A.V. Ryzhkov, 2002: Enhanced polarimetric radar signatures above the melting level in a supercell storm. Submitted to the *J. Appl. Meteor.*

Rasmussen, E. N., and J. M. Straka, 1998: Variations in supercell morphology. Part I: Observations of the role of upper-level storm-relative flow. *Mon. Wea. Rev*., **126**, 2406-2421.

Schuur, T. J., A. V. Ryzhkov, D. S. Zrnić, and M. Schönhuber, 2001: Drop size distributions measured by a 2D video disdrometer: Comparison with dual-polarization radar data. *J. Appl. Meteor*., **40**, 1019-1034.

Smith, J. A., M. L. Baeck, J. E. Morrison and P. Sturdevant-Rees , 2000: Catastrophic rainfall and flooding in Texas. *J. Hydrometeor*. **1**, 5-25.

Torres, S.M, and D.S. Zrnić, 2001: Optimum processing in range to improve estimates of Doppler and polarimetric variables on weather radars. Preprints 30th International Conference on Radar Meteorology, AMS, Munich, Germany, 325-327.

Zrnić, D. S., A. Ryzhkov, J. Straka, Y. Liu, and J. Vivekanandan, 2001: Testing a procedure for automatic classification of hydrometeor types. *J. Atmos. Oceanic Technol.*., **18,** 892-913.

Appendix A
CORE INVESTIGATORS AND MAJOR CONTRIBUTORS TO THE OVERVIEW DOCUMENT

Mark Askelson
Department of Atmospheric Sciences
University of North Dakota
Grand Forks, ND 58202
askelson@aero.und.edu

Larry Carey
Department of Marine, Earth, and
Atmospheric Sciences
North Carolina State University
Raleigh, NC 27695
larry_carey@ncsu.edu

V. Chandrasekar
Colorado State University
Fort Collins, CO 80523
chandra@engr.colostate.edu

Terry Schuur
University of Oklahoma
Cooperative Institute for Mesoscale
Meteorological Studies
Norman, OK 73019
schuur@nssl.noaa.gov

Jerry Straka
School of Meteorology
University of Oklahoma
Norman, OK 73019
jstraka@pig.ou.edu

Baxter Vieux
Civil Engineering and Environmental
Science
University of Oklahoma
Norman, OK 73019
bvieux@ou.edu

Appendix B
CURRENT LIST OF ADDITIONAL INVESTIGATORS

Kiran Alapaty
MCNC-Environmental Programs
Research Triangle Park, NC
alapaty@emc.mcnc.org

Ed Brandes
Research Applications Program
National Center for Atmospheric Research
Boulder, CO 80307
brandes@ucar.edu

Grzegorz Jan Ciach
Iowa Institute of Hydraulic Research
University of Iowa
Iowa City, IA 52242
gciach@ia.net

Claude Duchon
School of Meteorology
University of Oklahoma
Norman, OK 73019
cduchon@rossby.metr.ou.edu

J. J. Gourley
University of Oklahoma
Cooperative Institute for Mesoscale
Meteorological Studies
Norman, OK 73019
gourley@ou.edu

Witold Krajewski
Iowa Institute of Hydraulic Research
University of Iowa
Iowa City, IA 52242
witold-krajewski@uiowa.edu

Anton Kruger
Iowa Institute of Hydraulic Research
University of Iowa
Iowa City, IA 52242
anton-kruger@uiowa.edu

Sonia Lasher-Trapp
New Mexico Institute of Mining and
Technology
National Center for Atmospheric Research
Boulder, CO 80307
slasher@ucar.edu

Don MacGorman
University of Oklahoma
Cooperative Institute for Mesoscale
Meteorological Studies
Norman, OK 73019
Don.Macgorman@nssl.noaa.gov

Brooks Martner
Environmental Technology Laboratory
Boulder, CO 80305
Brooks.Martner@noaa.gov

Dev dutta S. Niyogi
Department of Marine, Earth, and
Atmospheric Sciences
North Carolina State University
Raleigh, NC 27695
dev_niyogi@ncsu.edu

Dave Rust
National Severe Storms Laboratory
1313 Halley Circle
Norman, OK 73069
Dave.Rust@nssl.noaa.gov

Alexander Ryzhkov
University of Oklahoma
Cooperative Institute for Mesoscale
Meteorological Studies
Norman, OK 73019
ryzhkov@nssl.noaa.gov

Ali Tokay
National Aeronautics and Space
Administration
Goddard Space Flight Center
Greenbelt, MD 20771
tokay@radar.gsfc.nasa.gov

Dusan Zrnić
National Severe Storms Laboratory
1313 Halley Circle
Norman, OK 73069
zrnic@nssl.noaa.gov