A DENSE NETWORK OF DIFFERENTIAL GLOBAL POSITIONING SYSTEM REFERENCE STATIONS FOR PRECISION FARMING

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CHAPTER I

INTRODUCTION

The Global Positioning System (GPS) ushers in a new era of navigation and positioning technology. GPS pinpoints the exact location of variability within fields, documents yield changes from site to site, and provides information that is critical for effective farm management. With this technology, a complete analysis of the performance of seeding rates, fertilizers, pesticides, varieties, and other inputs are documented to maximize profits. Precision farming uses GPS locations in the field for data collection to manage parts of fields for actual needs rather than whole fields for average needs.

This research proposed the development of a low-cost Dense Network of Differential GPS (DNDGPS) capability using a dense network of multiple reference receivers (RR). The research focused on the determination of possible resolution with the dense network of reference receivers as applied to precision farming applications. Resolution was defined as repeatability vs. accuracy at a location once a Differential GPS (DGPS) spot measurement had been made with the dense network of RR. The improved resolution offers potential innovative solutions to farmers faced with the need of increasing accuracy as a way of reducing labor, chemical and fertilizer costs and, at the same time, providing documentation for new regulatory requirements. If sufficient resolution precision can be achieved, it can provide a basis for guidance.

GPS location measurements to 100 meters are possible in native mode; however, location is limited by atmospheric signal propagation effects, satellite orbital errors, receiver noise, clock synchronization error, multipath signal reflections, signal processing delays, satellite geometry, and "selective availability" (deliberate introduction of clock error for military security). DGPS techniques provided real-time empirical measurement and correction of these errors by placing a single RR at known coordinates. The measured total location error is then collected and transmitted in real-time to secondary receivers (SR) at an unknown position (two meter accuracy is common). Typically, Wide Area Differential GPS (WADGPS) are sparse networks with RR every 200 miles or more. Sub-meter precision (e.g., 20 cm) is possible with sophisticated Doppler/carrier-phase systems which are cost-prohibitive for agriculture applications.

Limited availability and expense associated with high-precision location systems limits DGPS to large corporations, military applications, and government agencies having public safety or national security missions. WADGPS implementation with sparse networks, not to mention DNDGPS, has been slowed by the cost of GPS receivers, communications media, computing facilities and systems development. In addition, the capabilities being pursued offer specific solutions and will not be publicly available (e.g., Instrument Landing Systems by the FAA, harbor navigation by the US Coast Guard, and railway mapping by Burlington-Northern are examples). The intent of this project is to extend DGPS capability and facilitate its widespread use to include high-precision applications. For example, a high-precision DGPS would allow additional GPS applications in agriculture, including improved spraying operations and extended hours of equipment operation, surveying and mapping river bottoms, and justifying costs of wide area surveying during petroleum exploration, plus many others. Only the effective transfer of precision Differential GPS technology into the public domain remains to realize such rewards.

The proposed research seeks to perform a practical analysis of DGPS accuracy using a refined error correction based upon input from a large number of reference receivers, to identify agricultural applications and design a farm-based DNDGPS prototype, to identify key industry DGPS applications offering economical benefit when using the refined data, and to design a mesonet-based DNDGPS prototype capable of supporting those applications. Specific objectives were to improve upon DGPS accuracy, repeatability, and degeneration with RR-to-SR distance and offer a fault-tolerant architecture having negligible performance degradation with single or double RR failure.

Adequate iterations were performed to determine the resolution repeatability obtainable with DNDGPS corrections derived from a dense network of multiple RR. This was then mapped with DGPS applications requirements to identify the design parameters for a geographical DNDGPS.

The project focused on the technical, design, and economic considerations in establishing a productive mesonet-based DNDGPS. The project will move Oklahoma to the forefront of GPS technology with a leading-edge GPS group offering the application of DGPS to new areas requiring precise resolution. As other states implement "mesonetworks" similar to the Oklahoma Mesonetwork, Oklahoma would be in a position to export GPS precision technology. Several states, including Texas, North Carolina, Indiana, and Kansas, are currently investigating the implementation of similar mesonetworks.

Precision farming is the leading edge of farm management technology. By obtaining field data and turning it into useful information, there is a sound basis for making management changes that can help optimize input usage and increase crop yields. Farmers are able to acquire precise information about their fields, so they can make educated decisions. Using GPS with a yield monitor produces maps which identify the best and least productive areas within fields. In fact, the magnitude of variability in yield within a field is often surprising. A University of Minnesota study found that corn yields ranged from 60 to 160 bushels per acre, even in soils that appeared to be consistent. Having a better working knowledge of a field gives farmers the flexibility and capability to reduce or redistribute inputs based on site-specific needs. This can result in savings on inputs and increased yields. By targeting the site-specific needs of a field, many precision farmers have seen a decrease in the overall amount of inputs necessary to sustain high crop yields. This can protect the environment as well as their wallets. By using DGPS computerized records John Deere implement users know exactly what, how much, when, and where inputs were used. These records can document sound environmental practices already incorporated into their operations (Gerstner, 1994).

Statement of the Problem

Classical Differential GPS (DGPS) utilizes a master reference station, located on precisely known coordinates, to track the GPS satellites and determine their range errors through comparison with the known reference solution. The differential GPS corrections are then broadcasted to autonomous receivers in the local area. These local receivers produce a correction navigation solution by using the respective satellite range errors provided by the differential reference receiver and are said to operate in the pseudorange domain. Absolute navigation accuracy attainable in this way is a function of the accuracy of the pseudorange and delta range measurements. DGPS corrections, then, can be used to reduce or eliminate the GPS system errors.

Positional DGPS, explored in this project, used standard GPS receivers situated on precise coordinates. Positional error at each reference site was calculated and averaged; the average error was used to correct GPS navigational fixes produced by autonomous receivers in the vicinity. It has been shown that differential corrections produced in this positional domain with a single reference can be as accurate as those produced in the pseudo mode. The DNDGPS approach further refines both single-reference pseudorange and single-reference positional DGPS by having the benefit of multiple references.

Uncorrected GPS location measurements to within 100 meters at 95 percent probability are possible with an autonomous receiver not benefiting from DGPS. This large tolerance is due to the aggregate total of several error sources: signal reflection in the atmosphere, satellite orbital errors, receiver noise, clock synchronization, multipath signal reflections, receiver processing delays, satellite geometry, and selective availability.

Classical DGPS techniques involving a single pseudorange reference station for empirical error measurement provides reliable real-time correction of such errors to an accuracy of approximately two to five meters. Sub-meter precision has been possible with sophisticated Doppler/carrier-phase systems which are cost-prohibitive for most applications today.

Purpose of the Study

The purpose of this study was to assess the feasibility of a differential global positioning (DGPS) system having a dense network of reference receivers (RR) to enable advanced precision farming applications.

Objectives of the Study

In order to achieve the purpose of this study, the following objectives were established:

1. To validate previously published research that atmospheric effects increase as distance between receivers increase;
2. To identify economic justification for a Dense Network of Differential GPS (DNGPS) for individual farm applications;
3. To determine the resolution, repeatability and accuracy obtainable with DNDGPS corrections derived from a dense network of multiple reference receivers; and
4. To develop a farm-based DNDGPS prototype and a plan for Oklahoma Mesonetwork DNDGPS prototype which identifies the necessary resources required for implementation.

Scope of the Study

The scope of this study included seven National Geodetic Survey (NGS) High Accuracy Reference Network (HARN) monuments and three order B accuracy (1 ppm) sites surveyed using Trimble 400 DNGS equipment. These sites were located in portions of five counties of North-Central Oklahoma in the vicinity of Stillwater and adjacent to Payne County.

Research Questions

The research design was developed with the approval of the author's study committee, SBIR, OCAST and TRIP Committees. The research was motivated by the implications for further research identified in earlier studies: Blackwell, 1985; Wilkie, 1989; Georgiadou and Doucet, 1990; Puterski, et al., 1990; Wu, 1992; August, et al., 1994 and Gilbert, 1994. In order to achieve the objectives of the study, the following questions were developed:

Question 1. Do atmospheric effects within DNDGPS reference receivers (RR) and secondary receivers (SR) cause any notable differences in magnification as the separation between receivers increases?

Question 2. Can DNDGPS be implemented at a notably lower cost than off-the-shelf DGPS systems for precision farming applications?

Question 3. Were there notable differences in the resolution of GPS utilizing DNDGPS reference receivers in the positional domain, with averaging algorithm(s) for refining correction data, compared to DGPS systems utilizing the pseudorange mode?

Question 4. Did the DNDGPS system increase the efficiency for agriculture by: 1) identifying practical variability for investigating probable causes and 2) helping instigate possible solutions for precise evaluation which are notably greater than DGPS systems?

Rationale for the Study

The continuing high cost of receivers and differential losses point out the need for a economical fault-tolerant DNDGPS having negligible performance degradation with RR failures. Currently, DGPS uses a single reference station to correct for aggregated errors inherent in GPS measurements. The proposed DNDGPS would use several networked reference stations closely spaced to provide corrected accuracy that equals or surpasses that of single pseudorange DGPS at reduced costs. Additional objectives of DNDGPS are reduction or elimination of precision degradation with increasing baseline distance (reference receiver to autonomous receiver) and improved reliability and availability of corrected position information in the event of reference receiver outage. The overall mission of this project was to identify and enable precision farming operations which can greatly benefit from the reduced DGPS cost offered by the DNDGPS.

Assumptions of the Study

The study was based on the assumption that GPS positional calculation errors could be corrected with either pseudorange or positional Differential GPS (DGPS). The researcher assumed the results of aggregate effects of total error would apply at other sites.

SBIR and OCAST Grants

The dissertation serves as a report of Phase I of the U. S. Department of Agriculture (USDA) Small Business Innovation Research (SBIR) which was a six month $54,992 grant, and Phase I of the Oklahoma Center for the Advancement of Science and Technology (OCAST) which was a one year $88,866 grant. The original goal of this research was to design and develop an operational Dense Wide Area Differential Global Positioning System (DWADGPS), with a network of many reference receivers, which provided justifiable real-time positional information needed for precision farming. The methodology capitalized on the GPS cellular communications and computer science background of David C. Seibel, Principal Investigator. Researcher Seibel previously designed and developed a communicating GPS tracking system for the automobile industry using cellular technology. Kenneth R. Nixon, Project Director and Grant Writer, ensured all Phase I objectives were met, directed the project activities, and assisted with algorithm design and development. Jerry S. Speir, Agricultural Industry Consultant, provided guidance and assistance on all project tasks to ensure that precision farming requirements were identified and solution designs met specifications. He was responsible for developing precision farming GPS resolution requirements by operating and performing the benefits analysis. The project was well underway when it was decided by the research team to discard the GPS cellular phone tracking system as it proved too costly for precision farming applications. Based on research materials supplied by Dr. Marvin Stone on GPS, and an Ephemeris Error Report published by J. T. Wu in 1992, Researcher Speir presented Wu's concept of receiver positional domain for GPS precision farming applications. Motivated by possible cost savings and accuracy, the research team implemented the positional DGPS methodology.

Phase II of the Oklahoma center for the Advancement of Science and Technology (OCAST) was a one year $85,374 grant. The OCAST grants were a cooperative effort of the University of Oklahoma and Oklahoma State University. For the clarity of this author's role in this research only that portion of the OCAST contract containing his subcontract is presented within this paper (Appendix A). The results of OCAST Phase II research and TRIP research are not reported in this paper.

Definition of Terms

For a better understanding of the content presented in this study, the following definitions were deemed relevant (Johannsen, 1997; Searcy, 1995; Berry, 1993; Langley, 1997):

Accuracy: If applied to paper maps or map data bases, degree of conformity with a standard or accepted value, accuracy relates to the quality of a result and distinguished from position. If applied to data collection devices such as digitizers, degree of obtaining the correct value.

Differential Correction: Correction of the GPS signal to make it more accurate. An uncorrected signal will be accurate to about 50 yards. A corrected signal can be accurate to within one to five feet. Correction of a signal is done from a second GPS receiver at a known fixed location. The signal is then transmitted to the tractor, combine, or other equipment which corrects the proper location through differential processing. There are three common ways to transmit a correction signal from the base station to the farm implement: (1) A dedicated transmitter that is located on an existing tower, which has a range of 30-40 miles; (2) A separate, private corporation satellite to send the corrected signal, which has a range of thousands of miles; and (3) Piggyback the correction signal on a commercial FM radio station frequency, which has a range of 30-40 miles.

Differential Global Positioning System: (DGPS). A system for determining the relative coordinates of two or more receivers which are simultaneously tracking the same satellite.

Elevation Mask Angle: An angle below which is not recommended to track satellites. Normally set to 15 degrees to avoid interference problems caused by buildings, trees, and multipath errors.

Global Positioning System: (GPS). A network of satellites controlled by the Defense Department designed to help ground-based units determine their current location in latitude and longitude coordinates. Note that the term "GPS" is frequently used incorrectly to identify precision farming. GPS is only one technology that is used in precision farming to assist in the return to an exact location to measure fertility, pests and yield.

Ground Control Point: An easily identifiable feature with a known location which is used to give a geographic reference to a point on an image.

Iteration: The act or an instance of iterating; repetition. Mathematics. A computational procedure in which the desired result is approached through a repeated cycle of operations, each of which more closely approximates the desired result. Computer Science. The process of repeating a set of instructions a specified number of times or until a specific result is achieved.

Kriging (creeging): An interpolation technique for obtaining statistically unbiased estimates of spatial variation of known points such as surface elevations or yield measurements utilizing a set of control points.

Precision: (1) If applied to paper maps or map data bases, it means exactness and accuracy of definition and correctness of arrangement; (2) If applied to data collection devices such as digitizers, it is the exactness of the determined value; (3) The number of significant digits used to store numbers.

Precision Farming: Using the best available technologies to tailor soil and crop management to fit the specific conditions found within an agricultural field or tract.

Pseudorange: A measure of the range or distance. The time offset a signal takes to propagate from the satellite antenna to the receiver antenna multiplied by the speed of light. It is biased by the lack of time synchronization between the satellite's clock, which governs its signal generation, and the GPS receiver's clock.

Registration: A process where one can geometrically align maps or images to allow one to have corresponding cells or features. This allows one to relate information from one image to another or a map to an image, such as registering a yield image to a soil map to determine if soils are influencing the yield response.

Resolution: A way of detecting variation. In remote sensing, one has spatial resolution (the variation caused by distance separating adjacent pixels), spectral resolution (the variation from the range of spectral responses covered by a wave length band), and temporal resolution (the variation caused by time over the same location).

CHAPTER II

REVIEW OF LITERATURE

The purpose of this chapter is to provide an overview of the literature as it pertains to and relates to documentation of GPS technology in precision farming. Materials from books, professional journals, magazines, and other research studies compile the review. For the review to be more understandable, these topics will be reviewed: (1) Introduction, (2) What and Why Precision Farming, (3) Global Positioning System, and (4) Summary.

Introduction

The world population growth of 1.6 percent per year requires an additional 78,000 metric tons of grain per day just to satisfy consumption per person (p. 9) (Mangold, 1995). If 1950 agricultural technologies were used today, nearly 400 million additional acres would be needed to match food requirements for today's population (Pimentel, 1995). Or, if agricultural outputs remained at 1950 levels, food and fiber would cost $200 billion more (Fischer, 1995). Progress in the use of technology and resulting productivity gains have slowed this phenomenon, but in another 45 years, in the year 2042, mainstream agriculture will have to continue to move even more into the Information Age (Brown, 1995).

A Working Group of Spatial and Temporal Variability on Field Soil on behalf of Commissions I (Soil Physics) and V (Soil Genesis, Classification and Cartography) of the International Society of Soil Science was held at Las Vegas, NV on November 30 - December 1, 1984. The workshop consisted of invited papers and extended discussions in four general statistical concepts of quantifying variability and on applications to hydrology, soil survey, and miscible displacement and leaching. The first Soil Specific Crop

Management Workshop, held April 14 - 16, 1992, consisted of invited papers on the topics of soil resources variability, managing variability, engineering technology, profitability, environment, and technology transfer. The second International Conference of Site-Specific Management for Agricultural Systems was held March 27 - 30, 1994 in Minneapolis, MN. This program employed a system engineering approach to crop production where inputs were made on an "as needed" basis. The Third International Conference on Precision Agriculture was held June 23 - 26, 1996 in Bloomington, MN (Jones, 1996). These proceedings provided an overview of various aspects of precision agriculture similar to 1992 and 1994. The proceedings were published by the American Society of Agronomy, Inc. (ASA): Crop Science Society of America, Inc. (CSSA): and the Soil Science Society of America, Inc. (SSSA).

Precision farming will become widespread. The industrialization of agriculture will accelerate vertical integration for controlling quality and lowering costs (Badson, 1995). Most estimates indicate about 40 percent of farmers own computers. Perhaps one day computers will be as common a tool on the farm as the socket set. It is unrealistic to expect every farmer to be a computer user, unless you predict that only computer-using farmers will survive. Site-specific and information technologies being applied in agriculture today involve the process of turning data into information and decisions; however, much of agriculture still operates in the data acquisition stage. We need to organize data into understandable information that can be used by farmers to make decisions. The data is their destiny (Mangold, 1995).

As the NAVSTAR Global Positioning System (GPS) ushers in a new era of navigation and positioning technology, what is being called "precision farming" will harness recent space-age developments such as global positioning satellites, variable rate controllers on application machinery, real-time yield monitors, crop sensors, and powerful computer software to make farming vastly more scientific than it is today (Keller,1995). GPS links map coordinates to real-world locations, and remote sensing records classify current views of the landscape. A field GIS/GPS remote sensing unit forms the foundation of precision farming. It needs to be extended into the field and placed in the hands of people to support the spatial decisions they make and implement (Berry, 1995).

CENEX, a national agricultural management firm located in St. Paul Minnesota, offers diverse agricultural services including soil analysis, pest identification, and advice on applying fertilizer and pesticides. Their work demonstrates the great potential offered by the integration of field information, GIS, GPS, and aerial photography for a wide variety of environmental applications (Runyon, 1994). J.R. Simplot Co., one of the world's largest and fastest growing agribusiness firms, states that benefits from using Imaging GIS in precision farming are threefold. Harvest yields increase due to better management, farmers save money because chemicals are administered more efficiently, and environmental impacts caused by excess chemical application will be reduced. According to estimates provided by Deere, major crops are currently being cultivated on 411 million acres in the United States and Canada (Gerstner, 1994). Of those, only a minuscule fraction, about half a million acres, are now being cultivated with precision farming techniques. The complete precision farming system envisioned by Deere encompasses field mapping, which uses GPS to measure yields on a site-specific basis and tells farmers how well they are doing in their farming operations, as well as pesticide and fertilizer management, the ability to track crops through the year, and final documentation of yields. Farmers are using GIS, GPS, and remote sensing technologies in increasing numbers in California to make the leap from faith farming to fact farming, using scientifically controlled agricultural practices (Lang, 1996). With more than $22 billion at stake in California crop production; GIS, GPS, and remote sensing can offer a small measure of security to what has always been considered a risky business. There is a real value in having equipment for precise navigation in the field, to prevent overlaps and skips, save input costs and over- or under-application. We also need that accuracy to allow us to operate at night (McNulty, 1994).

Agriculture is about to enter a brave, new world, so technological it exhilarates some farmers and scares others (Gerstner, 1994). The proposed research seeks to implement a new low-cost, high precision Differential GPS (DGPS) capability utilizing a dense network of multiple reference receivers (RR) over a large geographic area, called Dense Network DGPS (DNDGPS). The enhanced availability and affordability of DGPS, in turn, will promote justification for precision farming never before realized.

What and Why Precision Farming?

Innovative agriculture known as site specific farming, or precision farming, applies a combination of new technologies to improve production and reduce environmental pollution. Precision farming can be represented as incorporating three main areas of management: data collection, data analysis and decision-making, and variable application treatment. Taking advantage of recent developments including GPS, remote sensing, GIS and variable rate technology; precision farming is used to manage spatial variability in fields through determination of spatially-referenced inputs, such as nutrients which affect soil fertility and chemical applications which control insects and weed pests (Chancellor and Goronea, 1994). The results are optimized production with minimal inputs of chemicals and a corresponding minimal impact on the environment. Precision farming requires management tools to turn data into decisions so production can be optimized on the farm, field, and field element levels. In order to manage spatial variability at these levels, modern farmers are looking for advanced GIS applications to perform site specific management to apply only as needed and when needed to maintain profitable production (Searcy, 1995). The potential benefit of the integration of these technologies to improve agricultural production while simultaneously reducing environmental degradation may be one of the greatest contributions of GPS/GIS to human populations. Precise GPS location in the field is the key to precision farming data management (Usery, et al., 1995).

The basis for precision farming is field variability. Ideas of within field variability surfaced as early as 1929 with approaches to measure the spatial variability of soil acidity (Linsley and Bauer, 1929). Modern manifestations of the concept have resulted in field positioning technology (GPS), variable rate technology, and yield monitoring (Goering, 1993). Variable applications of inputs may not increase yields but simply hold them constant while reducing input costs. The farmer reaps increased profits through better management and fewer chemical applications, which also helps preserve the environment. Others report (Lowerberg, 1997) that the technology does not increase profit, it only reduces the risk of a bad crop. In a three year study on six farms the average return was the same, with less spread. Precision farming is attracting a great deal of interest among producers, industry, and the public sector. Applying nutrients at rates according to plant need has the potential to increase profitability for the producer and in certain cases may reduce nutrient loss and lessen the environmental impacts associated with nutrient application (Malzer 1996). The challenge is to interpret field spatial variability in a manner that will allow the most profitable rates of application without over-fertilization.

Precision farming requires precise knowledge of soil properties and soil-landscape processes (Bouma and Finke, 1993; Burrough, 1993; Larson and Robert, 1993; Mulla, 1993). Detailed soil maps at scales of 1:6000 or 1:8000 and spatially variable soil attribute data are needed to guide soil specific crop management in most landscapes (Moore et al., 1993). Conventional soil survey maps, however, are produced at scales of 1:15,000 and larger and as such, these maps seldom delineate all of a field's variability (Fisher, 1991). Similarly, the range of soil attribute values reported for most mapping units is sufficiently large that these data cannot adequately represent soil attribute variation (Moore et. al., 1993). Moore reviewed the various sources of digital elevation models (DEMs) and noted that GPS technology provides a rapid and relatively inexpensive way of obtaining data for the development of DEMs. This new technology offers important advantages in terms of scale and accuracy for soil specific farming applications given that the traditional sources of elevation data (e.g., 1:240000-scale USGS contour maps) and the 30m DEMS derived from them with Z values rounded to the nearest meter offer data at too coarse a resolution for most precision farming applications.

Two years ago, Geophyta,Vickery, Ohio, looked at the variability of nutrients across the field as part of the process of developing a soil sampling machine (Wright, 1995). First, they documented the presence of significant vertical stratification for most all nutrients and all soil types. This stratification is typically linear. Hence, the depth of the soil sample may have a dramatic effect on results. This vertical variation in soil bound nutrients is a function of past production practices, particularly fertilizer application and tillage. Vertical stratification of water soluble nutrients such as nitrate are typically even more striking. They show that variability within a 10' by 10' area was just as great as expected across an entire field. The interpretation of the data shows that down to the 1' level has seen a significant reduction in variability. Note this is a reduction in variability not the elimination of variability. If the fertilizer was applied in strips across the field (i.e., banded), how many cores are taken to solve this small problem on non-uniform application. It has been estimated that >200 cores may be required to adequately estimate phosphorous with banded placement and narrow bands (Pierce, 1996). Wright (1995) interpretation is that a sample "may" represent a 5' square area. This is an interesting observation, since data from UC-Davis indicates that the maximum grid size for water soluble nutrients is 7' (Crosby, 1996). Also, engineers at UC-Davis are working on fiber-optic spectrometer based real time soil fertility monitors to analyze lignin, cellulose, NPK, and pH (Crosby, 1996). At present, research at Oklahoma State University is showing that field element size (measure of the available nutrients were the level of that nutrient is related with distance) will seldom exceed 21 sq. ft. (Raun, 1997).

The development of precision farming technology has encouraged several investigators to look at variability of nutrients across fields. Predicting the most profitable amount of N to apply at any given location in a field is the key component to a precision farming system. (Kachanoski, et. al., 1996). A typical Site-Specific Technology (SST) grid sample represents 3.7 acres or 0.27 samples per acre. USDA/ARS University of Nebraska researchers sampled fields at rates of 14, 22, and 42 samples per acre. They concluded the optimum sample rate (cell size) is field dependent. In no case was the 3.7 acre grid even close to optimum for mapping actual variability. Studies at Iowa State using 15-meter grids showed the sample results. Analysis of a representative sample from 10 acres costs $7/sample and should be good for 4 years for a value of 17.5 cents/acre/year. The average removal of N,P,K from two years of corn and two years of soybeans represents $22.20/acre/year. Hence, $0.175/acre vs. $22.20/acre is obviously a good investment (Neppel, 1996). Unless there is a reduction in soil fertility because of excessively high fertility levels, soil testing will not save money. Soil testing can only make money when it identifies an area of a field where nutrients limit yields. Crop yield and soil test levels are two of the main factors used to predict fertilizer requirements (Penney, et al., 1996).

The application of geostatistics aids in interpolating between sampling sites, reducing the number of samples needed to provide a given level of area-specific knowledge Webster and Burgess (1993). However, geostatistical approaches are still limited by fundamental mathematical considerations: the greater the variability of the soil, the more samples that need to be taken to achieve any given level of mapping accuracy. Mapping soil accurately is an important aid in deciding nutrient needs, application rates, and application locations (Miller, 1988). Soil and tissue sampling helps considerably but are limited by sampling density. Too few samples provide too little information, but a sufficient number of samples can cut into profitability. Aerial photography can be utilized to map soils and plant nutrition quickly and easily. Using the computer-enhanced photo as a guide, it is much simpler and less expensive to sample in key locations and use the photo as the map (Porter, 1996).

One of the limitations in the adoption of site-specific management techniques such as variable rate fertilization is the effort and resources required to obtain necessary soil information for the site (Cotter, et al, 1994). Information on soil fertility variations in landscapes can be provided by remote sensing, including aerial photography in which soil color is related to organic matter content and soil fertility. While this approach is simple and relatively inexpensive, it may be limited by the rather indirect relationship that often exists between soil color and fertility. (Schoenau and Greer, 1996). Remote sensing of environmental factors important to crop growth, both for long-range, such as aerial photography and satellite imagery, and short-range, such as ground penetrating radar (GPR) and electromagnetic induction, provides accurate information of field variability with geo-positioning (Rutchey and Vilcheck, 1994). For example, long-range sensing includes the determination of soil type variability from aerial photography to estimate spatial relations of soil fertility (Gerbermann, et. al, 1988). Nebraska research is showing how remote sensing tools such as aerial photography can increase the accuracy and cost effectiveness of soil sampling approaches for variable-rate fertilization. The study also shows how a composite soil sample from a variable area can underestimate phosphorus (P) fertilizer needs. Overall, aerial photographs help identify areas of a field that are likely to vary in certain soil properties. Caution should be employed to ensure that past management of the field or other factors have not mitigated the intended relationship. But if these relationships exist in other fields, it has the potential to provide a high resolution information layer at a potentially affordable price (Blackmer and Schepers, 1996).

Soil surface conditions can be detected with multi-spectral video (Everitt, et al, 1989). Aerial video imaging is used to identify vegetal conditions and discriminate between crop and weed species (Nixon and Menges, 1985). Plant stress and insect infestation can be determined from video images (Everitt and Nixon, 1986). Short-range sensing with GPR has been used to measure soil characteristics such as location and attributes of hardpans in clay soils and depth to bedrock (Raper, et al, 1990).

Electromagnetic induction uses a short-range sensor to determine soil conductivity and to estimate salt content, soil texture, water content, and yield potential across the field (Suddeth, et. al, 1994).

Each remotely sensed data set must be precisely registered to a standard set of control. The approach used is to establish ground control points (GCP) within each field and to use these GCPs to establish the locational coordinates for each data layer generated. While the GCPs account for locational correspondence among data layers, other factors such as precision of the collected data can introduce inaccuracies (Birrell, et. al, 1993). To minimize these inaccuracies, and coincide with remote sensing accuracy, GPS precision farming positioning accuracy of one meter is required.

Information picked up by airplanes and satellites will help farm operators maintain healthy, high yielding crops with minimum use of irrigation water, fertilizer, and pesticides. An Agricultural Research Service project now underway in Arizona is aimed at demonstrating how remote sensing can be used in farm management (Senft, 1996). Through observations, which included crop type, estimated plant height, growth stage, percentage crop cover, soil surface texture and dampness, and presence of insects and weeds, were matched to the video images. The advantages of video images for farm management are the fine spatial resolution (about three to four feet) and the potential availability of data immediately after the flight. The ARS in Texas has also established spatial signatures of dozens of plant, soil, and water conditions that can be used to identify pest and nutrient problems on range and croplands (Quattro, 1996). Within two years, plans call for launching the first commercial satellites for providing crop information to farmers within a day after it is obtained. By summer, 1999, four satellites will eyeball every crop acre on earth about twice a week, from 450 miles up.

All plants reflect sunlight differently. These differences are sensitive to Landsat bands four, five, and seven and are especially valuable as they measure the variance in the infrared range (Waits, 1991). Each crop has a major impact on the unique spatial signature that is produced (Stone, et al., 1996). Variations within crops can be considered; for instance, a well watered healthy crop in one field will reflect more infrared light than a poorly watered field next to it. This is based on the fact that healthy leaves reflect near-infrared light while absorbing red light (Denison, et al., 1996).

The spectral response of plants is affected by outside factors such as atmospheric particles, PM-10 produced by common agriculture particles from plowing and harvesting (Flocchini, 1994), plant spacing, and dust and moisture residue. Despite these problems, remote sensing is useful in monitoring vegetation because the variations in infrared reflectance between homozygous crops are less than variations in infrared reflectance in heterozygous crops (Hough, 1994). Until now, land cover and land use data have been merely acquired from terrestrial surveying and visual aerial photo interpretation. Photo interpretation is based on human vision and pattern recognition capabilities. Identification of terrain objects is based on nine interpretation keys: pattern, tone, texture, shadow, site, shape, size, association, and resolution (Avery and Berlin, 1985). The interpretation process can be facilitated by viewing the photographs stereoscopically. Air photo interpretation keys also assist the interpreter by offering guidelines for the identification of certain information classes. Objects are distinguished by a combination of both geometric and thematic properties (Lillesand and Kiefer,1987). A good example is the delineation of individual trees in a forest stand. As a result of an interpretation process, a representation of the world is obtained consisting of terrain objects with a geometric and thematic component. Therefore, both visual photo interpretation and terrestrial surveying are typically directed to vector-based data of terrain objects describing land cover or land use.

Remote sensing is a data acquisition technique by earth observation satellites, such as Landsat and SPOT, that measure the relative amount of electromagnetic radiation as reflected by the earth's surface. This is a simple process of dividing the earth's surface into equal areas called "sense elements". The corresponding image representation of a sense element is known as a picture element or pixel (Janssen and van der Wel, 1994) The measurements of these elements in several spectral bands are converted and stored in a limited number of quantization levels (Gilabert, et al., 1992). The stored values are referred to as digital numbers (DN). A remote sensing image can be characterized by an image space and a feature space. The portion of a pixel represented in the image space is determined by a unique row and column index (i,j). The relative spectral reflection values (DN_1,...,DN_n) can be represented in the N-dimensional feature space. In most projects, remote sensing images undergo two transformations:

- A registration of the image coordinate system into a certain map projection enabling other geodata to be used; and
- A classification of the continuum of spectral data into normal user desired classes (the most subjective transformation).

The classifications or interpretations of remote sensing images can be performed in a visual or a digital way (Janssen and van der Wel, 1994). Visual interpretation offers more or less the same characteristics and properties as visual photo interpretations. Until now, most digital interpretations have been based solely on the per-pixel multi-variate data. These per-pixel classifications are limited to the interpretation element "tone" used in visual interpretation. This limitation has two major implications:

- Per-pixel classifications by definition yield spectral classes mainly related to land cover, where land use is merely determined from contextual and associative information (Campbell, 1987). Land cover designates the visual evidence of land use to include both vegetative and non-vegetative features.
- Per-pixel classifications yield thematic information per raster element. When looking at a classification result, although one can distinguish fields for instance, it should be noted that terrain objects as such are not explicitly stored. The raster data derived from remote sensing should be considered as point data that have a certain spatial extent (Janssen and van der Wel, 1994).

Landsat satellite imagery records the average spectral characteristics of a 30 x 30 meter area. There are other methods of remote sensing with greater accuracy, e.g., the Panasonic 3 CCD S-VHS camera filmed from a height of 2400′ at full lens field of view gives a 200′ wide film path with a resolution of 2.86′ per pixel. At full 16-X telephoto magnification, the flight film path width can be reduced to 124' with a resolution of 2.25" per pixel (Baker, 1993). Where precise measurements are needed, individual scenes are geo-referenced using GPS procedures.

Remote sensing is most commonly used to identify vegetal conditions and discriminate between crop and weed species, detection of plant stress, and insect infestation (Barnes, 1994). Remote sensing uses recent GPS developments to manage spatial variability in fields through determination of referenced inputs (e.g., nutrients) which affect soil fertility and chemical applications for controlling insects and weed pests (Chancellor and Goronea, 1994). GPS precision tolerance for remote sensing is ≤ 10 meters based on current SPOT imaging capabilities.

Maintenance applications are determined from yield maps generated from on-the-go yield monitors, with yield data also geographically referenced by GPS systems. The expectations that crop yield maps will match variability in soil test maps will most likely lead to disappointment. If the field has been managed according to a good soil testing program, soil fertility has likely been eliminated as a major limiting factor in determining yield. Most yield variability is likely to be more directly caused by other factors such as compaction, water management, tillage, pest problems, etc. (Reetz, 1996).

Yield variation monitoring has been used to measure yield variation in corn, soybeans, wheat , peanuts, and cotton (Schueller and Bae, 1987; Hunsaker, 1992). Yield mapping combines accurate location information with the results of a variable flow rate sensor. The resulting yield variability map can then be used to spatially locate high and low yielding areas of marginal interest for future investigation (Aurenhammer, et al. 1994). The future of GreenStar™ precision farming systems looks bright. Combine yield mapping is only the first step of a precision farming program. John Deere is committed to completely integrating precision farming systems, across all its product lines (Gerstner, 1994).

The development of continuous yield sensors, and their subsequent linking to DGPS provides location information with the most important and influential development in precision farming data collection. Yield rates which vary spatially require different sensing techniques, depending on the type of crop being monitored. The greatest progress has been achieved with grain flow measurement for corn and wheat (Scheller and Bae, 1987). Continuous sensors for cotton yields have been tested (Hunsaker, 1992). The National Environmentally Sound Production Agriculture Laboratory in Georgia has developed and tested sensors for measuring yield variations in peanuts. Maps produced from these systems are hard evidence of the degree of within field variability (Baker and Carroll, 1996). The magnitude of this variability is a good indicator of the suitability of implementing a spatially variable management plan. Yield maps need to coincide with the boundaries of the field (Sampson, 1993). To minimize boundary violations and maintain confidence in the decision support system, a GPS precision accuracy of ≈ one meter is required for yield monitoring.

Variable rate technology has been implemented in the use of multiple flow rate fertilizer spreaders that vary application across the field to match the local requirements and manage weeds with flow-rate control sprayers. Variable rate technology herbicide applicators and sprayer designs have been developed (Shearer and Jones, 1991). The Variable rate technology operation must be linked to a geo-referenced fertilizer application map, providing combination GPS and application rate requirements simultaneously (Delcourt and Baerdemaker, 1994). Similarly, spatially variable treatments have been tested for control of pest from pest maps (Schueller and Wang, 1994). Also, federal regulations call for a spraying buffer zone along waterways and some environmentally sensitive areas (Sampson, 1993).

Currently, one of the driving forces behind variable-rate fertilizer applications is sugarbeet production. Sugarbeet profits come from both yield and sugar content. Nitrogen (N) is very important to achieve high yields, but excess N decreases the concentration of sugar, increasing impurities and reducing premiums paid to producers. Variable-rate N fertilization has helped maintain high yields while increasing sugar content, making it a highly profitable tool for sugarbeet growers. Studies in the northern Great Plains are indicating substantial within-field variability of several nutrients. Preliminary indications are that topography may be an important consideration in sampling these fields for variable rate applications (Franzen, et al.,1996). Grid sampling should identify variability in nutrient status, improve the sugarbeet grower's bottom line by identifying excess soil NO_3-N levels and reduce the levels before sugarbeets are again planted in a particular field (Smith and Rains, 1996). GPS and associated technologies have made variable rate technology applications of fertilizer easier to perform. The fertilizer is applied where it is needed and at the proper rate (Anderson and Bullock, 1996).

The first dollar of profit from precision farming will be generated by guiding fertilizer implements or manure applications to areas of the field where yields in the past have been hindered from inadequate nutrition. The resulting yield variability map can then be used to spatially locate high and low yielding areas of marginal interest for future investigation (Aurenhammer, et al., 1994). To link variable rate technology of fertilizer to a desired geo-referenced fertilizer application map, the operator must know field location and map location simultaneously. From the map location, the operator can identify the correction application rate for the current field position. In order to minimize overlaps and skips, a positioning accuracy of .9m is desired, 4.8m is the very maximum for variable rate technology (Lutter, 1997)

GIS can store yield data through time and allow a user to compare yield at a specific location with the nearest soil point. It is a technology for combining and interpreting maps. Like other new technologies, GIS concepts are simple; the terms are complex (ESRI, 1990). In the real world, the landscape is composed of soils, crops, water, biological life, etc. In the paper world, these are represented by words, numbers, and graphics.

Schueller (1992) presents a case for using a GIS as the hub of an integrated system for precision farming data management. GIS may be described by its processes, data, and analytical functions. The GIS processes involve encoding, storage, processing, and delay of computerized maps. Processing functions include computer mapping, spatial data base management, spatial statistics, and cartographic modeling. These functions are descriptive, imperative, and perceptive in nature.

Computer mapping is descriptive as it rapidly creates and updates map products. Spatial data base management combines and interprets map data. A data base map can be searched for map compartments with certain requirements (such as low water values in a certain soil type) then produce a map locating these areas (ESRI, 1993). Map compartments can have both a locational attribute and a thematic attribute -- what and where.

"To use a mapping program or a GIS program, it depends on what you want to do with your data. If you just want to display your maps of yield data, soil types, soil sample points, or where you planted certain varieties, then a mapping program is what you need. But if you want to analyze those maps spatially, then you need a GIS program. Just knowing about a particular aspect of your field in itself does not put money in the bank. Taking that knowledge and applying it properly is the only way that you will see that happen" (Niewohner, 1997). Template maps can be summarized for typical characteristics (such as crop for each mapping compartment) which can be added as a new field in the data base. Part of the revolution in GIS simply involves "digitizing" familiar maps (Berry, 1995). GIS map analysis involves spatial statistics and map-emetics, allowing users to model a complex resource or environmental system -- describing, interpreting, and prescribing its use (Lass and Callihan, 1993).

The precision farming system record the amount of grain harvested every few feet and the position of the combine as it moves across the field. The numbers are crunched by a GIS computer program to produce a color-coded map showing variations in grain yields across the field (Medders, 1996). Soil salinity and weeds are a major cause of reduced crop production in many soils of the Great Plains (Prather and Callihan, 1993). New measuring techniques combined with GPS are improving the accuracy of soil salinity and weed mapping. GIS allow data from yield, salinity, topography, fertility, weeds or other maps to be combined and analyzed to generate accurate variable rate input maps. Salinity maps are one more tool in a farmer's arsenal to better utilize and manage the information needed for precision agriculture (McKenzie, 1996).

To succeed, a precision farming GIS application must include precise geographic positioning for all data layers and ground control for all image sources and on-the-go coordinate measurements (Usery, et al., 1995). DGPS provides the needed accuracy and the capabilities for both static and dynamic measurements of coordinates associated with precision farming variables. Integrating the DGPS collected information with GIS allows the necessary manipulation and analysis to support generations of farm management decisions and digital maps which can be used to drive variable rate technology sprayers and fertilizer applicators.

Global Positioning System

Location expressed in geographic coordinates of latitude and longitude can be determined with GPS. Locations in the field are the key to precision farming data management. Each collected data set must be precisely registered to a standard set of controls. The development of continuous yield sensors and their subsequent linking to DGPS location information is the most important and influential factor in precision farming data collection (Kee and Parkinson, 1991). GPS positioning of GIS data layers allows analysis to determine local coincidence among yield rates, fertility, and pest control. The location coincidence may become input information to guide variable rate technology applicators to spraying targets.

Several studies have been undertaken to analyze and measure the accuracy achieved with different techniques including differential-corrected signals, sequential fixes for the same location using raw uncorrected signals, and multiple reference stations (Palmer, 1994). The Department of Defense states that 95 percent of GPS, Figures 1 and 2, fixes with four or more satellites will be ±100 meters horizontally when Selective Availability is operational (Georgiadou and Doucet, 1990). There are many sources of error that can degrade the quality of GPS-derived positional data. These include obstructions on the horizon, interference of satellite signals by forest canopy, atmospheric disturbances, poor satellite geometry, Selective Availability, and reflections (multi-pathing) of satellite signals (Puterski, et al., 1990; Hurn, 1993; Wilkie, 1989). Differential GPS, Figure 3, correction markedly improves the accuracy and position of GPS data. Differential correction under ideal conditions generates three to seven meter average distance from true for single fixes, with 95 percent of all fixes within 10 to 15 meters. Averaging 300 sequential fixes for the same location improves the accuracy to better than three meters with 95 percent of all fixes within four to six meters depending on the site (August, et al., 1994).

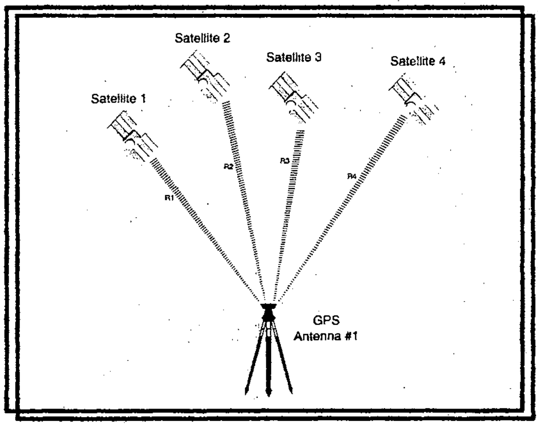

Figure 1. Point Positioning GPS

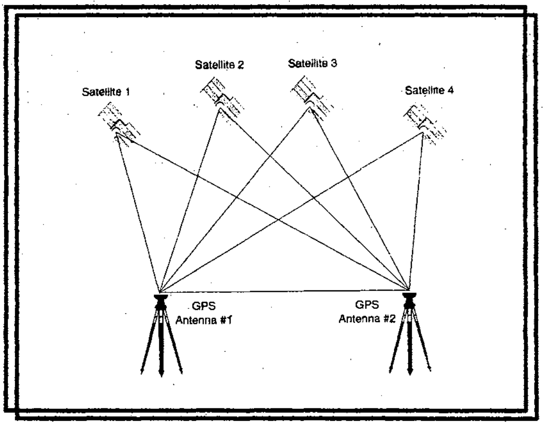

Figure 2. Relative Positioning DGPS

With static DGPS two receivers are required, one receiver is positioned on a point of known position, each observes one satellite at the same time (Figure 3). At that instant (epoch), the receiver at point 1 and 2 have determined the pseudorange to the satellite (Rockwell, 1994). The distance from 1 to 2 is unknown, but as can be seen, the three lines (1 to S1, 2 to S1, and 1 to 2) form a triangle. All three lines are in the same plane. When each receiver observes four or more satellites at the same time, receiver position is established. With the position of the receivers and satellite are known, Figure 3 becomes a vector diagram (Reilly, 1997e). Vector (1 to 2) = Vector (1 to S_1) - Vector (2 to S_1). This is called the coplanarity condition. If the vectors to the satellites were accurate, the distance and direction from 1 to 2 would also be accurate (NMEA, 1994). When the same receivers determine the vectors to the same satellite a few seconds later, Figure 4, the following condition exists: Vector (1 to 2) = (Vector 1 to S_2) - (2 to S_2). For every satellite observed by the two receivers, a new set of observations are generated to determine the vector from 1 to 2. This is the basic concept of DGPS (Trimble, 1993).

The work proposed herein closely parallels the research conducted by Jiun-tsong Wu of Cal-Tech for NASA's Jet Propulsion Laboratory, entitled "Compensating for GPS

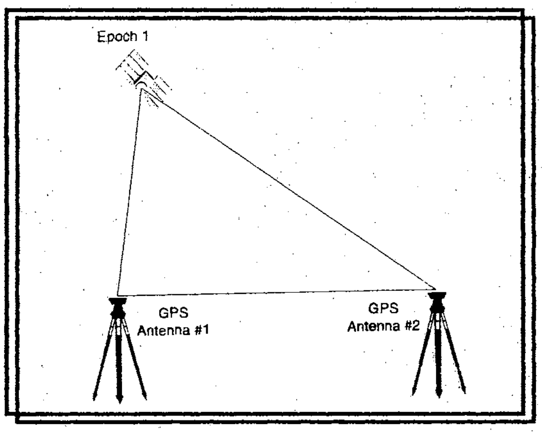

Figure 3. Vector Diagram I

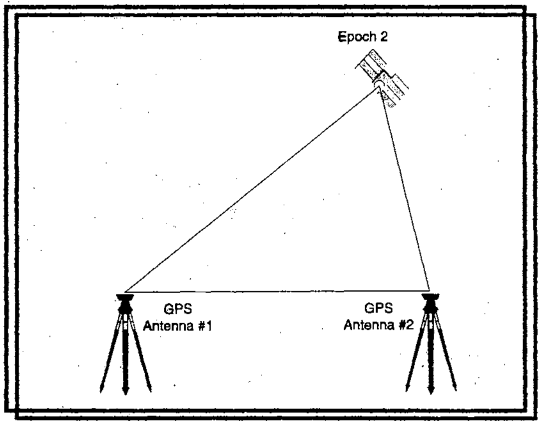

Figure 4. Vector Diagram II

Ephemeris Error." For the simulations performed in this research, multiple receiver stations several hundred miles apart were used (sparse network). The conclusions drawn from the simulations were very encouraging to the proposed dense network of reference stations. In Wu's research, a linear combination method using two reference stations several hundred kilometers apart is shown analytically to cancel the GPS ephemeris errors. Numeric simulations indicate that the combination reduces the errors by about an order of magnitude compared to the conventional differential techniques. The degree of improvement over the conventional differential techniques is dependent on the relative links of the baselines, the distance from the reference receivers to the user station (Wu, 1992).

The groundwork for precision farming was laid in February 1978 when the Department of Defense launched its first Global Positioning Satellite (GPS) to assist artillery batteries pinpoint targets and submarines to determine their locations (Reilly, 1996c). Now accessible to civilians, these satellites transmit longitude, latitude, and altitude signals necessary to pinpoint exact locations on earth. GPS is a navigation system consisting of a constellation of 24 satellites in six orbital planes that provide accurate three-dimensional positioning and velocity as well as precise time to users 24 hours a day. Each of the satellites transmits on the L-band frequencies (1575.42 MHz) using independent Pseudo Random Noise code for their spread spectrum modulation (Wells, 1987). Satellite data consisting of system status, ephemeris, and clock characteristics are also transmitted using modulation at 50 bits/sec. User receivers measure their apparent range to the satellite by processing the received signals to determine transit and correction for atmospheric delay using stored and broadcast models. Since the location of the satellites at the time of signal transmission is known from the broadcast ephemeris, the location of the receiver can be triangulated from the range measurements. The receiver's local clock error can be estimated by incorporating one or more satellite's range measurement to the number of dimensions being solved.

The accuracy of position determined by GPS is highly variable, depending on the mode employed. A single receiver which records the commonly degraded (selective availability) signal will provide geodetic position accuracy of approximately 100 meters (Hoffman, et al.,1994). If the signal is not degraded (a security consideration), the accuracy may be in the range of 25 meters. If differential GPS (DGPS) is utilized, the accuracy approaches one meter (Reilly, 1996a), accuracy of two to five meters can be consistently obtained (Kee and Parkinson, 1991). This mode involves one or two receivers being located on a control point with the other on the point to be located. The distance between the two receivers should not be more than 100 km (Colvocoresses, 1993). GPS for environmental applications using inexpensive three-channel GPS receivers derived within 75 meters of true coordinates without differential correction and within six meters with correction (August, et al., 1994). Differential GPS (DGPS) has provided a solution to the SA problem for many years. DGPS requires access to these corrections either through real time radio links or through computer data files for post-processed application.

United States authorities have announced a partial solution to the Global Positioning System (GPS) Selective Availability (SA) problem. Beginning at the transition between 23:59:59 GPS Time (GPS Time is currently ahead of UTC by eleven seconds) on March 31, 1997 and 00:00:00 GPS Time on April 1, 1997, the new Global Positioning System Availability Function (GPS AF) became operational. This will impact GPS receivers error which is divided into broad categories: bias and noise. Bias is represented as offset from truth in the GPS position. A bias is typically evident as a relatively constant or slowly changing error. A GPS system that has a bias may still offer a very high repeatability, but the positions are not necessarily accurate with respect to truth. System noise, on the other hand, is often evident as a random fluctuation in the positions that are computed. Noise can be represented as recurring errors that are periodic (Gilbert, 1994). SA is the intentional degradation of the GPS Standard Positioning Service (SPS) through the introduction of slowly varying biases with correlation times from as few as five seconds to several hours. Because the SA bias introduced into each GPS Space Vehicle (SV) signal is controlled separately through an encrypted pseudo-random noise (PRN) generator, the simple averaging of positions obtained while tracking GPS SV signals does not provide a significant reduction in error unless this averaging is done over periods of several hours.

GPS SPS users have had to accept the 100 meter horizontal (156 meter vertical) position error in GPS or pay for the required equipment and be within range of a DGPS service (Langley, 1997). This has placed severe restrictions on the civil use of GPS. Some users who require accurate positions only occasionally, or time and frequency users who only need precise GPS timing signals periodically, have lobbied for some time for a sub-set of SVs to operate without SA. Others have suggested only emergency implementation of SA. Most users who already know their position (through long term averaging or by utilization of a United States Geological Survey 1:24,000 scale topographic map) have noticed that GPS position solutions do occasionally approach a minimum error at least once during each hour (Mueller, et al., 1993).

What may be a solution for many GPS SPS users was implemented on April 1, 1997. The Global Positioning System Availability Function (GPS AF) is a method by which users can compute specific moments in time when SA reaches a minimum for the combination of SVs tracked by any SPS receiver. The simple AF algorithm can be implemented either in real time or in post-processed applications.

AF is a simple algorithm based on the GPS Week Number (the number of weeks from the GPS epoch of June 5, 1980), the GPS Second (the seconds in GPS Time from the beginning of the week (Saturday midnight GPS Time), and the PRN (the satellite C/A code identification number) number of each of the SVs tracked by the receiver. The GPS week number (899 for the week of March 30 through April 5, 1997) is first added to the sum of each of the PRN numbers of the tracked SVs (NMEA, 1994). The result modulo the GPS Second divided by 1023 is the time during that hour when the SA terms for those satellites combines to a minimum value.

One should be aware that this does not remove ionospheric delays, multi-path errors, receiver noise, or tropospheric delays in the GPS SPS signals (Wells, 1987). The Availability Function only reduces the effects of SA for those users who apply the algorithm. The AF algorithm does not provide a means of removing the effects of SA except for those specific moments of time (+/- 5 seconds) predicted by the AF algorithm. The AF algorithm is designed to allow prediction of SA minimums only and does not provide a means of removing SA between these predicted SA nulls.

Users should cautiously apply the GPS AF algorithm, and it is suggested that they always compare results with a DGPS-derived solution. Timing users can simply check the GPS time solution by comparing to a known one-pulse per second standard. Frequency users can compare the special purpose GPS frequency control receiver output to an inexpensive rubidium standard. After a period of initial operational testing (not specified), AF may be considered as a part of the full operational capability of GPS.

The ability of GPS to establish accurate horizontal control is widely accepted, and differential elevation accuracy over limited areas is nearly as good. Absolute elevation accuracy is limited by knowledge of the geoid (which is a surface closely approximating Mean Sea Level). Its shape is affected by topography and mass anomalies in the earth's crust. At any point, the elevation determined directly from the GPS geometry is the elevation (h) of the terrain above the reference ellipsoid (Reilly, 1995). To convert this to the conventional orthometric height (H) above Mean Sea Level, the height of the geoid (N) referenced to the ellipsoid must be subtracted from the ellipsoid height ($H = h - N$). World-wide geoid heights (for WGS 84) range from plus 75 to minus 104 meters. In the continental U.S. the geoid is always below the ellipsoid, with values ranging from -5 to -53 m. The NGS has developed an improved model, GROID 96, with a Lat/Long grid spacing of 2 minutes (Cheves, 1997). At each post the value is given to convert GPS ellipsoid heights to the latest North American Vertical Datum of 1988 (NAVD 88), with an accuracy of ± 6 centimeters (Featherstone and Langley, 1997). Appropriate use of GEOID 96 takes agriculture closer to the goal of using GPS for every day three-dimensional data.

The former Soviet Union has developed a satellite system similar in design to the GPS called Global Navigation Satellite System (GLONASS). There are 24 GLONASS satellites in the Soviet constellation, the same as in the United States GPS constellation. GLONASS, like GPS, is a military system. Unlike GPS, there are no premeditated measures for the precision dilution of navigation parameters. That means no selective availability (SA) or Anti-spoof (A/S). Because of this the European geodetic community is supportive of GLONASS, perhaps more so than GPS (Reilly, 1996b).

Using the increased accuracy and availability of GPS, the National Geodetic Survey (NGS) is establishing a nationwide High Accuracy Reference Network (HARN) survey. In Georgia, NGS is establishing stations to A and B order accuracy that are spaced no more than 50 km apart (Johnson and Lyle, 1994). The coordinates of the HARN are referenced to the NAD83 coordinate reference system, which is the national horizontal datum.

The HARN provides states and county agencies, local municipalities, and the private sector a well-defined and consistent reference system for the creation of Land Information System (LIS) and GIS databases. The Federal Geodetic Control Subcommittee (FGCS) Standards and Specifications Table I, Federal Geodetic Control Subcommittee Accuracy Level, were modified (Hartzheim and Forsburgh, 1995) to include a 1:500,000 (2 ppm) and 1:250,000 (4 ppm) classification. Order A accuracy (1:10,000,000 or 0.1 ppm) relative to the Cooperative International GPS Network (CIGNET) and the Eastern Strain Network was not used in this research study.

There are compilations of GeoData Information Sources (digital cartographic data) on the Internet, which include over two dozen links to individual data source directories; lists of federal, state and regional sources; and links to documentation, data formats and standards. There are topic sections for Remotely Sensed Data, Topographic Digital

TABLE I

MODIFIED FGCS DISTANCE ACCURACY STANDARDS

NETWORK DENSIFICATION	ORDER	CLASS	RELATIVE ACCURACY	
			Proportional 1:a	ppm
Primary	B	I	1:1,000,000	1
Secondary	B	II	1:500,000	2
Tertiary	B	III	1:250,000	4
Geodetic	1		1:100,000	10
Section Corners	2	I	1:50,000	20
Photogrammetric	2	II	1:20,000	50
Topographic and Construction	3		1:10,000	100

Elevation Model (DEM) Data, Atmospheric Data, Climatic/Meteorologic Data, Hydrologic Data, Oceanographic Data, Biochemical Dynamics (Ecosystems). Geological and Geophysical Data, Paleoclimatic Data, Environmental Data, Census Data, and Geodetic and GPS Data (Riley, 1997).

Some Geodetic and GPS data links include: FGDC Clearinghouse Gateway at http://fgdclearhs.er.usgs.gov/ and the Center for Advanced Spatial Technologies at the University of Arkansas, http://www.cast.uark.edu/local/bunt/index.html. These are free on-line U.S. Geospatial and Atrribute Data sources.

These HARN sights provide the starting point for establishment of necessary ground control points (GCP) within each field. The GCPs are used to define locational coordinates for each GIS data layer generated. Typically, the GCPs are established using precise DGPS techniques to horizontal and vertical accuracy less then 0.1 meter. A minimum number of GCPs are determined based upon field size and shape with an absolute minimum of four points. The GCPs are targeted to appear in aerial photographs and visual images and are used to rectify GIS data layers (Lachapella, (1992). DGPS provides the needed accuracy for both static and dynamic coordinate measurement associated with precision farming variables, and its integration with GIS is necessary for manipulation and analysis supporting farm-management decisions. In addition, digital maps for variable rate technology sprayers and local control of variable rate technology equipment need GPS input.

GPS accuracy needed for precision farming is a function of soil variability. Large differences in soil tests from one part of a field to another have been observed. This variability stems from both differences in soil types and past soil management. GPS resolution is dictated by the agronomic-based field element size, based upon a linear drift of soil nitrogen content vs. distance. The first investigated drift of nitrate nitrogen was measured for cotton (Tabor, et al., 1985). It was observed that nitrate nitrogen has the shortest range ($\leq$ 5 meters) of spatial correlation of five elements or compounds (organic carbon, soil water, phosphate, potassium, and nitrate nitrogen) (Chan, et al., 1994). An investigation of spatial variability effects of mineral nitrogen on wheat found a field element size of one meter (Chancellor and Goronea, 1994). Other research indicates that total nitrogen field element size varies from 0.86 to 1.5 meters, depending on whether nitrogen had been applied in the previous fall (Solie, et al., 1996).

In order to optimally manage a field, an agronomic optimum field size must be defined. As the name implies, this is the field element size that can be managed to economically optimize production (maximize yields while minimizing inputs). The agronomic optimum field element size establishes the key positioning criteria for precision farming.

Research by Stone, et al., (1996) and Solie, et al., (1996) established an agronomic-based field element size in the range of one meter in their studies of the total nitrogen uptake in winter wheat. The sensor data collected as part of Stone's research was used to determine fundamental field element sizes based on the total nitrogen uptake of the wheat plants. Research by Solie, et al., (1996) established a fundamental field element size for total nitrogen uptake at between .86m and 4.6m, depending on whether nitrogen had been applied in the fall, and a field element size of .86m to 1.5m was established for both fall and non-fall applications. Although the agronomic optimum field element size is considered the key criterion, analysis of other important variables, considerations, and operations in precision farming (e.g., soil variability, variable rate technology, yield monitoring, environmental conditions) also supports a one meter (or better) GPS positioning requirement. Table II, Precision Farming Positioning Requirements, summarizes selected positioning criteria established in the analysis.

Manufacturers of precision farming equipment and DGPS service providers are dictating accuracy requirements for agriculture operations. This is backward from the way it should be. It has been observed that users generally do not understand the origin of the GPS requirement nor do they have confirmation that the equipment operates within specifications, which is a source of great concern. Very little basic research is available that focuses on defining precision farming's "true" requirements with Solie, et al., (1996) being an exception.

The precision farming requirements (Table II, Precision Farming Positional Requirements) were developed as part of the project effort and represents the result of the research performed to specifically define by requirement by operation. This table represents a composite of information gathered from: (1) A survey of growers regarding their operations using precision farming technologies, (2) Review of research and journal articles, (3) Review of companion technologies emerging from basic research projects, (4) Review of manufactures of precision farming equipment, and (5) Planned

TABLE II

PRECISION FARMING POSITIONING REQUIREMENTS

KEY VARIABLES	POSITION REQUIREMENT*	KEY CONSIDERATIONS
Agronomic Field Element Size	.86m ≤ 1.5m	Optimize yield, Stone et al. (1995), Solie et al. (1995)
Soil Variability and soil sampling	1m - 2m	Optimize yield, nutrient lateral migration, Solie et al. (1995), Lutter (1997)
Yield Monitoring and harvest mapping	1m	Management of yields, boundary conditions, Lutter (1997), Sampson (1993)
Tilling, Guidance, Control Applications and ground control points	.1m ≤ 1.8m	Varies by crop Lutter (1997), Lachapella (1992)
Remote Sensing	1m - ≤10m	Correlation of GPS Positioning with remote sensing image resolution Barnes (1994), Chancellor and Goronea (1994)
Regulatory Compliance	1m	Boundary conditions Sampson (1993)
Variable Rate Technology, fertilizer/pesticide application	.9m to < 4.8m	Optimize yield, minimize overlap and skips, Lutter (1997), Crosby (1996)

*m = meter cm = centimeter

enhancements in companion technologies (e.g., SPOT providing 10 meter resolution).

For most farmers, the initial GPS startup cost to enter this brave new world of precision farming is price prohibitive $20,000 for one meter accuracy (Corbley, 1997). Wide Area System unit is about $4,500 with an ongoing cost of approximately $600 to $800 per year for the GPS signal service. Each piece of farming equipment used in the precision farming operation must be equipped with an "appropriate" GPS receiver. It is interesting to note that in some manufacturers' advertising literature; the cost of an "appropriate receiver" is not given. This can be as high as $7,500 per receiver, or in the case of Omnistar™ it is bundled with the service. The most inexpensive option is the U.S. Coast Guard Differential Navigation Service, $1700 for a black box which hooks into a standard GPS receiver.

Receiver costs vary depending on capabilities. Small civil standard positioning system (SPS) receivers can be purchased for under $200, and some can accept differential corrections. Receivers capable of storing files for post-processing with base station files cost more ($2,000 to $5,000). Receivers that can act as DGPS reference receivers (computing and providing correction data) and carrier phase tracking receivers (and two are often required) can cost many thousands of dollars ($5,000 to $40,000). Military PPS receivers may cost more and be difficult to obtain. Other costs include the cost of multiple receivers when needed, post-processing software, and the cost of specially trained personnel (Swiek, 1995). Project tasks can often be categorized by the required accuracy which will determine equipment costs (Lutter, 1997).

- Low-cost, SPS receiver projects (100 meter accuracy), $150 - $400
- Medium-cost, differential SPS code positioning (1-10 meter accuracy), $3K - $9K
- High-cost, single-receiver PPS projects (20 meter accuracy)
- High-cost, differential carrier phase surveys (1 mm to 1 cm accuracy), $12K - $25K

Summary

Profitably and environmentally sound farm management planning may be achieved by managing within field variability. Precision farming planning involves recording yield, soil test, and soil properties with a precise description of the location (GPS) within the field where the georeferenced data were collected. Nutrient applications are varied based on maps that are created from geo-referenced (GPS) records of soil test values, soil yield potential, previous yield histories, and nutrient applications that can be coded into the computerized (GIS) record keeping system.

To begin a computerized record keeping system, select a software package (Waits, et al., 1997), that will allow organizing and linking field data with precise locations (GPS) within the field. Select a positioning referencing system such as latitude-longitude or a state plane coordinate system to spatially link all records. Soil test information, nutrient application, and yield record referenced to specific locations (GPS) within a field are important components of the field records. Additional information from photographs and other maps can be digitized into the record keeping system as the availability of time and technology permits. Investigate GIS computer software packages that can analyze and display geo-referenced field data as maps. Work with a consultant or advisor in analyzing computerized records to develop site-specific interpretations of individual fields. Farm level GIS applications are rapidly evolving with several companies developing farm level applications for sophisticated GIS packages currently used in research and education.

- Use GPS technology to pinpoint soil sample sites on a grid basis; soil test maps (through GIS) can be generated to serve as a basis for GPS guided variable rate nutrient applications.
- Pesticide applications can also be developed with GPS methods to fit application rates to soil type and specific pest trouble spots in the field.
- Portable electronic GPS scouting tools allow instant on-site analysis of soil and crop nutrient status to aid in identifying management problems in the field.
- Electronic communication systems permit ready access to suppliers, advisers, and other information sources to provide support services and reduce down-time during critical seasons. Cellular phones, fax machines, satellite and phone-modem communications, and hand-held, pen-based and voice-activated computers are becoming common farm tools.

Goals for farms in developing strategic plans that work toward precision farming:

- Make a commitment to keep accurate, detailed records of production inputs and yields for each field, including variability within the field.
- Begin collecting soil test and nutrient application information and crop yield data on a grid basis. Identify each sample with its exact location in the field. Use GPS location-referencing.
- Analyze records and develop a nutrient management plan that takes into account the variability within a field. Use spot spreading or variable rate application where appropriate.
- Measure yields for each field. Using on-the-go yield measurements to develop a yield map for each field is even better. Individual field yield records are a good starting point, but yield variations across the field must be measured to get an accurate check on response to site-specific management.
- Continue to add information each year and begin more detailed analysis of the records to refine the site-specific nutrient management plan. Even though the level of detail in different data sets will vary, each point in the field can be associated with each data set if all the records are properly geo-referenced. As technology improves, some data sets can be replaced with more accurate or more detailed data sets from the same parameters.
- DGPS provides the needed accuracy and the capabilities for both static and dynamic measurements of coordinates associated with precision farming variables. Integrating the DGPS collected information with GIS allows the necessary manipulation and analysis to support generation of farm management information/decisions and digital maps which can be used to drive variable rate technology sprayers and fertilizer applicators.

CHAPTER III

METHODOLOGY

Introduction

The purpose of this chapter was to describe the methods and procedures followed in conducting this study. In order to acquire data, in this Phase I of the SBIR/OCAST project, a project task plan was developed (Appendix B), GPS and computing requirements were defined, equipment was selected and procured or fabricated, software was acquired or developed, and NGS monument sites were selected for data collection. GPS data were recorded, validated, filtered, analyzed, and visualized. GPS latitude/longitude data were stored, simultaneously, in one second intervals for several hours at five or six surveyed locations on four different occasions. Selected NGS monument sites simulating different network densities (distances between sites) in the vicinity of Stillwater, Oklahoma were used. The positional error for each one second datum at each site was calculated. The derived error for two, three, four, and five sites were averaged in turn and used to correct the measured position at the sixth site (treated as autonomous receiver); these were compared with the single reference case. Statistical analyses were performed to demonstrate the improved accuracy with additional reference sites.

The DNDGPS approach was a network solution to DGPS operation in the positional domain, as opposed to the pseudorange domain used in classic DGPS. This offered a unique challenge in the definition of procedures, equipment selection/fabrication, planning, and execution of data collection and analysis. Rather than dealing with GPS errors individually (as in pseudorange DGPS), this research measured the aggregate effect of total errors for latitude/longitude. This methodology was required in the research project due to high pseudorange equipment costs; however, accuracy comparable with pseudorange methods resulting from this positional approach (RTCM-SC104 Standards, Ver. 2.1, pp. 1-9) represents a potential tenfold reduction in implementation costs and, therefore, has become the primary methodology for evaluation.

Technically, the DNDGPS positional approach imposes a critical restriction of data collection: ensuring that all GPS receivers at the respective NGS monument positions utilize exactly the same complement of satellites (PRN numbers) (Blackwell, 1985). Because each raw data set collected contains the result of errors due to satellite, receiver, atmosphere, and location, the error sources must be held constant when possible across datasets for the DNDGPS concept to be valid (i.e., all receivers experience the same errors). It can be shown that the total aggregate GPS error is (Wu, 1992):

$$\text{Error}_{\text{total}} = \text{Error}_{\text{satellite}} + \text{Error}_{\text{receiver}} + \text{Error}_{\text{atmosphere}} + \text{Error}_{\text{location}}$$

Controlling satellite PRNs used by the multiple receivers forced the same satellite clock and orbital error at the multiple DNDGPS nodes (Langley, 1997). The All-In-View receiver algorithm, plus imposing a 15 degree elevation mask in receiver setup, provided synchronized PRN control (Reilly, 1996c). This is of primary importance to the concept of correcting data from one GPS site with error information from different sites.

Receiver dependent errors were present in the form of clock synchronization, noise, firmware algorithms, and calibration. These were minimized by performing a “common antenna” test, with the data collection receivers connected to a single antenna at a known position (Reilly, 1996d). The equality of data produced by the multiple receivers was verified. Confirmation of identical firmware levels in the multiple receivers ensured identical algorithms, resulting in identical receiver operation. These procedures verified near identical performance of the AIV-10V receivers used in this project. The relative performance of receivers was defined using a ratio of respective errors generated by the “common antenna” test; accordingly, the receiver differences were negligible.

Atmospheric errors at different DGPS locations are proportional to the distance between the positions. Also, ionospheric effects on radio propagation (GPS signal transmission) are directly related to solar radiation (ARRL Handbook, 1993). The distance considerations between sites were precisely the rationale favoring the density of the DNDGPS network; however, stations were located in close proximity to minimize atmospheric impact. Pseudorange DGPS does not refine error calculations with multiple measurements, while wide-area DGPS (WADGPS) roughly approximates atmospheric differences at DGPS sites (Kee and Parkinson, 1991) because the sites are hundreds (or thousands) of miles apart. This research included one data collection at night to minimize error due to the ionosphere (solar radiation) and troposphere.

Location error differences were minimized by careful NGS site selection for monument locations. Monuments free from interference and obstructions, such as buildings, hills, trees, fences, and metallic objects, minimize error differences due to location. The 15 degree elevation mask also assists with elimination of location error.

To achieve the purposes of this study, this researcher established the following specific objectives:

1. To validate previously published research that atmospheric effects increase as distance between receivers increase;

2. To identify the economic justification for a Dense Network of Differential GPS (DNDGPS) for individual farm applications;

3. To determine the resolution, repeatability and accuracy, obtainable with a DNDGPS corrections derived from a dense network of multiple reference receivers; and

4. To develop a farm-based DNDGPS prototype and a plan for an Oklahoma Mesonetwork DNDGPS prototype which identifies the necessary resources required for implementation.

The project addresses the following technical issues which were established to evaluate the feasibility, utility, and implementation of a DNDGPS (Seibel, et al, 1995):

- Define and implement a methodology for remote collection of GPS receiver output simultaneously from multiple receivers at the geographical reference positions.
- Develop required algorithms for calculation of an improved DGPS error value based upon data from multiple reference receivers.

  -High-Precision Differential Algorithm for correction of autonomous GPS receiver positioning using data from multiple reference receivers.

  -Optimal Separation Algorithm for calculating the optimal reference-to-autonomous receiver distance (where accuracy falls off).

  -Maximum Latency Algorithm for determination of maximum DGPS latency (delay in correcting autonomous receivers for real-time applications).

  -Resolution Algorithm for analyzing repeatability vs. accuracy for each test scenario.
- Design an algorithm for correction of multiple RR datum into a single, improved error value.
- Create the software for correction of remote GPS data using the improved error value to determine obtainable resolution.
- Define reference receiver density to achieve reliable resolution required for precision farming.
- Identify benefits to agricultural operations when using resolution results of a DNDGPS. Additional questions to be answered include:
- Can algorithms based on DNDGPS data be developed that provide an improved error value (i.e., provides improved correction of autonomous receiver location)?
- What reference receiver density is sufficient to allow consistent accuracy and repeatability over a large geographic area?
- What is the maximum latency permitted with DGPS error-processing without degradation of position calculations for precision farming applications?

- What are the technical issues surrounding use of the Oklahoma Mesonet in harmony with the DNDGPS?

Research Questions

Research questions stemming from the research objectives were developed and tested:

Question 1. Do atmospheric effects within DNDGPS reference receivers (RR) and secondary receivers (SR) cause any notable differences in magnification as the separation between receivers increases?

Question 2. Can a DNDGPS be implemented at a notably lower cost compared to off-the-shelf DGPS systems for precision farming applications?

Question 3. Were there notable differences in the resolution of GPS utilizing DNDGPS reference receivers in the positional domain, with averaging algorithm(s) for refining correction data, compared to DGPS systems utilizing the pseudorange mode?

Question 4. Did the DNDGPS system increase efficiency for agriculture by: 1) identifying practical variability for investigating probable cause, and 2) helping instigate possible solutions for precise evaluation which are notably greater than DGPS systems?

Scope of the Study

The scope of this study included portions of five counties of north-central Oklahoma adjacent to Payne County. GPS data collection involved seven National Geodetic Survey (NGS) High Accuracy Reference Network (HARN) monuments and three order B accuracy sites in the vicinity of Stillwater, Oklahoma.

GPS Receivers

The Magellan AIV-10V was selected for the DNDGPS-SBIR project. GPS receiver evaluation and selection was based upon criteria critical to maximizing accuracy (minimizing error) at an affordable cost (Appendix C; Appendix D). The AIV-10V is a 10 channel receiver using an onboard Motorola 68000 processor for fixed calculations. The receiver used an All-In-View algorithm, which provided good resolution and low power and met the selection requirements for the DNDGPS project in all categories. The receiver boards were packaged with customized engineering specifications, specific to the DNDGPS project, by Realtime Control Systems International of Richardson, Texas. A Magellan A50 Active Quadrifilar Antenna with a 37dB preamplifier and 50 feet of RG-58U coaxial cable was selected for its high gain and wide beam (typical of helical antenna elements).

Six IV-10 receivers were used, allowing data collection site geometry to surround one position with five others, an important consideration in networked DGPS. The six receivers offered sufficient opportunity to demonstrate the DNDGPS concept while at the same time kept data collection cost and logistics to manageable levels.

Computer Equipment

IBM-compatible laptop PCs with MS-DOS were used for GPS data collection. The PC was powered by a 12-volt cigarette lighter connection in an automobile. This method proved to introduce fewer errors and less expense when compared to the use of cellular telephones. The minimum PC requirements for data collection were 80286 laptop processors having MS-DOS, 10MB of file space, and a 9600 baud port. Data reduction and analyses were performed using a 75 MHz Pentium PC processor with MS-Windows.

Software

Mission planning was performed using the National Geodetic Survey (NGS) Data Extraction Program Version 4.3 for locating surveyed monuments as data collection sites. The monuments were surveyed as Order B, an accuracy of one part per million (ppm). The GPS Monitoring Software, SMS Version 2.11c by Global Satellite Software, Inc., was used to model GPS satellite behavior. This predictor allowed examination of satellite visibility and geometry in advance of data collection, providing the opportunity to choose the best data collection times at the respective positions (Figure 5, Satellites Visible at Stillwater, DC4). Data collection (DC) was accomplished with the Magellan NAV10.EXE Exerciser for the AVI-10V receiver (Appendix E). Data reduction was done with "C" language programs developed with Borland C++, Version 4.5. Data analysis (statistical calculations and plots) used "C" programs developed in DOS and the EXCEL Analysis Toolpack and SAS, both in MS-Windows.

Mission Planning

Planning the mission data collection dates and time was accomplished with the aid of the GPS Monitoring Software, which uses a "current" GPS satellite ephemeris table downloaded by a GPS satellite transmission the day before the projected collection session to model orbital dynamics. The model calculates the orbital positions of all 24 satellites at a requested earth location for a particular date and time. It indicates satellite visibility (azimuth and elevation), shows overall satellite geometry (GDOP-Geometric Dilution of Precision, PDOP-Positional Dilution of Precision, HDOP-Horizontal Dilution of Precision, the VDOP-Vertical Dilution of Precision), and indicates the time satellites are visible above specified elevations. This tool is a valuable aid in maximizing the data collection opportunity and was considered critical to the success of this project (Figure 5, Satellites Visible at Stillwater, DC4).

Operator training and equipment checkout, along with proper configuration of the AIV-10V receivers, was performed the day before a scheduled data collection session. The receivers were initialized with a 15 degree cutoff mask for satellite elevation to minimize low-angle multi-path reflections and atmospheric error due to signal refraction and for

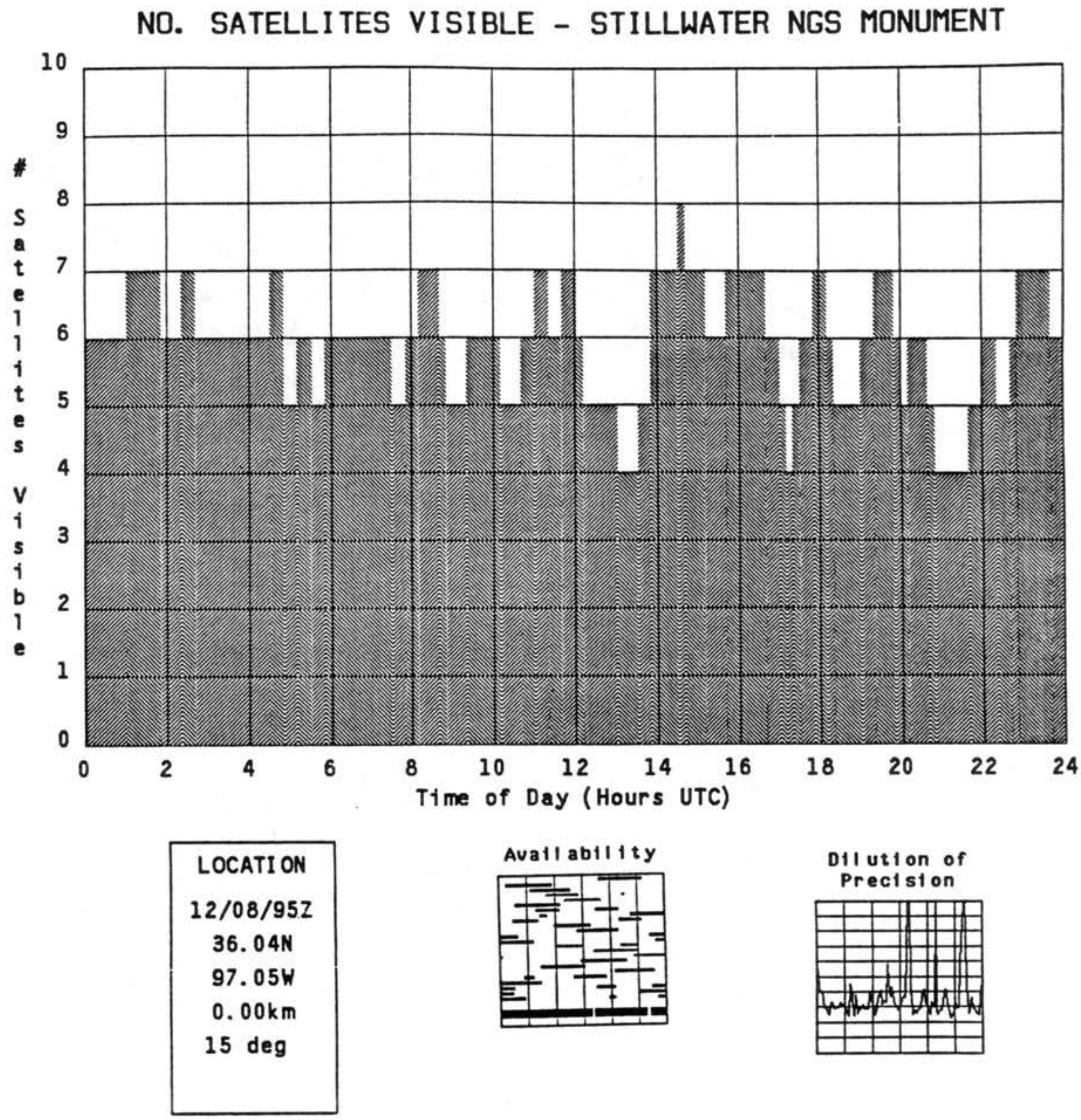

Figure 5. Satellites Visible at Stillwater, DC4

synchronization control of all five AIV-10Vs in using the same satellites (which is imperative in the positional domain for differential correction to work). Setup also provided for latitude/longitude calculations using the NAD83 ellipsoid of revolution for compatibility with monument data. The National Geodetic Survey (NGS) DSDATA Extraction Program provides directions to the prospective monuments, along with visible landmark information to assist in locating the bronze plaques marking the monument positions. Monuments were selected which afforded a clear view of the horizon without obstruction (no trees, fences, buildings, hills, etc.) to minimize the possibility of introducing errors due to multi-path signal reflections (Figure 6, Map Research Area Around Stillwater and Figure 7, Map of Monument Locations).

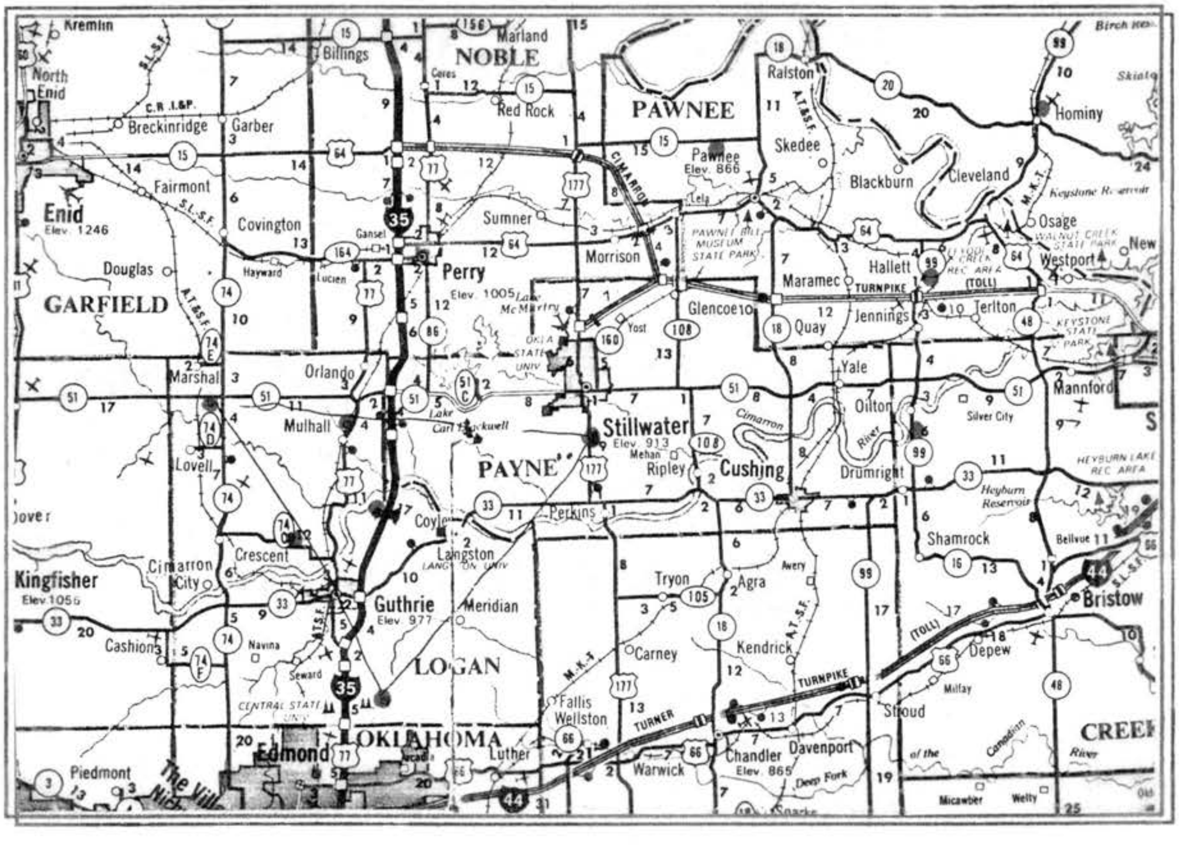

Figure 6. Map of Research Area Around Stillwater, OK

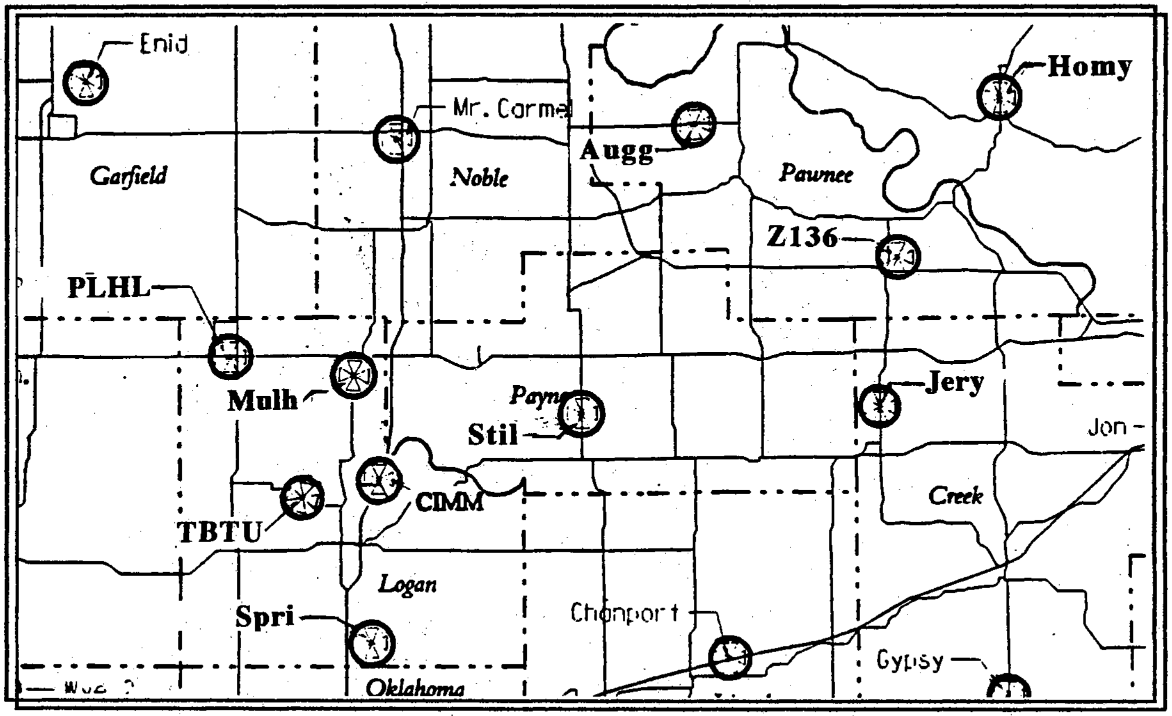

Figure 7. Map of Monument Locations

Mission Execution

Data collection at each of five NGS monuments involved setup of the survey antenna tripod over the target cross-hairs (or dimple) on the bronze monument, mounted in concrete or rock. The GPS antenna was centered and leveled directly over the monument target with a reference mark facing north for orientation. The operator's vehicle was positioned 50 feet away from the antenna (full length of the coax) and oriented with minimal reflective surface facing the antenna. The GPS receiver and laptop computer were powered on and allowed to run for approximately 30 minutes, sufficient time for the receivers to acquire satellite signals and begin fixed calculations; this also allowed the operator time to verify the system setup. At exactly five minutes prior to the designated start of the data collection, as determined by the cesium GPS receiver clocks displayed on the laptop screen, all five (or six) operators cycled the AIV-10Vs power through an OFF/ON routine. The power-on initialization in the receiver firmware synchronized all receivers with the same satellite signals processed via the same receiver channels. AIV-10V output data were recorded in one-second intervals on each laptop computer for a period of two hours. After two hours of field operations were completed, all researchers attended a debriefing meeting to discuss and document findings. Four data collection sessions were performed over a six month period.

Data reduction required developing several "C" language programs. First, the five AIV-10V raw data files were validated for integrity. A program was written to verify the checksum byte appended to each GPS data message recorded (Seibel, et al., 1995). This procedure eliminated bad data due to dropped bits, truncated messages, etc. Next, the five files were synchronized in time (another "C" program), aligning the start and stop times to be identical for all five data sets. Third, the five files were "filtered" by a program for eliminating GPS data records that should not be used for processing. For example, one filtering criteria was verification of records that were generated using exactly the same complement of satellites as the counterpart record in the other files (since GPS errors at one or more receivers were to be used in the correction of errors at another, the error sources must be the same). Other filtering functions (for each one second data record in all files) included certification that all receivers were operating normally in 3D mode and PDOT $\leq$ 5.0 (reflecting acceptable satellite geometry). Fourth, the five synchronized files were converted and reformatted from binary to ASCII for compatibility with EXCEL and SAS statistical analysis and plotting tools. Fifth, normally distributed treatment populations were drawn by Monte Carlo (a computerized random sample) from which analysis of variance was conducted. Other ancillary programs were developed for displaying raw AIV-20V data, common-antenna receiver testing, and conversion of latitude/longitude coordinate differences into metric distance using the NAD83 ellipsoid definition (Reilly, 1995).

Data analysis utilized EXCEL Analysis Tool Pack and Statistical Analysis System (SAS) for the calculation of the positional error statistics for each one second interval in all files and correction of a designated receiver file using error values from combinations of one, two, three, four (and five) other files (Seibel, et al, 1995). EXCEL and SAS were used to evaluate the distribution of raw, corrected, and error data via means, standard deviations, and ranges (difference between minimum and maximum values). These tools provided plots of raw data, corrected data (with one, two, three, four and five reference fields), and error data.

Data Collection - NGS Monuments

The DNDGPS project required GPS data to be collected from multiple (five and six) surveyed locations, for which the precise latitude and longitude were known. It was decided early in the research to use the recently validated National Geodetic Survey (NGS) monuments in the vicinity of Stillwater, Oklahoma (Figure 7, Map of Monument Locations). The NGS DSDATA Extraction Program identified and located these monuments; furthermore, it described and mapped survey markers within a specified radius of a target location (Appendix F). Latitude and longitude for these monuments were marked with Order B accuracy (1 ppm) relative to the NAD83 ellipsoid of revolution (and GEOID93); this yields degrees/minutes/seconds to six decimal places for seconds. Data collection exercise #4 required greater network density than provided by the NGS monuments, so three additional reference locations were surveyed (Order B) “inside” the NGS grid. The research team used Trimble 4000S DGPS equipment for this exercise. Order B accuracy exceeds the resolution of the AIV-10V GPS receivers (Appendix E), which have 10^{-7} degrees. All the sites for this feasibility study were easily accessible, having good visibility to the horizon, and little opportunity for multi-path reflections (Table III, NGS Location Data Collection Sites for Four Scenarios).

TABLE III

NGS MONUMENT LOCATIONS - DATA COLLECTION SITES FOR FOUR SCENARIOS

	Latitude (N)	Longitude	Type	DC1	DC2	DC3	DC4
Springer	35 45 15.609530	97 22 38.738840	NGS	X	X		X
Pleasant Hill	36 06 57.310730	97 35 46.894760	NGS	X	X		X
Jery	36 02 55.870910	96 35 00.655440	NGS	X	X	X	
Augg	36 24 21.790860	96 52 15.127050	NGS	X	X	X	
Stillwater	36 02 37.980190	97 03 03.225390	NGS	X	X	X	X
Z136	36 14 14.571100	96 33 12.349680	NGS			X	
Hominy	36 26 18.822360	96 23 21.880190	NGS			X	
Cimarron	35 57 28.420480	97 21 55.233941	User				X
Mulhall	36 05 25.226305	97 23 46.453783	User				X
Timbuktu	35 56 32.299063	97 28 36.315616	User				X

NGS = National Geodetic Survey
User = Surveyed by Researcher
DC1 = Data Collection Session #1
DC2 = Data Collection Session #2
DC3 = Data Collection Session #3
DC4 = Data Collection Session #4

Data Collection Scenarios

After planning the mission, training operators, checking out equipment, and setting up receivers; research personnel were deployed to their NGS monument locations (Table IV, Monument Separation in Meters). The data collection systems were set up and verified. At the designated start time GPS receiver output data were recorded for approximately two hours to files on laptop computers (≈ 1MB of data per location). This procedure was executed four times on different occasions after one practice session performed by the research principals (Seibel, et al., 1995). Data collection (DC) sessions one, two, and three used five monument positions, and DC #4 used six data collection sites. Following each trip, a debriefing meeting was held to discuss the principals' findings and recover the GPS raw data file from each PC. Each of the four scenarios offered important new information, and subsequent outings were planned accordingly.

TABLE IV

MONUMENT SEPARATION IN METERS

	PLHL	Jery	Augg	Stil	Z136	Homy	Cimm	Mulh	TBTU
Spri	44712	78771	85500	43598			22609	37314	22699
PLHL		91528	72706	49772			27217	18239	22072
Jery			47316	42123	21097	46640			
Augg				43324	34104	43335			
Stil					49660	73856	29909	31533	40017
Z136		21097	34104	49660		26749			
Homy		46640	43335	73856	26749				
Cimm				29909				14955	10201
Mulh				31533			14955		17956
TBTU				40017			10201	17956	

Data Collection Session #1 (DC1)

Rationale:	The initial session was defined with the reference sites surrounding the corrected position, in a simulated network configuration.
Date/Time	July 21,1995 (202) @ 1630 -1800 UTC
Monuments:	Springer (SPRI), Pleasant Hill (PLHL), Jerry (JERY), Augg (AUGG), Stillwater (STIL - corrected position).
Avg. Baseline:	44,705 km
Weather:	Partly cloudy, 88°F, wind 20 mph.
Problems:	A power supply failure in the PC prevented adequate data from being collected at the Stillwater location. The data for the other sites were intact and analyzed.

Data Collection Session #2 (DC2)

Rationale:	This is a repeat of the scenario for DC1 due to the power failure at STIL. It was anticipated that the DC1 results could be improved and that the DNDGPS concept of multiple, averaged GPS reference stations correcting an "unknown" position could be demonstrated.

Date/Time: August 23, 1995 (235) @ 0030 - 0230 UTC (night).

Monuments: Springer (SPRI), Pleasant Hill (PLHL), Jerry (JERY), Augg (AUGG), Stillwater (STIL - corrected position).

Avg. Baseline: 44,705 km

Weather: Clear, 78°F, wind calm.

Problems: A Southwestern Bell Telephone Co. truck approached the antenna position at AUGG at 0215 UTC and ran over the coaxial cable. However, sufficient data were collected at all sites to perform the desired analysis.

Data Collection #3 (DC3)

Rationale: Sites were selected which allowed further evaluation of the balanced-linear-correction observation (BLC) and weighted inverse-distance algorithm.

Date/Time: September 29, 1995 (272) @ 1800 - 2000 UTC

Monuments: Stillwater (STIL), Jerry (JERY), Augg (AUGG), Hominy (HOMY), Z136 (corrected position).

Avg. Baseline: 27,317 km

Weather: Partly cloudy, 82°F, wind gusting to 45 mph.

Problems: Power supply overheating in the PC prevented adequate data from being collected at the STIL location. High winds blew over the antenna repeatedly at JERY during the first 30 minutes of the session. Quality data were stored at four sites during the last 1.5 hours (1830 -2000 UTC). Z136 measurements were corrected.

Data Collection Session #4 (DC4)

Rationale: Refinement of results using a reference grid on the order of the Oklahoma Mesonetwork was approximately twice the density of

DC1, DC2, and DC3. The BLC concept is emphasized.

Date/Time: December 8, 1995 (342) @ 1400 - 1600 UTC.

Monuments: Springer (SPRI), Stillwater (STIL), Pleasant Hill (PLHL). Three new sites were surveyed by the research team, using Trimble 400 DGPS equipment, to Order B accuracy (1 ppm). They were located within a triangle defined by the three "balanced" NGS monument sites and named Cimarron (CIMM), Mulhall (MLHL), and Timbuktu (TBTU).

Avg. Baseline: 26,579 km

Weather: Overcast, drizzle, 40°F, wind calm.

Problems: Operations during DC4 were essentially without problems. Six data files were recorded (one more than for DC1 - DC3). Emphasis was on network density scaled to the Oklahoma Mesonetwork, balanced reference sites, and multiple observable scenarios were conducted from the network geometry.

Analysis

The goal of data analysis in this research was to use the calculated difference between measured and true latitude/longitude at four and five GPS receiver positions to correct the measured coordinates at a fifth and sixth target position. The target location data, representing an autonomous GPS receiver at an "unknown" position (e.g., STIL), was corrected by subtracting the error derived from measurements at the other reference sites. This was done using one, two, three, four, and five reference files, in turn, with an averaging algorithm applied to the multiple combination of data sets. A program was written to translate latitude error plus longitude error into linear distance error (Seibel, et al, 1995). It was utilized to calculate the actual error distance in meters for each one second entry in the corrected target files for the distinct histograms. Means, standard deviations, and range errors were determined for the individual reference files, and used to correct the target files. Plots of the individual raw latitude/longitude, corrected target latitude/longitude (for one to five references), individual positional error, and error in corrected target measurements were selectively created. Histograms reflecting the frequency of distribution for the statistical tables were produced to allow visualization of the various cases.

CHAPTER IV

PRESENTATION AND ANALYSIS OF DATA

Introduction

The purpose of this study was to assess the feasibility of a differential global positioning system (DGPS) having a dense network of reference receivers (RR) for advanced precision farming applications. Data analysis in this research was used to calculate the difference between measured and true latitude/longitude at four or five GPS receiver positions to correct the measured coordinates at a fifth or sixth target position. The target location data, representing an autonomous GPS receiver at an "unknown" position (e.g., Stil), is corrected by subtracting the error derived from measurement at the other (reference) sites. This was done using one, two, three, four, and five reference files, in turn, with an averaging algorithm applied to the multiple combination of data sets. A program was written to translate latitude error and longitude error into linear distance error, this was utilized to calculate the actual error distance in meters for each one second entry in the corrected target files for the different histograms. Mean and standard deviation calculations along with the range (difference between minimum and maximum) of error for the individual reference files and the corrected target files was performed. Plots of the individual raw latitude/longitude, corrected target latitude/longitude (for 1 - 5 references). individual positional error, and error in corrected target measurements were selectively created. Histograms reflecting the frequency distribution were produced to allow visualization of the various cases.

Algorithms

The research focused on two High-Precision Differential Algorithms: Simple error averaging and Inverse-distance averaging:

1) Simple error averaging is defined by

$$\mathrm{Lat}_{\mathrm{err}} = \sum(\mathrm{Lat}_{\mathrm{imeas}} - \mathrm{Lat}_{\mathrm{itrue}}) / N$$

and

$$\mathrm{Lon}_{\mathrm{err}} = \sum (\mathrm{Lon}_{\mathrm{imeas}} - \mathrm{Lon}_{\mathrm{itrue}}) / N,$$

participating reference receivers. $\mathrm{Lat}_{\mathrm{err}}$ and $\mathrm{Lon}_{\mathrm{err}}$ are then subtracted from $\mathrm{Lat}_{\mathrm{meas}}$ and $\mathrm{Lon}_{\mathrm{meas}}$ values for the autonomous receiver to produce its "corrected" Latitude and Longitude ($\mathrm{Lat}_{\mathrm{cor}}$ and $\mathrm{Lon}_{\mathrm{cor}}$):

$$\mathrm{Lat}_{\mathrm{icorr}} = \mathrm{Lat}_{\mathrm{imeas}} - \mathrm{Lat}_{\mathrm{ierr}}$$

and

$$\mathrm{Lon}_{\mathrm{icorr}} - \mathrm{Lon}_{\mathrm{imeas}} - \mathrm{Lon}_{\mathrm{ierr}}$$

2) Inverse-distance averaging reflects inverse relationship of error similarity and baseline distance. $\mathrm{Lat}_{\mathrm{err}}$ and $\mathrm{Lon}_{\mathrm{err}}$ contributions by the multiple reference receivers are inversely proportional to the respective baseline distance between those receivers and the position being corrected. This concept is based upon knowledge of atmospheric affect on GPS satellite signal propagation (Sennott and Pietraszewski, 1987). As baseline distance increases, chances for atmospheric refraction also increases; thus, less weight is given the reference sites as distance to the corrected position grows (Mueller, 1994b). For weighted averaging, the equation for $\mathrm{Lat}_{\mathrm{err}}$ and $\mathrm{Lon}_{\mathrm{err}}$ above become:

$$\mathrm{Lat}_{\mathrm{err}} = W_i \sum(\mathrm{Lat}_{\mathrm{imeas}} - \mathrm{Lat}_{\mathrm{itrue}}) / N$$

and

$$\mathrm{Lon}_{\mathrm{err}} = W_i \sum(\mathrm{Lon}_{\mathrm{imeas}} - \mathrm{Lon}_{\mathrm{itrue}}) / N,$$

reference receivers, and where the weighting factor is given by (Boman et. al., 1995):

$$W_i = (1/\ d_i^x) \ / \ \Sigma \ (1/\ d_i^x)$$

where N is the number of points averaged

d_i is the baseline distance for the ith reference receiver

X = 0 for linear distance averaging

X = 1 for inverse distance weighting

X = 2 for inverse distance squared weighting

Validation and Synchronization of Raw GPS Data

The AIV-10V GPS receiver data format is a Magellan-specific binary code, with GPS information created as individual messages (records) every second. The first three data collection sessions (DC1 through DC3) produced five files, while DC4 generated six. The reduction of raw data required several steps:

First, individual raw data files produced by the five or six receivers were verified for validity before becoming input for analysis. A program written to calculate the checksum value for each record was used to verify appended checksums. Records were discarded when calculated and recorded checksums did not match, as this indicated possible truncated data. New files were created containing the edited files, as well as raw data records with integrity. As a final measure, the edited files were converted from binary to ASCII to accommodate input requirements for analysis.

Second, the five or six edited files became input to the synchronization program. The function provided by synchronization was to align the start times of the five or six edited files on the exact same second in time, respectively. This allowed statistical analysis to be performed on GPS data for precisely the same time interval.\

Third, the synchronized files were filtered by a program which passed through the synchronized files and discarded records not meeting rigorous GPS requirements. This ensured that normal receiver operation were present, conditions necessary for accurate latitude/longitude measurement. If a record was discarded by the filter program, file counterpart records in the other synchronized files were also discarded to maintain time synchronization (a procedure which will be modified in the future). The data were filtered to: 1) ensure that each GPS message in every file was created while the receiver was in 3D mode (using at least 4 satellites), 2) check that all participating receivers used exactly the same complement of satellites, and 3) that satellite geometry was acceptable (PDOP $\leq$ 5.0). These five or six edited, synchronized, and filtered files were ready for statistical analysis.

Data Collection Findings and Analysis

The following tables and charts are representative of the results that were achieved with the dense network of reference receivers. Without exception, a simulated dense network of multiple receivers (three or four) produced the best corrected results in all data collection scenarios.

Data Collection No. 1: Data collection from five survey points. Data used for algorithm development.

Results: Plots of the raw latitude and longitude data for four monuments (PLHL, SPRI, AUGG, JERY) have the same shape and phase. DC1 plots are not shown here; however, similar plots are shown for DC2. These four plots demonstrate equal low frequency oscillations of the measured values about the respective true positions, characteristic of the introduced Selective Availability errors applied to the GPS Space Segment (Kremer et. al., 1989). When superimposed and aligned in phase, the curves overlap almost exactly (Figure 8). Measurements collected in DC1 were used to begin algorithm and software development. Only limited analysis was performed due to insufficient data at STIL.

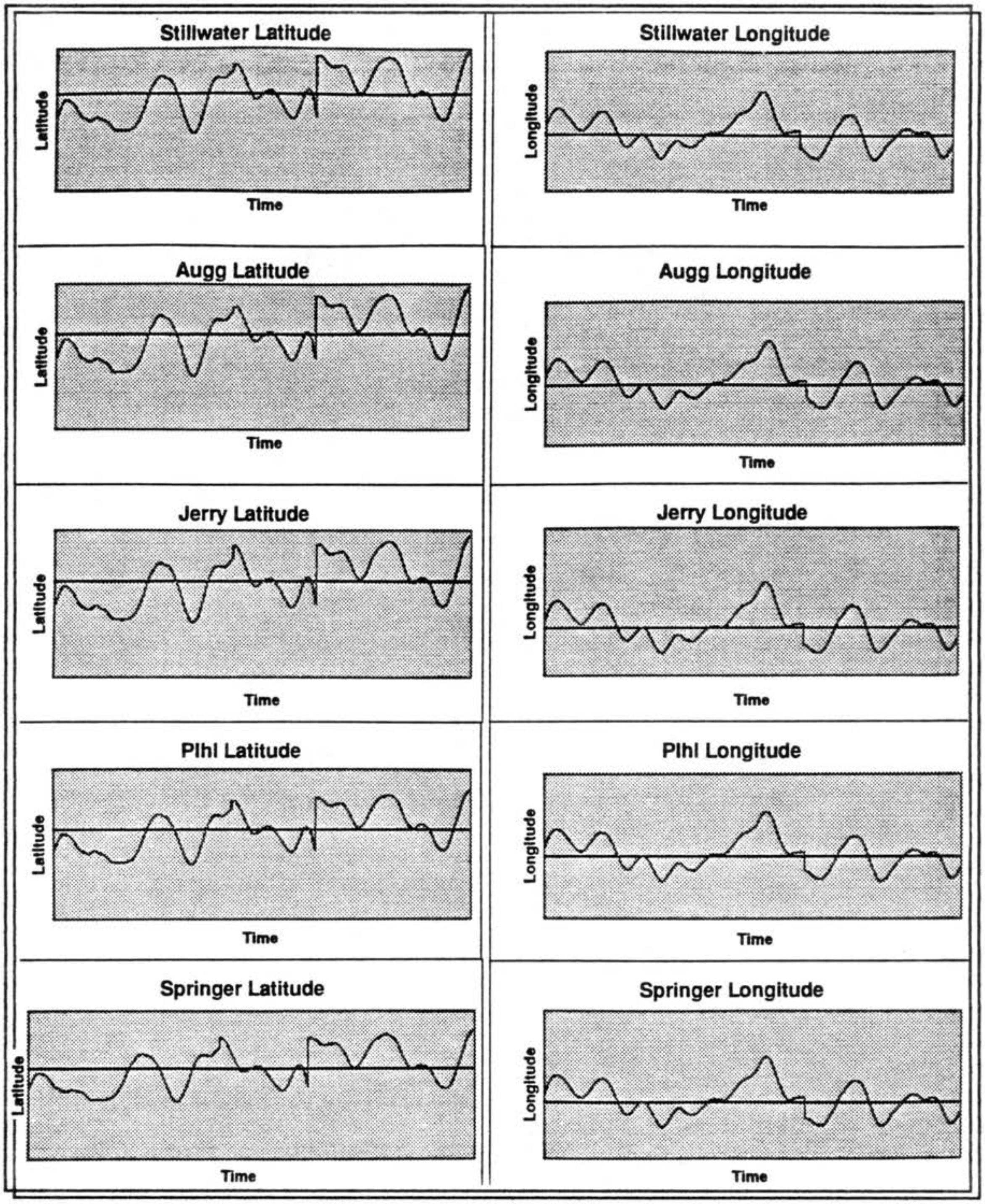

Figure 8. DC2 Raw GPS Measurement Plots

Data Collection No. 2: Two-hour data collection from five surveyed points. Best results: 87 percent within 100 cm. Analysis No. 15 used all four reference receivers.

Results: Plots of the raw data for SPRI, PLHL, JERY, AUGG and STIL verified the results of DC1, showing identical curve shape and phase for the five sites (Figure 8). The five files were edited, filtered, and synchronized. All combinations of calculated reference errors for SPRI, PLHL, JERY, and AUGG were used to correct the raw STIL measurements (Figure 9), using both unweighted averaging and weighted averages with inverse distance. Table V, Correcting Stillwater with Known References, and Figure 10, DC2 Improvement with Dense Network of Reference Receivers, is a summary of STIL corrections.

Table V, Correcting Stillwater with Known References, contains the percent of corrected measurements within 50 cm, 100 cm, 150 cm ... 350 cm. These percentages were based on approximately 3700 individual measurements at each reference and autonomous receiver location. Correction was made to Stillwater using one, two, three and four reference receivers. Figure 10, DC2 Improvement With Dense Network of Reference Receivers, is a bar chart showing percentage of corrected measurements within 50 cm, 100 cm, and 150 cm.

Data Collection No. 3: Two-hour data collection from five surveyed points. Data from STIL (Stillwater location) was lost due to inverter overheating (Figure, 9). The planned simulation was created with the remaining three reference receivers.

TABLE V

CORRECTING STILLWATER WITH KNOWN REFERENCES

Sorted on Cumulative 100 cm Column

	50cm	100cm	150cm	200cm	250cm	300cm	350cm
15 All Four Sites*	36%	87%	98%	100%	100%	100%	100%
6 Springer + Augg*	44%	85%	100%	100%	100%	100%	100%
10 Augg + Jery	31%	85%	100%	100%	100%	100%	100%
11 Springer + PLHL + Augg*	40%	85%	100%	100%	100%	100%	100%
14 PLHL + Augg + Jery*	30%	84%	100%	100%	100%	100%	100%
12 Springer + PLHL + Jery*	36%	83%	96%	98%	99%	100%	100%
13 Springer + Augg + Jery	36%	83%	98%	100%	100%	100%	100%
5 Springer + PLHL	35%	81%	96%	98%	100%	100%	100%
8 PLHL + Augg	34%	81%	100%	100%	100%	100%	100%
3 Augg	33%	81%	96%	100%	100%	100%	100%
7 Springer + Jery	34%	80%	93%	96%	98%	99%	100%
9 PLHL + Jery	27%	78%	95%	98%	99%	100%	100%
1 Springer	37%	75%	90%	96%	98%	99%	100%
2 Pleasant Hill (PLHL)	20%	66%	96%	100%	100%	100%	100%
4 Jery	25%	63%	85%	95%	96%	98%	100%

*BLC - Balanced Linear Correction

Results: Using a single reference receiver, histogram plots for DC3 show a corrected Z136 error of ≤ 1.5 meter 91 percent of the time for Hominy and 91 percent of the time for Jery. Z136 is corrected by Hominy to ≤ 1.0 meter 76 percent of the time and 79 percent of the time by Jery. Hominy corrected Z136 to ≤ 0.5 meter 36 percent of the time, and Jery corrected Z136 to ≤ 0.5 meter 38 percent of the time. When Jery and Hominy error were combined with an unweighted average algorithm, the corrected Z136 error was ≤ 0.5 meters 48 percent of the time, ≤ 1.0 meter 83 percent of the time, and

≤ 1.5 meter 93 percent of the time. Jery, Hominy and Augg combined to correct Z136 to ≤ 1.0 meter 96 percent of the time, ≤ 0.75 meter 91 percent of the time, and ≤ 0.5 meter 54 percent of the time (Table VI).

The correction calculations using the weighted-with-inverse-distance algorithm did not show any improvement due to the close proximity of the NGS monuments. Analysis No. 10 with three references produced outstanding results; however, STIL data lost due to inverter overheating resulted in analysis number's four, six, seven, eight, nine, eleven, twelve, and thirteen not being produced (Table VI and Figure 11).

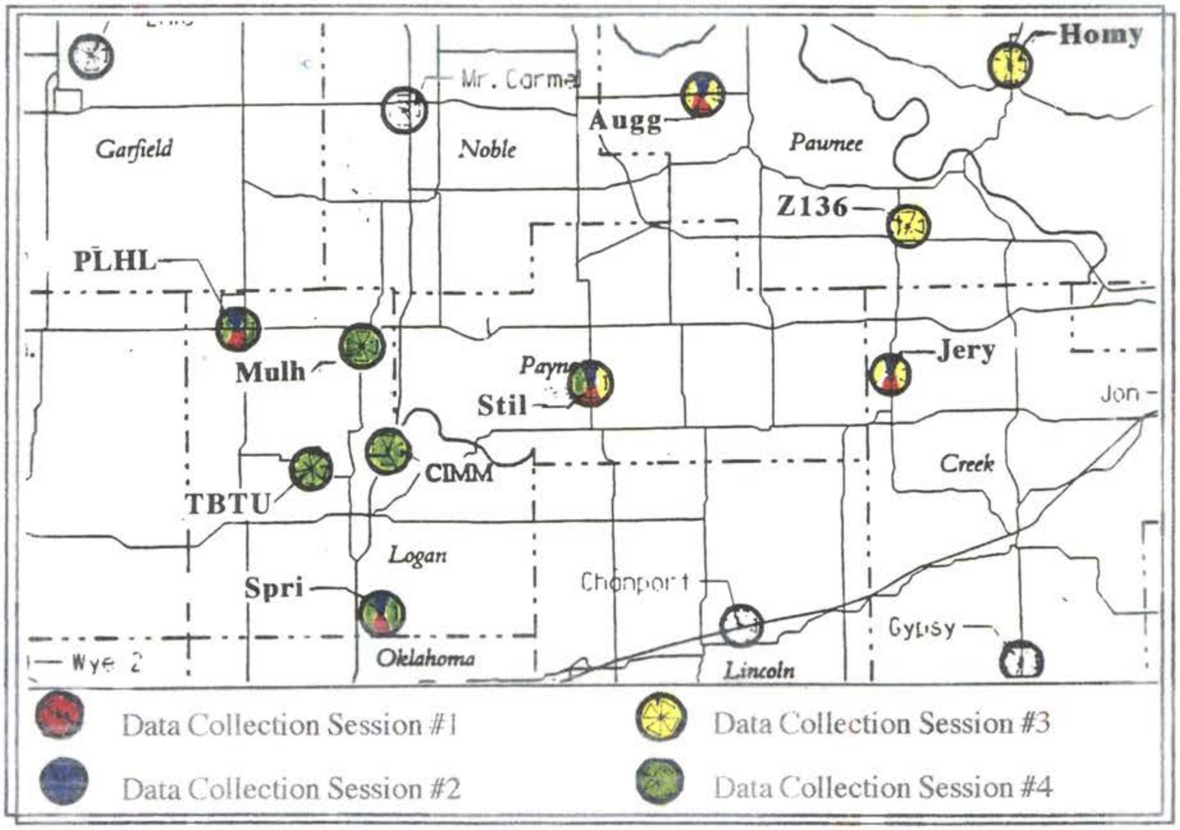

Figure 9. Data Collection Scenarios Map

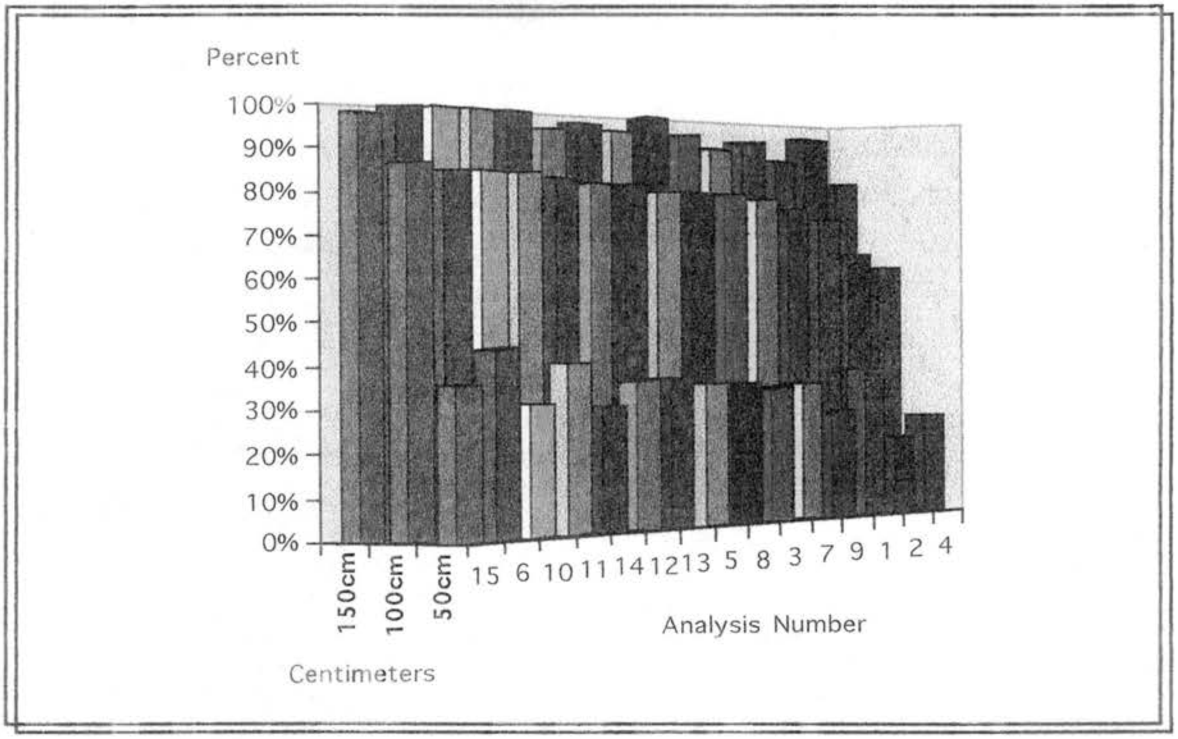

Figure 10. DC2 Improvement with Dense Network of Reference Receivers

TABLE VI

CORRECTION Z136 WITH KNOWN REFERENCES

Analysis Number	Reference Receivers	50cm	100 cm*	150 cm	200 cm	250 cm	300 cm	350 cm
10	Hominy+Jery+Augg	54%	96%	99%	99%	99%	99%	100%
3	Augg	34%	95%	99%	99%	99%	99%	100%
5	Hominy+Jery	43%	85%	95%	97%	98%	99%	100%
2	Jery	33%	79%	92%	94%	95%	96%	100%
1	Hominy	36%	76%	92%	97%	99%	100%	100%
4	Stil**							

*Sorted on cumulative 100 cm column

**Stil data lost due to inverter overheating

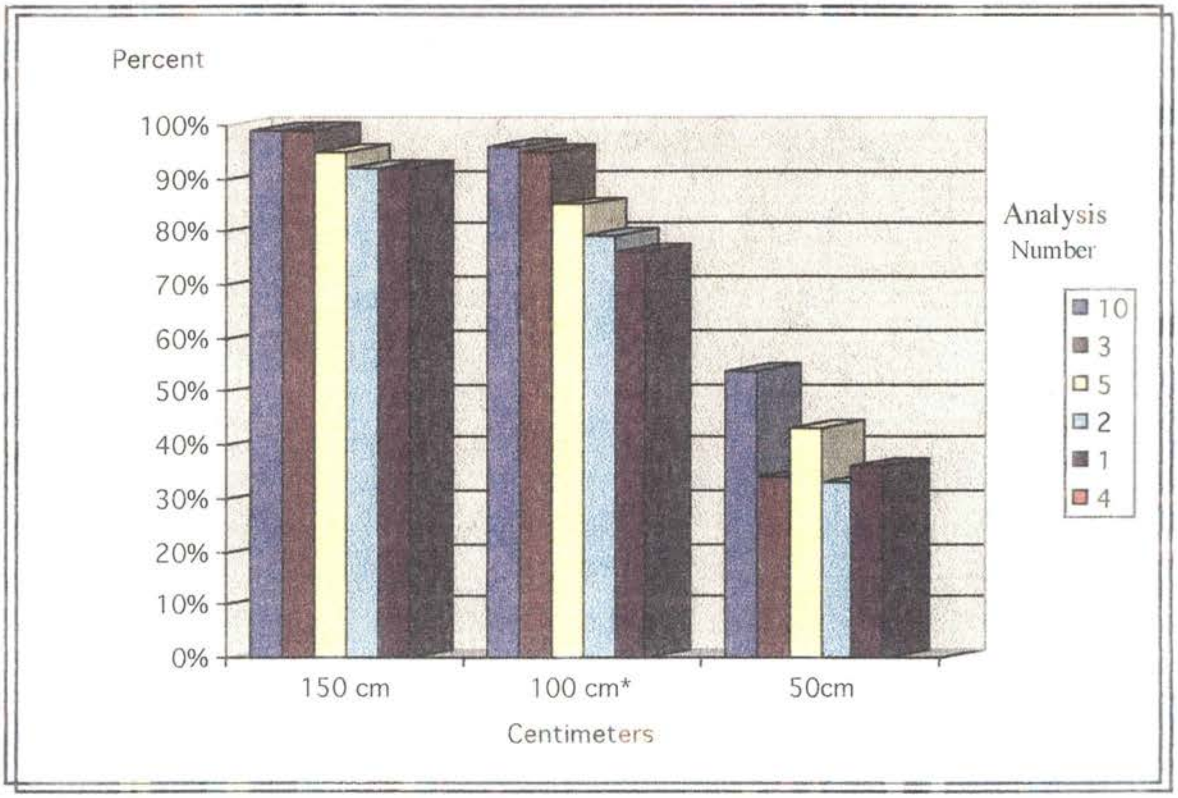

Figure 11. DC3 Improvement with Dense Network of References

Best results: 96 percent within 100 cm. Analysis No. 10 correcting Z136 using remaining three reference receivers. Table VI, Correcting Z136 with Known References, contains the percentage of corrected measurements within 50 cm, 100 cm, 150 cm ... 350 cm. These percentages were based on approximately 4500 individual measurements at each reference and autonomous receiver location. Correction was made to Z136 using one, two, and three receivers. Figure 11, DC3 Improvement with Dense Network of Reference Receivers, is a bar chart showing percent of correct measurements within 50 cm, 100 cm, and 150 cm. Figure 12, DC3 Results of Dense Network of Reference Receivers, is a bar chart showing percentage of corrected measurements within 25 cm, 50 cm, and 75 cm for Analysis No. 7 (25 cm scale vs. 50 cm scale shown in previous figure).

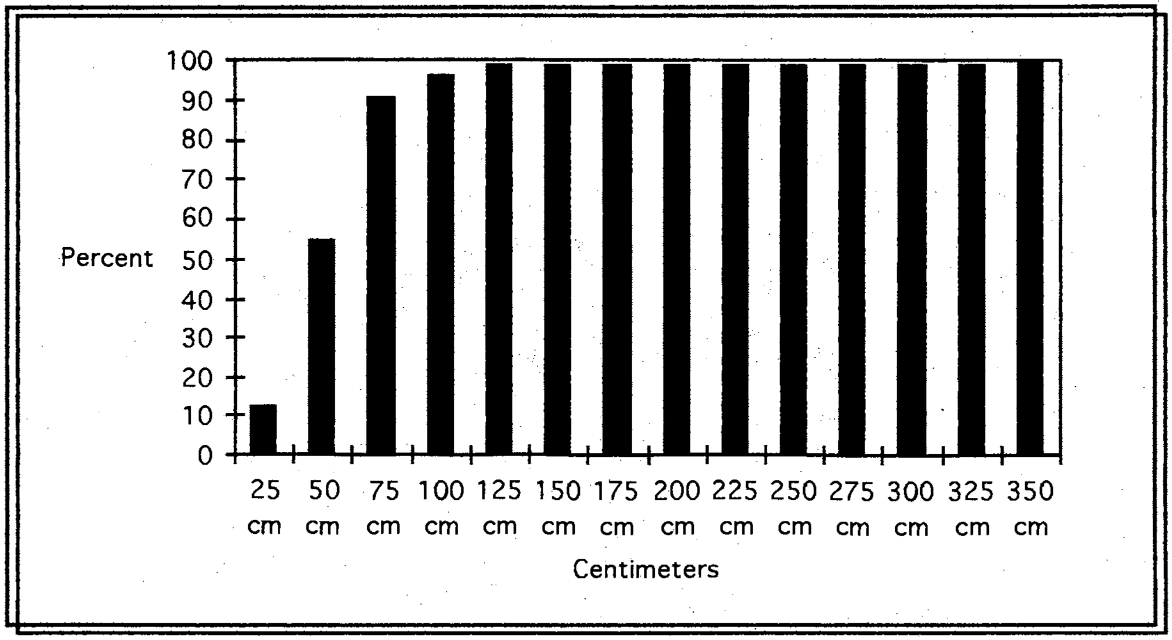

Figure 12. DC3 Results Of Dense Network Of Reference Receivers

Data Collection No. 4: Two-hour data collection from six surveyed points.

Results: Histogram plots for DC4 show a corrected CIMM error of ≤ 1.0 meter 94 percent of the time, ≤ 0.75 meter 87 percent of the time, and ≤ 0.50 meter 65 percent of the time using three symmetric reference sites (Stil, Pleasant Hill, and Springer). Results are shown in Figure 13, DC4 Percent Distribution of Accuracy.

Best results (of cases analyzed) 96 percent within 100 cm. Table VII, Correcting Cimarron with Known References, contains the percent of corrected measurements within 25 cm, 50 cm, 75 cm ... 350 cm. These percentages were based on approximately 5700 individual measurements at each reference and autonomous receiver location. Correction was made to Cimarron using one, two, and three reference receivers. The best results, 96 percent within 100 cm, were achieved using three reference receivers. Figure 13, DC4 Improvement with Dense Network of Reference Receivers, is a bar chart showing corrected measurements within 25cm, 50cm, 75cm, and 100cm. Figure 14, DC4 Percent

Distribution of Accuracy, is a bar chart showing percent of corrected measurements on a 25 cm scale of Analysis No. 7.

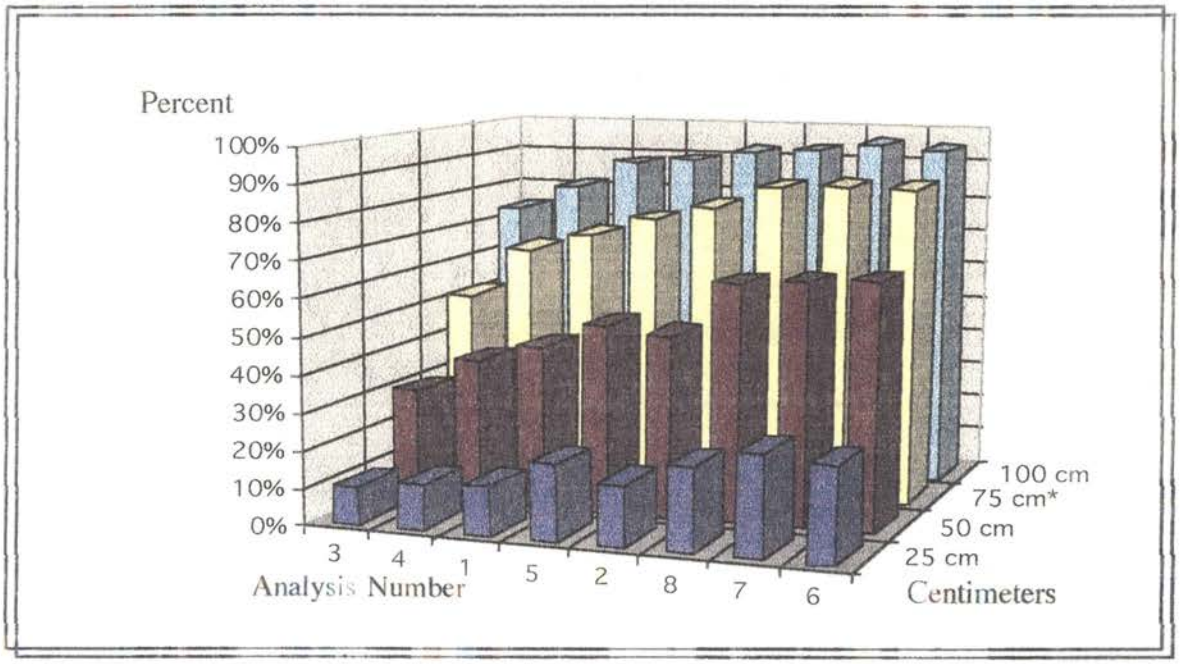

Figure 13. Improvement with Dense Network of Reference Receivers

TABLE VII

CORRECTING CIMARRON WITH KNOWN REFERENCES

Analysis #	6	7	8	2	5	1	4	3
Reference Receivers	P.H. + Springer	P.H. + Springer + Stil	Mulhal + Springer + Stil	Pleasant Hill	Stil + P.H.	Stil	Mulhal	Springer
25 cm	25%	27%	22%	16%	20%	13%	12%	10%
50 cm	66%	65%	64%	49%	51%	44%	39%	30%
75 cm*	87%	87%	86%	80%	76%	71%	66%	52%
100 cm	95%	96%	94%	93%	90%	89%	81%	74%
125 cm	97%	96%	96%	96%	96%	96%	89%	86%
150 cm	98%	97%	97%	97%	97%	97%	93%	93%
175 cm	99%	98%	98%	98%	98%	98%	96%	95%
200 cm	99%	98%	98%	98%	98%	98%	97%	97%
225 cm	99%	99%	99%	98%	98%	99%	97%	98%
250 cm	99%	99%	99%	98%	99%	99%	98%	98%
275 cm	100%	99%	99%	99%	99%	99%	99%	98%
300 cm	100%	99%	100%	99%	99%	99%	99%	99%
325 cm	100%	99%	100%	99%	100%	99%	100%	99%
350 cm	100%	100%	100%	100%	100%	100%	100%	100%

*Sorted on Cumulative 75 cm Column

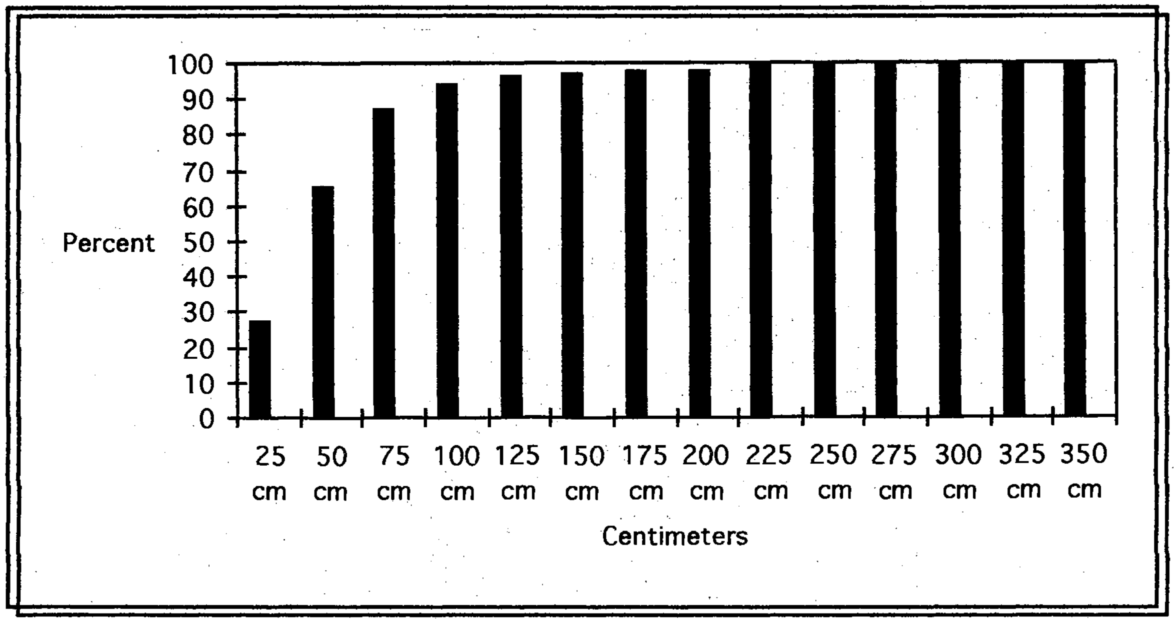

Figure 14. DC4 Percent Distribution of Accuracy

Latency Analysis

Maximum Latency (ML) is the ultimate error correction age which can be applied to autonomous receiver data before accuracy degradation disallows precision farming (Seibel, et al., 1995). Determination of ML provides a design point for network response time (i.e., band width), computing capacity requirements at a central data center, and for DGPS signal transmissions from a data center to an autonomous GPS receiver. ML is calculated simply by applying aged error to current Latitude/Longitude measurements. For example, the averaged reference receiver error calculated one second ago is used to correct the current measurement at the receiver site being corrected. Then, two-second old data is used, three-second old data, etc. This process continues several seconds, or until sufficient time has lapsed to observe the accuracy degradation with latency. Mathematically, the averaging process for latency calculation is identical with that described previously; the only difference was the time reference for the derived error used in the averaging process

(Figure 15, Latency Analysis Using "best case" Results from DC4 and Figure 16, DC4 Mean Error Distance vs. Latency Delay).

The positional error correction value from a reference receiver must be applied within two to three seconds in order to meet the 0.75 meters requirement for precision farming. As shown in Figure 15, Latency Analysis Using "best case" results from DC4, the percentage of measurements within 1.0 meters falls off rapidly. Only 40 percent of corrected measurements are within 0.75 meters with five second latency correction applied. The mean error distance doubles in five seconds and grows linearly to 20 seconds (Seibel, et al, 1995), (Figure 16, DC4 Mean Error Distance vs. Latency Delay). With refined correction algorithms resulting in improved accuracy, usable precision farming latency can be increased. For example, if accuracy can be improved another 0.25 meters, the allowable latency was increased to more than three seconds.

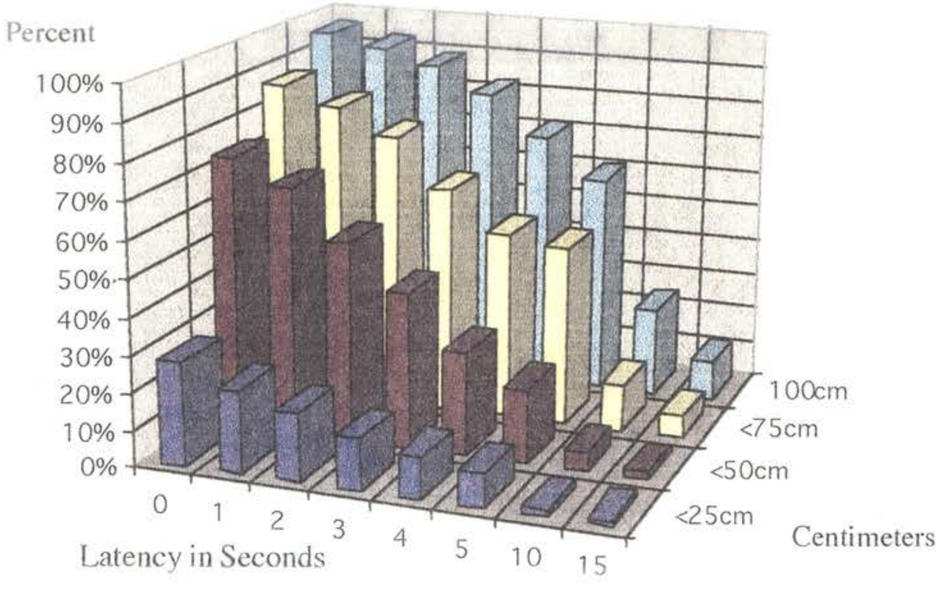

Figure 15. Latency Analysis using "best case" results from DC4

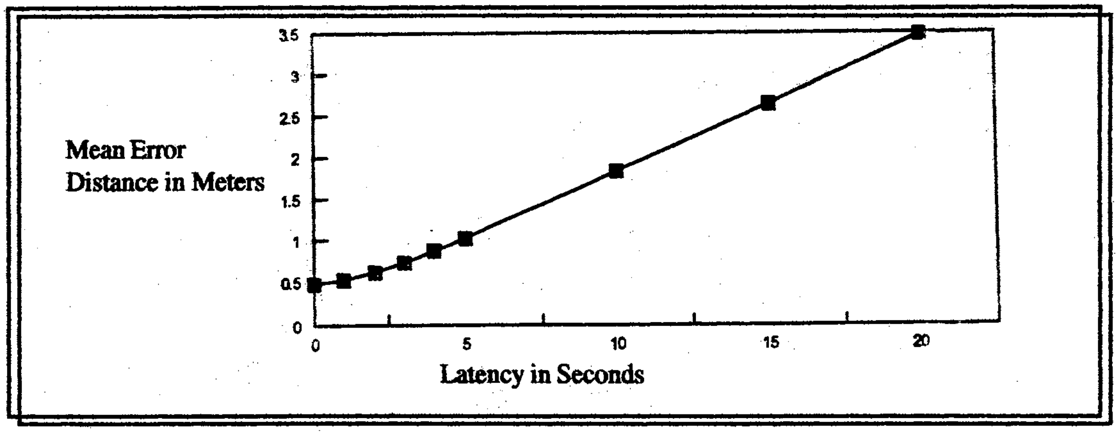

Figure 16. DC4 Mean Error Distance vs. Latency Delay

GPS Accuracy

GPS location positioning in the field is the key to precision farming data management. The results of this research met the requirements for: 1) A GPS field positioning system which consistently achieved one-meter positioning accuracy or better to meet the requirements of precision farming. 2) A GPS field positioning system that consistently achieved a 50 cm to one meter positioning accuracy a high percentage of the time would meet all but the most demanding positioning requirements of precision farming, (Table VIII, Comparison of GPS Accuracy and Options Available). The basis for precision farming is field variability. Ideas of within-field variability surfaced as early as 1929 with approaches to measure the spatial variability of soil acidity (Linsley and Bauer, 1929). Modern manifestation of the concept has resulted in field positioning technology (GPS), variable rate treatment, and yield monitoring (Goering, 1993). Variable applications of inputs may not increase yields but simply hold them constant while reducing input costs. The farmer reaps increased profits through better management and applications of less chemical treatments which also helps preserve the environment.

TABLE VIII

COMPARISON OF DGPS ACCURACY AND OPTIONS AVAILABLE

SYSTEM	SIGNAL DELIVERY	REFERENCE STATION	RANGE	ACCURACY / COST
US Coast Guard (Corbley, 1997)	Coast Guard Beacon	20 -40	120 -150 Miles	8-20cm (published). Users in Stillwater get 1-10m. Accuracy diminishes ≈ 1m/100 miles Cost: Standard GPS Receiver plus $1700
DCI	FM Subcarrier	120 -180	55 -85 Miles	Three levels of Accuracy 1m - $600/Yr. Service 5m - $250/Yr. 10m - $75/Yr. Plus the Receiver
Omnistar™ Wide Area system (Corbley, 1997) Ashtech, Topcon, and Magellan (Allen Precision Equipment, 1997)	Satellite	10 Base Stations around the Perimeter of the US		Sub-meter Advertised Standard Deviation=0.5m Bundled Solution: $2,895 - $19,900 8 channel receiver and 12 mos. service
Accqpoint Wide Area	GTE Spacenet Satellite and Simulcast on FM	10		# Users Service Cost 1 to 25: $600 / Yr. 26 to 100: $500 / Yr. 101 to 200: $400 / Yr. 201 to 500: $300 / Yr. Plus Receiver
DNDGPS Network Phase 1 research Hardware $295 Software $135		Spatially distributed every 45 km	35 - 45 km*	Accuracy** 87% of time <.75m 96% of time <1.0m Standard Deviation = 0.35m Cost: GCP Survey $700 plus four Receivers Cost: $2000

*Projected - Based on Data Table VII

In order to optimally manage a field, an agronomic optimum field size must be defined. As the name implies, this is the field element size that can be managed to economically optimize production (maximize yields while minimizing inputs). The agronomic optimum field element size establishes the key positioning criteria for precision farming.

Research by Stone, et al., (1996) and Solie, et al., (1996) established an agronomic-based field element size in the range of one meter in their studies of the total nitrogen uptake in winter wheat. The sensor data collected as part of Stone's research was used to determine fundamental field element sizes based on the total nitrogen uptake of the wheat plants. Research by Solie, et al., (1996) established a fundamental field element size for total nitrogen uptake at between .86m and 4.6m, depending on whether nitrogen had been applied in the fall, and a field element size of .86m to 1.5m was established for both fall or non-fall applications. This 1.5m field element size would require a .75m GPS.

Although the agronomic optimum field element size is considered the key criteria, analysis of other important variables, considerations, and operations in precision farming (e.g., soil variability, variable rate technology, yield monitoring, environmental conditions) also support a one meter (or better) GPS positioning requirement. Table II, Precision Farming Positioning Requirements, summarizes selected positioning criteria.

Manufacturers of precision farming equipment and DGPS service providers are dictating accuracy requirements for agricultural operations. This is the reverse of how it should be. It has been observed that users generally do not understand the origin of the GPS requirement nor do they have confirmation that the equipment operates within specifications, a source of great concern, Very little research is available that focuses on defining precision farming's "true" requirements with Solie, et al. being an exception.

The precision farming requirements Table II, Precision Farming Positioning Requirements, along with the 0.75 meter GPS, demands that a DNDGPS network be capable of supporting the precision farming operations described.

Results for simple error averaging and inverse-distance averaging did not demonstrate quantifiable differences at the network densities utilized in the four field exercises. This is understandable, with reference receiver separations on the order of 10 - 50 miles and satellite altitudes of 12,500 miles. Atmospheric effects on the multiple receivers are quite similar, if not identical, since propagation paths are very nearly the same. Results from simple averaging of reference receiver errors was therefore utilized throughout the proof of concept.

Derivation of an Optimal Separation Algorithm for calculating the optimum reference-to-autonomous receiver distance (where accuracy falls off) was needed to prove the feasibility of DNDGPS. This turned out not to be the case. The optimum separation of reference receivers can be derived by analyzing the results achieved and comparing these to the precision farming requirements. Based on the results achieved, precision farming requirements can be met by a balanced DNDGPS network configuration with average separation of 27 km between reference receivers. This approximates the density of Oklahoma Mesonet stations.

Resolution, having been defined as a measure of repeatability vs. accuracy, is a way of quantifying the stability, reliability and availability of the DNDGPS concept. The idea is simply to demonstrate the consistency of results over time, with the system under evaluation being stretched to its limit. The research results demonstrate confirmation of the DNDGPS concept with each data collection session. Sufficient resolution to validate the feasibility of a DNDGPS was achieved. Figure 17, Four Superimposed Plots of Latitude Error Data Collection #4 and Figure 18, Four Superimposed Plots of Longitude Error Data Collection #4, show superimposed plots of calculated positional error vs. time (at the reference receiver sites). These four reference receiver error curves overlap nearly completely. With four reference receivers, a corrected accuracy within 1.5 meters was achieved 98 percent of the time, 1.0 meter 87 percent of the time, and 0.50 meter 36 percent of the time (Table V, Correcting Stillwater with Known References). The increased accuracy as additional reference receivers were included, and the observed accuracy improvement with "balanced" reference receiver location geometry, demonstrated a high degree of repeatability.

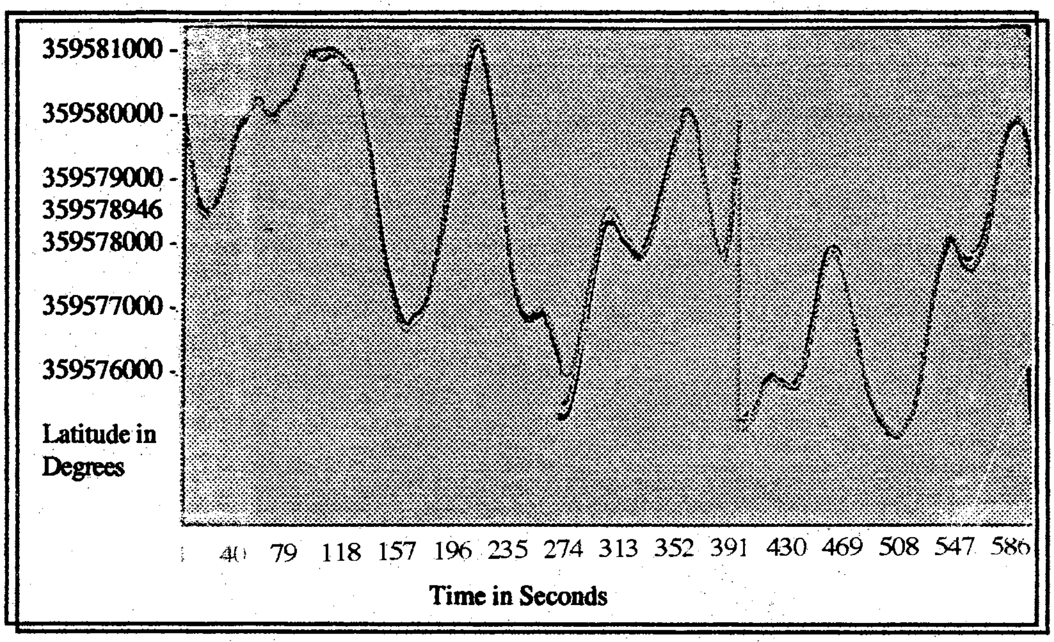

Figure 17. Four Superimposed Plots of Latitude Error from Data Collection #4

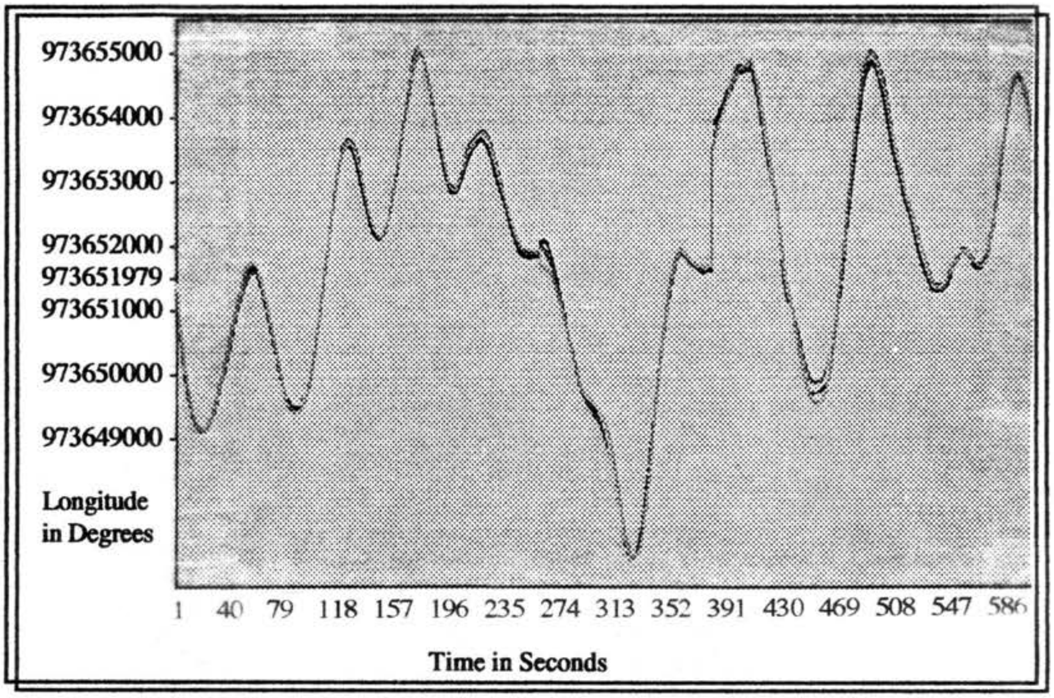

Figure 18. Four Superimposed Plots of Longitude

Scientific and Technical Feasibility

The State of Oklahoma is strategically positioned to advance the use of the NAVSTAR Global Positioning System to a new level of navigation and positioning technology. This research explored a dense network of multiple reference receivers over an area based on the Oklahoma Mesonetwork (Appendix G) to provide differential GPS (DGPS) capabilities with positioning resolution not currently available, i.e., a Dense Network Differential GPS (DNDGPS). This new level of resolution will enable innovative GPS applications with precision requirements not being fulfilled with existing DGPS offerings. New applications in precision farming vehicle guidance and control, surveying, and other areas will be enabled. Existing studies show the degree of improvement over conventional techniques is dependent on the relative lengths of the baselines, and the distance from the reference receiver to the user station. The Oklahoma Mesonet, a network of 111 solar powered meteorological stations geographically dispersed throughout the state, offers a cost effective solution to implementing a dense network of multiple reference receivers.

DNDGPS will offer innovative solutions to many industries faced with the need for increased positional accuracy as a way of reducing operational costs and improving competitiveness in world markets. Potential commercial users include the agricultural industry for precision farming and environmental applications, transportation, security, and public services. It can also be used to determine the precise location of buried pipelines or hazardous waste containers, for the mapping industry, real time surveying, and the construction industry. Potentially, DNDGPS can provide the basis for sophisticated guidance and control systems.

This research project was a two-and-a-half year endeavor that in the first half year performed a practical analysis of differential GPS accuracy using a refined error correction based upon input from several local reference receivers (RR). Specific applications that require a refined error correction were identified and their economic benefits qualified. In the second year, design and implementation plans were developed for a DNDGPS based on the Oklahoma Mesonetwork. Specific goals were to improve upon DGPS cost, accuracy, repeatability, degeneration with receiver separation distance, and offering a fault-tolerant architecture having negligible performance degradation with reference receiver failures.

Implementation Considerations

A Dense Network of Differential Reference Stations research should focus on the design, development, and implementation of a prototype network of Differential GPS (DGPS) reference stations, and selection of appropriate precision farming operations which uses the prototype network. An implementation plan for the overall research would first be developed and used as the "road map" for managing the research. The plan would address the goals of the prototype, along with the technical requirements, task definition, resource requirements, significant milestones, and a completion timeline. With the use of appropriate research management tools, the research "critical path" would be identified, along with crucial resources. A work plan would be developed which assigns resources and task priorities, identifies dependencies, and optimizes parallel activities. After agreement and sign-off the research plans, work would begin.

Detail design and development work to be performed in Phase II are identified in the following paragraphs. These tasks are part of the comprehensive implementation plan and represent significant aspects of the research that have direct influence on the technical successes of the system. The work plan, also to be developed during the Phase II research, will associate a time-line for the detail tasks performed in the following areas. The major elements of Phase II technical work for the DNDGPS research are: Phase II Technical Objectives; Phase II Plan of Work; and Relationship with Future Research (R&D)

Phase II Technical Objectives: The overall Phase II objective is to design, develop, and demonstrate a DNDGPS prototype that can be replicated in Phase III to a wide area. Therefore, the following Phase II technical objectives have been established and will be met:

1. Validate the primary DNDGPS design as offering the best technical and most affordable solution for precision farming.
2. Define detail requirements and specifications for GPS equipment, computational processing, network (telecommunications), transmission (radio), and software for DNDGPS system. This will address the most critical aspects of a real time DGPS system with a moving autonomous receiver: latency in the communications and processing of the differential error.
3. Design the DNDGPS system which meets the requirements, including all supporting hardware and software. The design will minimize communications

and processing DGPS latency to ensure precision farming requirements are not compromised.

4. Develop and implement a DNDGPS prototype consisting of five base reference stations.

The Phase II work plan will focus on the design, development, and implementation of a prototype dense network of DGPS reference stations, and the validation/demonstration of selected precision farming operations using differential corrections from the prototype network. A preliminary high-level DNDGPS design has been developed and is illustrated in Figure 19, DNDGPS Preliminary High-Level Design, and Figure 20, Mesonet Reference Site and Farming Vehicle Prototype Hardware Components (Seibel, et al.,1995). These designs capitalize on the characteristics of a "Dense Network of Reference Receivers" and addresses the problems inherent in currently available DGPS offering (e.g., latency).

The DNDGPS preliminary design features:

1. Distributed processing with special-purpose microcontrollers, Figure 20, Mesonet Reference Site and Farming Vehicle Prototype Hardware Components.
2. Multiple transit sites which minimizes latency and reduces UHF transmitter requirements.
3. Redundancy: the network can withstand multiple reference receiver outages with minimal loss in positioning accuracy; once operating it is not dependent upon a sophisticated central or satellite communications network.
4. Minimized bandwidth for land network communications. The Oklahoma Mesonet will be used to monitor the DNDGPS network and remotely configure GPS receivers. Utilization of the infrastructure of the Oklahoma Mesonet will minimize prototype developments costs and also offer a wide area initial implemention once the phototype is fully developed and successfully demonstrated.

5. Easily expanded to include additional reference stations for improved positioning accuracy.

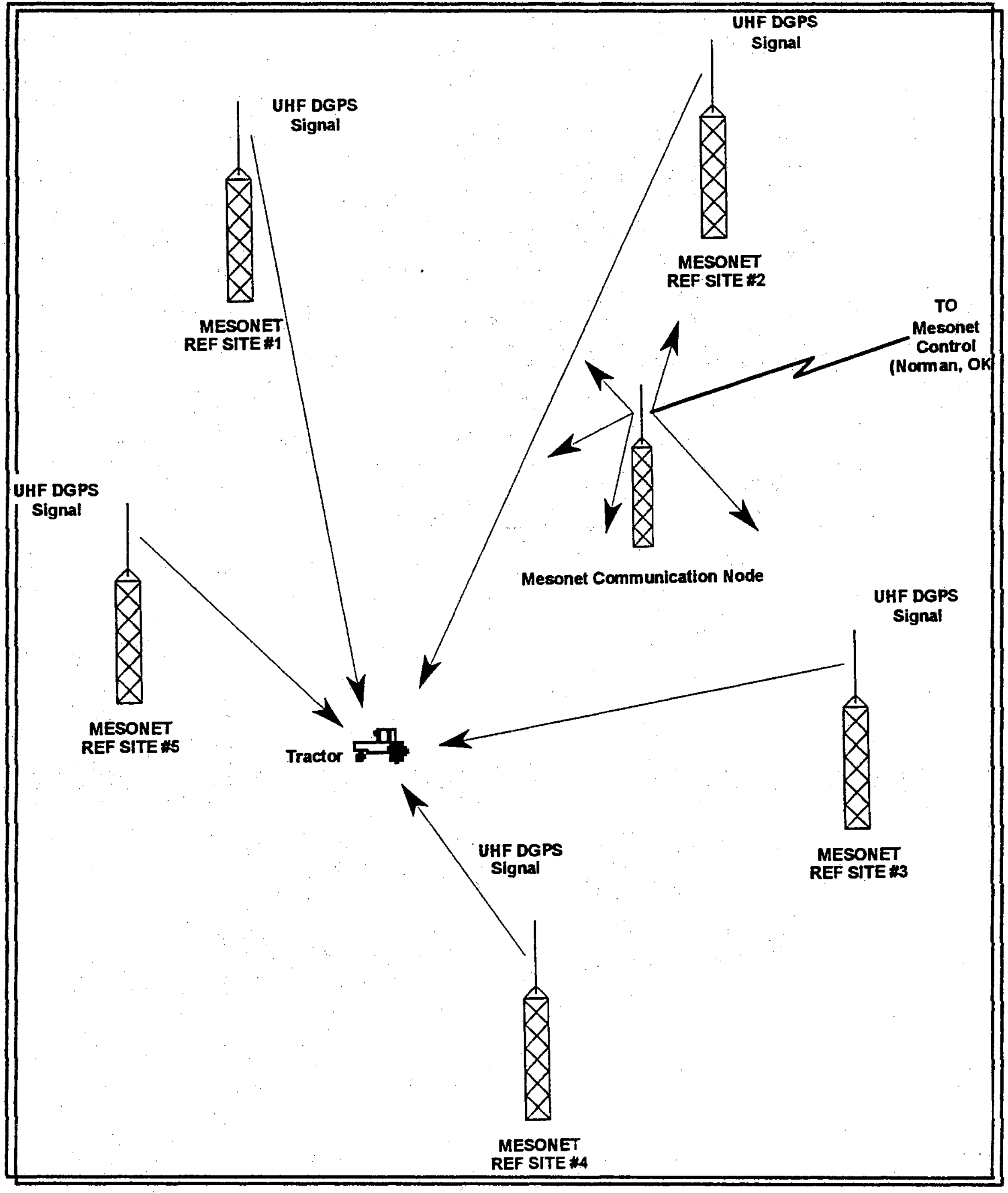

Figure 19. DNDGPS Preliminary High-Level Design

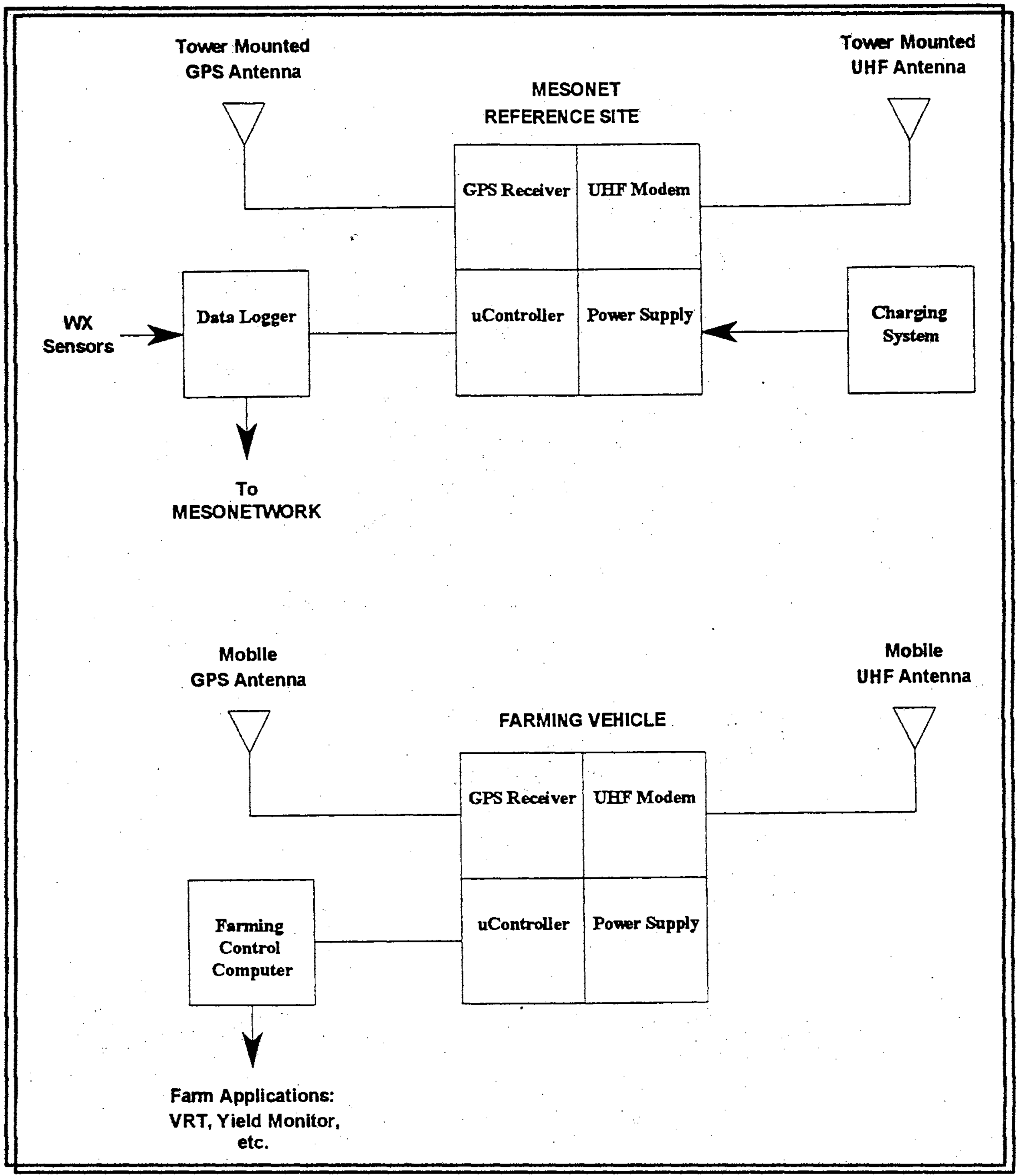

Figure 20. Mesonet Reference Site and Farming

Vehicle Prototype Hardware Components

The detail design and development work plan tasks are identified in the following paragraphs and are visualized in Figure 19, Schedule Milestone Chart for Phase II.

Task 1: Validate/refine preliminary DNDGPS design.

Step 1. Select Pseudorange or Positional DGPS as the DNDGPS strategy -- research, evaluation, and compare currently available DGPS Pseudorange vs. measurement Positional Technology. Critical factors are achievable accuracy, receiver specifications and costs, manufacturer support, receiver hardware interfaces, supporting software requirements, and the impact upon other aspects of the design, implementation and operation of the DNDGPS.

Step 2. Define specific data transmission requirements to provide DGPS signals to autonomous receiver. Calculate data volume per unit time requirement. Define network response-time (bandwidth) requirements for DGPS. This includes defining DGPS latency, UHF (telemetry) data acquisition time to the network, computer processing time, DGPS message transmission time (to autonomous receiver), and GPS receiver processing time for DGPS correction.

Step 3. Define macrocontroller requirements for reference receiver base stations and autonomous receivers.

Step 4. Define land-network data transmission requirements and Mesonet UHF telemetry link bandwidth requirements to monitor DNDGPS network and perform reference receiver initialization and configuration setup. This analysis will provide specific information regarding additional communication loan on Oklahoma Mesonetwork for prototype and fully operational “wide area” network. The prototype will provide additional information on location and network geometry, capacity for GPS equipment support, software functionality and ease of modification, and operation/maintenance. This information will be useful in evaluating the Mesonetwork as a protential DNDGPS foundation.

Task 2: Select GPS, Micro Controller, and Communications Equipment:

Step 1. Acquire GPS, micro controllers, communications equipment specifications, availability and cost information.

Step 2. Determine ancillary equipment provided by vendors (e.g., GPS antennas and software).

Step 3. Evaluate product specifications and vendor information vs. DNDGPS requirements, industry standards, ease-of-use and cost.

Step 4. Select equipment for DNDGPS implementation. Note: micro controller throughput requirements for reference receiver data and autonomous receiver. Activities include estimating the number of lines of executable code (per unit time), floating point content of software (scientific and mathematical calculations).

Task 3: Detail Design of Prototype DNDGPS System

Step 1. Hardware design. Included are GPS systems integration, GPS receiver interface to the selected network (e.g., Mesonetwork data logger), inbound and outbound communications, computing (DNDGPS averaging), and precision farming applications.

Step 2. Software design. Functional areas are data collection and validation, averaging and latency, algorithm development for the dense network, DGPS error transmission, precision farming applications, performance analysis and tuning, and maintenance. Custom firmware for onboard GPS receiver processing will also be defined.

Step 3. DNDGPS operations definition and documentation.

Step 4. Maintenance procedures.

Step 5. Documentation. Included are any limitations and deficiencies with DNDGPS design and alternatives to DNDGPS requirements not met by the Mesonetwork.

Task 4. Logistics Management. This encompasses an array of time-consuming activities: Communications with Mesonet resources (if Mesonetwork is used), FCC issues surrounding UHF radio components/applications, precision farming equipment availability, test bed for initial development, and overall project management and coordination.

Task 5: Build the Prototype DNDGPS System

Step 1. Hardware acquisition and installation. This potentially involves GPS receiver implementation and interfacing to the network (e.g., Mesonet), UHF telemetry for inbound GPS communications, land network facilities, central data center computing and outbound communications for DGPS error transmission.

Step 2. Software development. Functional modules include inbound GPS data collection, data reduction and processing, outbound DGPS error transmission, GPS reference receiver maintenance and configuration, network performance monitoring and tuning, and system operations.

Step 3 Documentation of all system components, operations and maintenance procedures, for both hardware and software implemented in the DNDGPS.

Task 6. Develop and Implement Test Plan:

Test plan facilitates early problem identification for newly developed components of the DNDGPS. This requires minimal impact on existing sub systems in production (e.g. Mesonetwork), and provide formal feedback to the designers and developers of the DNDGPS .

Step 1. Acquire/develop diagnostic tools which allow the capturing of DNDGPS performance information.

Step 2. Execute the plan as completion of earlier tasks permit: Code and Unit Test, Component Test, System Test.

Task 7. Precision Farming Application Demonstration

Step 1. Select precision farming applications for DNDGPS test demonstration (e.g., yield monitoring). Selection criteria will include economic benefit, available equipment and resources, farm location, "best" crop, and technical feasibility.

Step 2. Develop a demonstration plan and how results will be measured.

Step 3. Development of a precision farming operational demonstration, including GPS hardware and software for initial applications.

Step 4. Schedule and arrange for resources: equipment, application software, and volunteers (researchers, farmers, agribusinesses) to participate in demonstration.

Step 5. Design and develop software to import data into GIS and precision farming application packages for post-analysis and validation.

Step 6. Develop formal presentation of results of demonstration to facilitate Phase III.

Task 8. Develop Commercialization Plan (Phase III) and Fan-Out of Prototype DNDGPS to Statewide Production.

Step 1. Develop business case for DNDGPS Network.

Step 2. Secure financing commercialization and network expansion (additional network sites and upgrade software to accommodate the statewide system).

Step 3. Expand DNDGPS application that suite additional precision farming applications. This exercise will also be sensitive to related research at OU and OSU which could benefit from the DNDGPS .

Step 4. Market affordable, high-accuracy DNDGPS service.

Step 5. Expand to new geographic markets and other strategic industries.

The research and development of field level locations is the key for precision farming data management. For precision farming to succeed and fulfill its promise, a precise GPS positioning system that meets the precision farming requirements at an affordable price must be developed and made available to the farmers. This DNDGPS test plan technologies meets both precision farming positioning and affordability requirements. DNDGPS technologies has the potential to accelerate the implementation of precision farming applications and therefore, the accrual of benefits. Precision farming, with the promise to simultaneously increase crop yields and reduce environmental pollution, is key to achieving the productivity gains necessary to meet the world's increasing need for food.

Milestones: Four milestones have been identified to track progress toward achieving the Phase II technical objectives. The relationship of these milestones to the overall Phase II effort is indicated in Figure 21, Scheduled Milestone Chart for Phase II.

1. Preliminary design validated, equipment selected and detail design underway. Time: End of month 4.
2. Design completed, DNDGPS implementation started. Time: End of month 12.
3. Initial three months of DNDGPS prototype testing completed. Time: End of month 15.
4. DNDGPS prototype implementation completed, precision farming demonstration development started. Time: End of month 18.

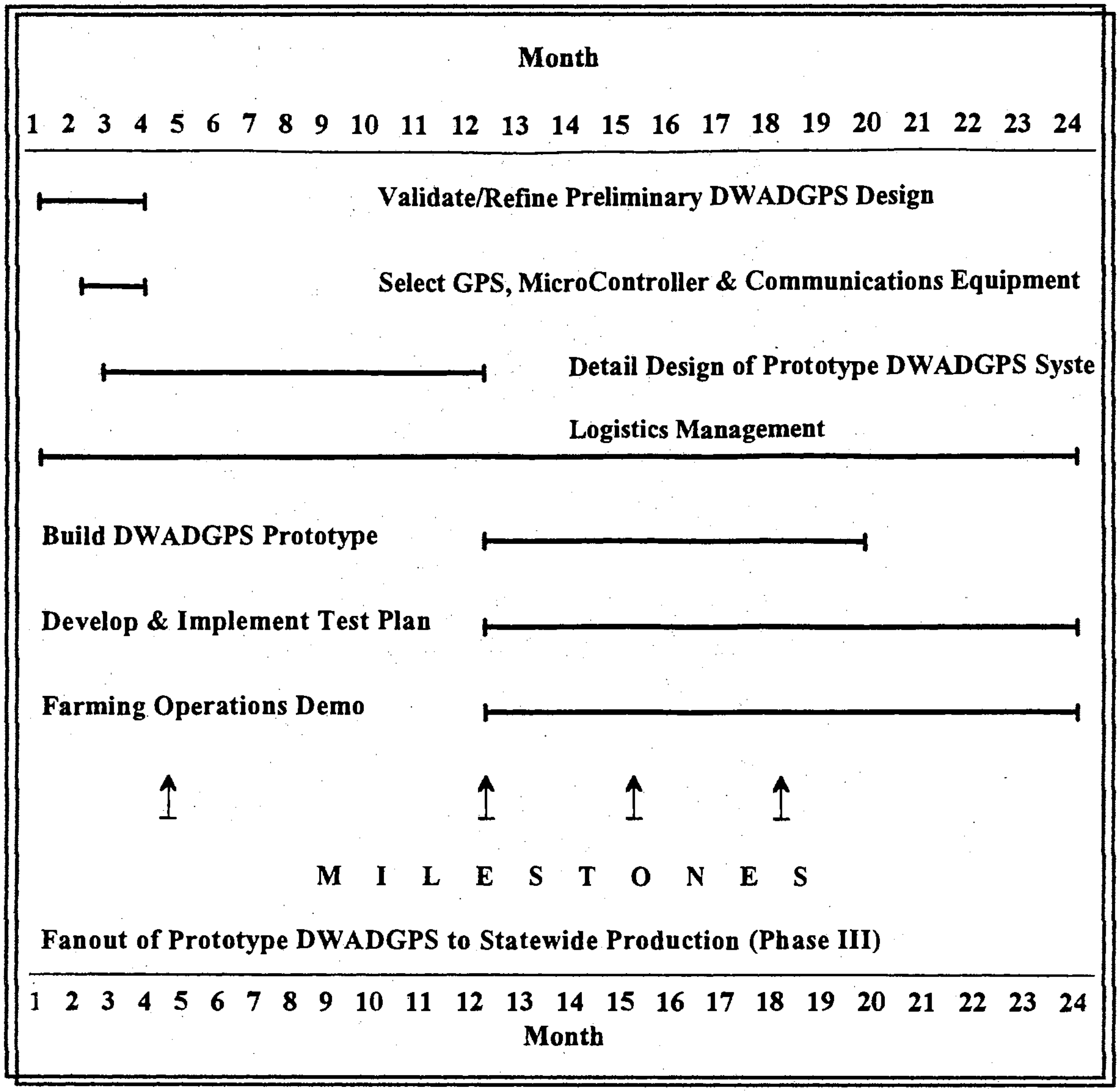

Figure 21

Scheduled Milestone Chart for Phase II

CHAPTER V

SUMMARY, CONCLUSION AND RECOMMENDATIONS

Introduction

General goals are to increase agriculture's efficiency and reduce its energy usage and environmental impact by optimizing use of the resources. This is being done in precision farming by integrating component technologies such as GIS, GPS, yield measurement sensors, variable rate technology, environmental and soil sensors, crop models, expert systems, and computerized decision support systems. Specific goals in this Phase I SBIR/OCAST study are to improve upon DGPS cost, accuracy, repeatability, degeneration with receiver separation distance, and to offer a fault-tolerant architecture having negligible performance degradation with reference receiver failures.

Statement of the Problem

Classical Differential GPS (DGPS) utilizes a master reference station, located on precisely known coordinates, to track the GPS satellites and determine their range errors through comparison with the known reference solution. The differential GPS corrections are then broadcasted to autonomous receivers in the local area. These local receivers produce a correction navigation solution by using the respective satellite range errors provided by the differential reference receiver and are said to operate in the pseudorange domain. Absolute navigation accuracy attainable in this way is a function of the accuracy of the pseudorange and delta range measurements. DGPS corrections, then, can be used to reduce or eliminate the GPS system errors.

Positional DGPS, explored in this project, used standard GPS receivers situated on precise coordinates. Positional error at all reference sites was calculated and averaged; the average error was used to correct GPS navigational fixes produced by autonomous receivers in the vicinity. It has been shown that differential corrections produced in this positional domain with a single reference can be as accurate as those produced in the pseudo mode. The DNDGPS approach further refines both single-reference pseudorange and single-reference positional DGPS by having the benefit of multiple references.

Uncorrected GPS location measurements to within 100 meters at 95 percent probability are possible with an autonomous receiver not benefiting from DGPS. This large tolerance is due to the aggregate total of several error sources: signal reflection in the atmosphere, satellite orbital errors, receiver noise, clock synchronization, multipath signal reflections, receiver processing delays, satellite geometry, and selective availability. Classical DGPS techniques involving a single pseudorange reference station for empirical error measurement provide reliable real-time correction of such errors to an accuracy of approximately two to five meters. Sub-meter precision has been possible with sophisticated Doppler/carrier-phase systems which are cost-prohibitive for most applications today.

Purpose

The purpose of this study was to assess the feasibility of a differential global positioning system having a dense network of reference receivers to enable advanced precision farming applications.

Objectives of the Study

In order to achieve the purpose of this study, the following objectives were established:

1. To validate previously published research that atmospheric effects increase as distance between receivers increase;
2. To identify economic justification for a Dense Network of Differential GPS (DNGPS) for individual farming applications;
3. To determine the resolution, repeatability and accuracy, obtainable with DNDGPS corrections derived from a dense network of multiple reference receivers; and
4. To develop a farm-based DNDGPS prototype and a plan for Oklahoma Mesonetwork DNDGPS prototype which identifies necessary resources required for implementation.

Rationale of the Study

The continuing high cost of receivers and differential losses point out the need for a economical fault-tolerant DNDGPS having negligible performance degradation with RR failures. Currently, DGPS uses a single reference station to correct for aggregated errors inherent in GPS measurements. The proposed DNDGPS would use several networked reference stations closely spaced to provide corrected accuracy that equals or surpasses that of single pseudorange DGPS at reduced costs. Additional objectives of DNDGPS are reduction or elimination of precision degradation with increasing baseline distance (reference receiver to autonomous receiver) and improved reliability and availability of corrected position information in the event of reference receiver outage. The overall mission of this project is to identify and enable precision farming operations which can greatly benefit from the reduced DGPS cost offered by the DNDGPS.

Design of the Study

To accomplish the purpose of this research, GPS and computing requirements were defined, equipment was selected and procured/fabricated, software was acquired and developed, and NGS monument sites were selected for data collection (Appendix B). GPS data were recorded, validated, filtered, analyzed, and visualized. GPS latitude and longitude data were stored, simultaneously, in one second intervals for several hours at six surveyed locations on four different occasions. Selected NGS monument sites simulating different network densities (distances between sites) in portions of six counties of North-Central Oklahoma in the vicinity of Stillwater were used. The positional error for each one second datum at each site was calculated. The derived error for two, three, four, and five sites was averaged in turn and used to correct the measured position at the sixth site (treated as autonomous receiver); these were compared with the single reference case. Statistical analyses were performed to demonstrate the improved accuracy with additional reference sites. GPS requirements for precision farming were defined.

Summary of Findings

It was found that low-cost DNDGPS reference receivers (RR) were feasible and meets or exceeds a high percentage of precision farming operations. All of the objectives were accomplished. The study found that averaging DGPS error data derived from a multiple reference receiver network dramatically improved corrected position accuracy for an autonomous receiver at an unknown location, as compared with single reference corrections. Improvement is a function of network topography, density, and node (monument) position preciseness. A simulated network density on the order of the Oklahoma Mesonet (19 miles between RRs) produced consistent accuracy within the 0.75 meter requirement defined for most precision farming operations; precision improved proportional with additional reference stations.

This study focused on the feasibility of DNDGPS reference receivers for precision farming. In order to achieve the objectives of the study, the following questions were developed:

Question 1. Do atmospheric effects within DNDGPS reference receivers (RR) and secondary receivers (SR) cause any notable difference in magnification as separation between receivers increases? The DNDGPS Question 1, as conceived, was based upon comprehensive knowledge of GPS functionality and limitations, rigorous engineering development practices, and previously published research dealing with Wide Area (Ashkenazi and Hill, 1992; Mueller, 1994a and 1994b) and Extended DGPS (with sparse, rather than dense networks) (Brown, 1989). This research has proven there were no notable differences of atmospheric effects within a DNDGPS system; however, the process has revealed that the original algorithms proposed for evaluation were valid but in the DNDGPS environment may become insignificant due to a high density of reference receivers. Thus within DNDGPS, atmospheric effects upon reference receivers (RR) and the secondary receivers (SR) caused no noticeable difference in magnification as separation between receivers increased.

Question 2. Can DNDGPS be implemented at a lower cost than off-the-shelf DGPS systems for precision farming applications? The results of the research found that DNDGPS receivers with sub-meter accuracy and low cost, can be supplied for precision farming. Additional retail receiver cost are reviewed on pages 47 and 48, DNDGPS receiver hardware and software cost are reviewed in Appendix D and E. A system of four DNDGPS receivers can be purchased for less than one DGPS receiver (Table VII). A DNDGPS system represents a tenfold savings for farmers who purchase their own local base station (Corbley, 1997), (Allen Precision Equipment, 1997). Yes, a DNDGPS can be implemented at a notably lower cost than off-the-shelf DGPS systems for precision farming applications.

Question 3. Were there notable differences in the resolution of GPS utilizing DNDGPS reference receivers in the positional domain, with averaging algorithm(s) for refining correction data, compared to DGPS systems utilizing the pseudorange mode? The combination of three or four multiple receivers reduced the variation caused by time over the same location. The DNDGPS corrected measurement within approximately one foot of the actual position 96 percent of the time. Networks on the order of the Oklahoma Mesonet density achieved positioning accuracy of 50 cm and 75 cm, with probabilities of 65 and 87 percent, respectively. Based on GPS publication advertisements, the positioning accuracy achieved with the DNDGPS of multiple-based stations is better than any positioning service generally available over a wide area. Omnistar™ (John Chance) which advertises a standard deviation of 5.0 meters compares to DNDGPS .35 meters. Thus, in response to the third question, there were no notable differences in the resolution of GPS utilizing DNDGPS reference receivers in the positional domain (vs. pseudorange mode) with an averaging algorithm(s) for refining correction data. The system was proven to be as accurate or better than off-the-shelf DGPS systems.

Question 4. Did the DNDGPS system increase the efficiency for agriculture by: 1) identifying practical variability for investigating probable causes and 2) helping identify possible solutions for precise evaluation which were notably greater with DGPS systems? Table I, Precision Farming Positioning Requirements, along with the 1.5 meter field element size requirement (Solie et al., (1995), require a .75 meter DGPS farm system. That requirement was met by a DNDGPS network with reference receiver separation of 27 km, as outlined in this research with capabilities of supporting the precision farming operations described. A high resolution DNDGPS network is feasible and produces better positioning accuracy results than DGPS services currently available and at a much lower cost. The positional accuracy of an autonomous receiver was improved on the order of 25-30 percent with positional correction from multiple reference receivers clustered around the autonomous receiver, compared to classical Differential GPS with one reference receiver. This system allowed field personnel to gather precision information for building a farm data base. Field digitization was used to update or correct the GIS base map and to provide exact locations on crop status. The system's GPS receiver would send positional information to the main computer as often as once per second. These techniques enabled the user to document locations of probable cause and location where possible solutions were applied.

Conclusions

The results of this research demonstrates that the DNDGPS network concept provides locational accuracy required for precision farming. Nominal GPS precision farming has been defined in prior research as an accuracy of 0.75 meter; this study achieved that goal using only five GPS reference receivers, simplistic algorithms and manual operations. In a production DNDGPS system (Phase II), much larger numbers of reference receivers will be available, algorithms will be refined to higher levels of sophistication, and data collection will be automated (eliminating human involvement). Dense network capabilities at that time will extend well beyond what has been used in this research. Based upon the achieved results in this research effort, DNDGPS was certainly feasible and the positional accuracy achieved with a simulated dense network meets or exceeds a high percentage of the requirements defined for precision farming operations.

It was further concluded that accuracy improved with increased numbers of reference receivers. The geometry of the reference receivers (RR) also influenced the corrected accuracy. A symmetrical or "balance" network of RR produced the best results. Although observations from the results indicated three to five reference receivers properly spaced met precision farming needs, a "production" DNDGPS having much greater numbers of reference locations (e.g., Oklahoma Mesonetwork Density) would be expected to show improved results. Furthermore, this additional influence of reference locations on corrected accuracy of GPS readouts at an autonomous position would only serve to provide even greater accuracy for precision farming applications.

Data Collection Session #1 (DC1)

Conclusion:	Initial results verified the ability to control the GPS receivers in their selection of identical satellite configuration, a necessary requirement

for the DNDGPS concept to work (Blackwell, 1985). The overlapping plots for the four data sets collected indicates the positional errors at those sites were very close to being equal; this presents strong evidence that the DNDGPS Research question number one was accurate. It was decided to further analyze this scenario by repeating data collection at these sites (Data Collection Session #2) (Seibel, et al., 1995).

Data Collection Session #2 (DC2)

Conclusion: The corrected STIL measurement data exhibits improved accuracy as additional reference monuments were included in the error-averaging calculation (unweighted) with certain combinations of reference sites. It was observed that the unweighted corrections using reference monuments which were "balanced" (being approximately equi-distant and opposite in direction from STIL) produced the best results (Table V, Correcting Stillwater with Known References). This balanced-linear-correction (BLC) offers the best opportunity for the average error to compensate for the satellite and atmospheric contributions to the error at STIL. The BLC trend observed will be further studied by analysis of data from the next field trip (DC3).

DC2 analysis of weighted-average corrections (weighting inversely proportional to the reference site distance from STIL) did not result in a quantifiable difference from the corrections with unweighted averaging. The question was that atmospheric effects upon reference receivers and the STIL receiver will magnify as the separation between the two increases (RTCM-SC104 Standards, Ver. 2.1, pp. 1-9). However, this did not validate the DNDGPS research question (Seibel, et al., 1995).

Data Collection #3 (DC3)

Conclusion: Results demonstrate that the representative improvement progression as observed in the analysis of the research data were maximized, when the reference sites used for correction were balanced (BLC) as described before. The DC3 results indicate that a dense network with average reference distance separation of 47 km adhering to a BLC concept can achieve corrected accuracy with a consistently high probability. The weighted-with-inverse-distance averaging algorithm is not needed with networks having a density on the DC3 scale (Seibel, et al., 1995).

Data Collection #4 (DC4)

Conclusion: DC4 confirmed results obtained in DC2 and DC3. Results demonstrate the representative improvement progression observed in the analysis of the research data, when the reference sites used for correction were balanced (BLC), as described before. The DC4 results indicate that a dense network with average reference distance separation of 46 km adhering to the BLC concept can achieve corrected accuracy with a consistently high probability. This meets or exceeds the requirements for precision farming operations: remote sensing, variable rate technology, yield monitoring, soil analysis, and water quality. The corrected Cimarron latitude and longitude plots demonstrate the accuracy being achieved. Note the close coincidence of the corrected curves with the truth line in Figures 22 and 23 (Cimarron Surveyed, Measured & Corrected Latitude/Longitude) (Seibel, et al., 1995).

The overall objectives were accomplished and all technical objectives were achieved in this research: 1) Overall conclusion: A DNDGPS network was feasible and provides positive benefits in developing precision farming practices. 2) The positional accuracy of an autonomous receiver was improved with positional corrections from a dense network of reference receivers (DNDGPS network), compared to classical DGPS.

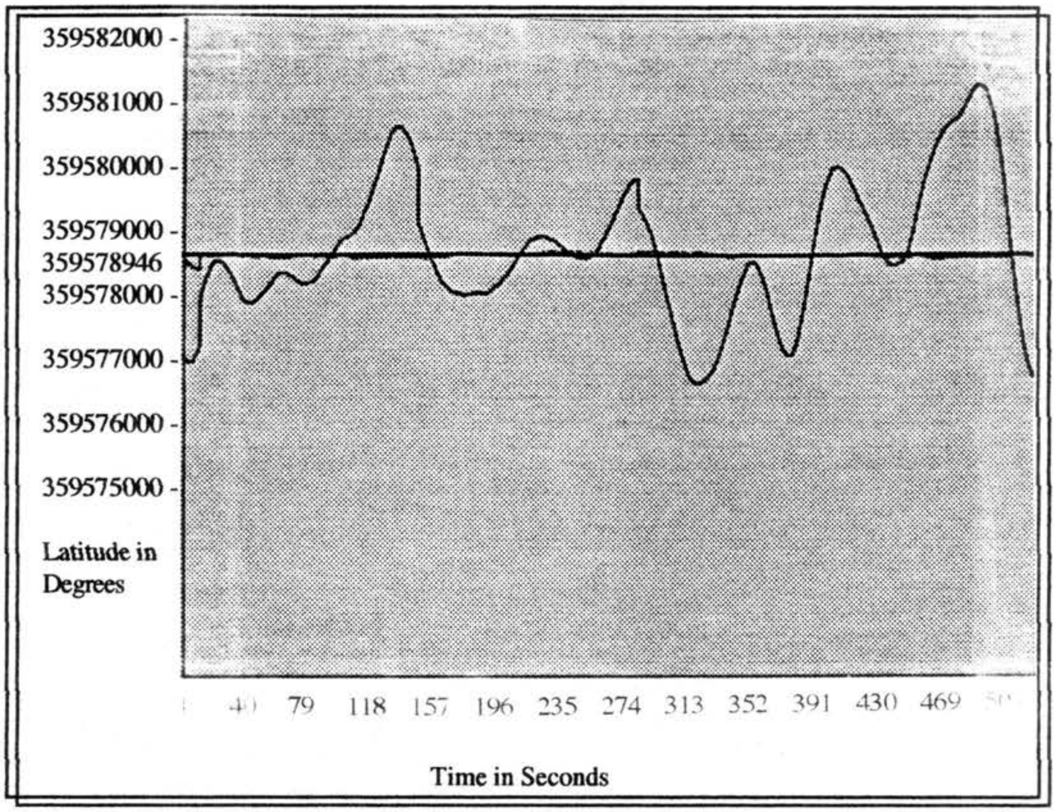

Figure 22. Cimarron Surveyed, Measured and Corrected Latitude

3) Accuracy improved with increasing numbers of reference receivers, Table V, Correcting Stillwater with Known References; VI, Correcting Z136 With Known References; and VII, Correcting Cimarron With Known References. Three or four reference receivers, properly spaced, removed a high percentage of positional error. Implementation of the error-

averaging scheme on a larger scale (i.e., more than four or five GPS references stations) could accommodate fine tuning of the system and the potential for additional correctness. 4) DNDGPS networks with average distance of 27 km between reference receivers meet or exceeds GPS positioning accuracy requirements defined for most precision farming operations, Table IX, DNDGPS Summary Results.

5) The geometry of the reference receivers (RR) also influenced the corrected accuracy. A symmetrical or balanced network of RR produced the best results. 6) Latency analysis indicates that references receiver corrections be applied to the autonomous receiver to meet precision farming requirements, based upon the current accuracy achieved (Latency

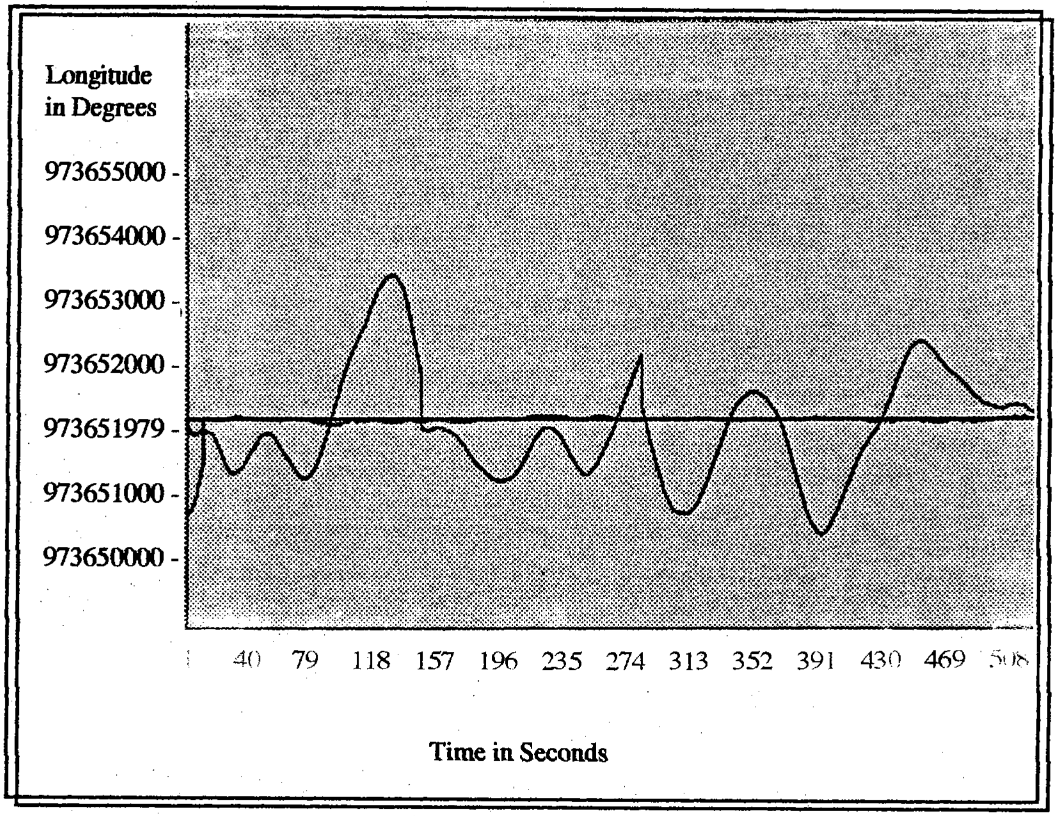

Figure 23. Cimarron Surveyed, Measured and Corrected Longitude

Analysis for Data Collection (DC) #4). 7) Further improvements in positional accuracy were possible by statistically eliminating noise in reference receiver measurements due to multi-pathing, etc., and by minimizing divergence with satellite constellation changes (new satellite appears above horizon mask or disappears below horizon mask). 8) A prototype DNDGPS was the next logical step in the technical evolution of DNDGPS. A prototype with several RR locations would serve as a platform for the development of hardware/software needed to support GPS farming operations, provide a demonstration facility, and act as a test bed for DGPS precision farming research developments already underway.

TABLE IX

DNDGPS SUMMARY RESULTS

Data Collection #	Analysis #	Average Distance between RRs (km)	Distance Range From RR to SR (km) Min/Max/Avg	# RRs	Percent of Corrected Measurements within: 50 cm	100 cm
1	Note 1	70.0	42.1/49.8/44.7	4		
2	15	70.0	42.1/49.8/44.7	4	36	87
3	10	45.7	21.1/34.1/27.3	3	54	96
4	7	46.0	22.6/29.9/26.6	3	65	94

Note 1: Only limited data collected at autonomous because of PC power supply problems.

RR - Reference Receiver

SR - Secondary or Autonomous Receiver

Recommendations

Phase II of the "GPS for Precision Farming: A Dense Network of Differential Reference Stations" was both indicated and recommended. The accuracy achieved in this research, less than 75 cm 87 percent of the time using three to five reference stations, will support precision farming applications. Implementation of the error-averaging scheme on a larger scale than Phase I could accommodate "fine tuning" of the system and the potential for additional correctness due to more than five GPS reference stations. Such a prototype is the next logical step in the technological evolution of DNDGPS. It will provide a more stable date-collection environment. Data quality will be immediately improved, as will the ability to fine tune the averaging algorithms and turn around results. The prototype, although not statewide, would serve as a platform for the development of hardware/software needed to support farming operations, provide a "demonstration" facility and act as a test case for DGPS farming research and development already underway. Financing of this research is available through the North Central Regional Project on Site Specific Management (NCR 180) and Precision Farming H.R. 3795.

This researcher recommends implementation of a DNDGPS prototype network in Phase II, capable of supporting the 0.75 meter accuracy requirements of precision farming. The resource infrastructure is available in Oklahoma (University of Oklahoma and Oklahoma State University) to support Phase II prototyping: industry knowledge, access to prior research, communications pipelines into the agriculture industry, Oklahoma Mesonetwork and its developers. All expertise needed to provide continuity beyond Phase I, solve technical design and implementation issues, and address end-user application of Phase II results, is presently available to participate in Phase II. These ingredients maximize the opportunity to realize DNDGPS success in the shortest possible time.

While the technologies are out there, people formally trained in them are not (Keating and Franz, 1997). Therefore, a second recommendation is teaching precision farming analysis with GIS/GPS and remote sensing for on-farm use. The universities should be involved in developing the knowledge that will in the long run determine the usefulness of precision farming data and management. The private sector has the comparative advantage in developing, manufacturing and servicing the equipment and software needed to make a precision farming system work. It will take a consortium of university, cooperative extension, agricultural education, agricultural producers, and private industry to put together the critical mass of expertise needed to develop the tools to help interpret precision farming data and use it in fine tuning crop production strategies (Lowenberg-DeBoer, 1997). These technologies have the potential to revolutionize agriculture, but most are in the early stages of development and will need extensive research before they are proven effective. The focus of agricultural research will need to shift from conducting controlled laboratory experiments to gathering data and studying results on the farm. This is where Cooperative Extension and agricultural education are critical. There are several priorities that should be addressed: 1) Create data - gathering and analysis tools for agricultural purposes. Many existing technologies, such as GPS and data base systems, were designed for other uses and will need to be adapted for farm settings. 2) Clarify intellectual property and data privacy rights. The value of information will greatly increase as more sophisticated technologies are introduced, and farmers may want to make data about their fields available to outside vendors such as aerial and satellite sensing companies, fertilizer and seed dealers, and farm cooperatives. Extension educators should ensure that farmers are aware of intellectual property and data privacy rights. 3) Link rural farm communities to high speed data networks. Public-private partnerships are being formed to meet a national goal of providing computers to all American schools by the year 2000. Agricultural organizations should work with public agencies and industry to ensure that farmsteads have access to computer networks. 4) Provide unbiased assessments of the economic and environmental impact of precision farming methods. Many innovative growers are experienced with technologies on their farms, but few have the resources to scientifically evaluate results or possible environmental effects, and 5) Educate and train agricultural professionals and students. Universities, technical colleges, and professional associations should emphasize a multi-disciplinary approach to gathering and analyzing new types of data.

Problems facing precision farming at the university level are 1) Academic traditions discourages distribution of preliminary results outside of a narrow group of scientists working on similar problems. 2) Most of the activities operate on a shoestring budget. It is hard to start new activities when the Land-Grant mandate itself is under threat, when USDA leadership appears to believe that precision farming will be used only by very large farming operations, and problems exist in muli-disciplinary research. Some of these problems can be alleviated by building environmental concerns into precision farming analysis tools and software, creating consortiums, and incorporating other disciplines such as social sciences. If the public benefits from improved environmental conditions and the public support for this part of the research is added into the equation, the chances of covering costs are improved. Solving the riddle of precision farming data will require tools that can analyze numerous interactions and linkages. It will take regression and natural networks, in addition to analysis of variance.

GPS locations in the field are the key to precision farming data management. Precision farming is rapidly expanding in both research and production agriculture, and is already demonstrating its potential to simultaneously increase crop yields and reduce environmental pollution. Variable soil treatment and soil-mapping strategies need improvement which only greater locational accuracy with GPS can provide. Finally, water quality maintenance demands that chemical applications be controlled so as not to infiltrate streams and rivers. Most importantly, the economics of applying positioning technology to these critical farming applications must be affordable by the farmer. DNDGPS offers an exciting answer to these questions, and in the opinion of this researcher, will provide an effective solution to the research objectives.

The world-wide market for GPS receiver equipment is expected to grown to more than $8 billion by the year 2000, according to a report released by the U.S. GPS Industrial Council (Swiek, 1995). The GPS industry expects site-specific or precision farming to become the largest, single consumer of high precision GPS navigation (Havermale, 1994), so this technology could be very important to our state's agricultural industry. In order for these expectations to be realized, an affordable Differential GPS with positioning accuracy which meets the requirements of precision farming must be made available to the producers. The DNDGPS technology provides a low-cost solution to end user applications, like precision farming, requiring consistent sub-meter accuracy.

A dense network of differential global positioning system reference stations for precision farming provides the information to improve both economic and environmental sustainability. It is a win - win technology.

A SELECTED BIBLIOGRAPHY

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APPENDIXES

THE UNIVERSITY OF OKLAHOMA
Norman, Oklahoma

SUBCONTRACT NO. 1996-10

UNDER

CONTRACT 4912

FROM

OKLAHOMA CENTER FOR THE ADVANCEMENT OF SCIENCE AND TECHNOLOGY

SUBCONTRACTOR:	**Oklahoma State University** **ID#73-6017987**
ADDRESS:	**Agronomy Department** **371 North Ag Hall** **Stillwater, Oklahoma 74078**
PROJECT:	**High Resolution DGPD**
TYPE OF SUBCONTRACT:	**Cost Reimbursable**
PROJECT PERIOD:	**May 1, 1995 to April 30, 1996**
TOTAL FUNDS ALLOTTED:	**$ 12,000.00**
ISSUED BY:	**University of Oklahoma** **Office of Grants and Contracts** **1000 Asp Avenue, Room 210** **Norman, Oklahoma 73019**

SUBCONTRACT NO. 1996-10

PREAMBLE

This Subcontract, entered into August 7, 1995 by and between the University of Oklahoma, Norman, Oklahoma (hereinafter called the "University), and Oklahoma State University (hereinafter called the "Subcontractor") constitutes a Subcontract under OCAST Contract 4912.

WITNESSETH THAT

The Subcontractor agrees to furnish and deliver the supplies and perform the services set forth in this Subcontract for the consideration stated herein.

SCHEDULE

ARTICLE 1. STATEMENT OF WORK

The Subcontractor will provide the Agriculture consultant. Mr. Jerry Speir brings thirty+ years of practical experience in Agriculture as well as experience and knowledge in leading-edge technologies being used and developed for Agriculture. He has performed "site-specific Agriculture research" at Oklahoma State University using GPS and GIS. He will be involved in all analysis and design tasks of the project to ensure "precision farming" requirements are identified and solutions designed to meet specifications identified. He will have the lead responsibility for developing "precision farming" GPS resolution requirements by farming operations and for performing the benefit analysis.

ARTICLE 2. PROJECT PERIOD

(a) The project period of this Subcontract is from May 1, 1995 through April 30, 1996.

ARTICLE 3. ALLOWABLE COSTS AND PAYMENT

(a) The estimated total cost of performance of this Subcontract is $12,000.00. Invoices for these costs shall be submitted in triplicate to the Grants and Contracts Office for approval and processing. Funding is for the salary and fringe benefits for Mr. Jerry Spier only.

ARTICLE 4. TECHNICAL REPORTS

As required by the University to meet the reporting requirements of OCAST.

ARTICLE 5. FINANCIAL REPORTS

None

ARTICLE 6. DISPUTES

Should the parties to this Subcontract be unable to resolve between themselves any dispute arising from any of the provisions within this Subcontract, each party shall have recourse under the law.

ARTICLE 7. INDIRECT COST RATES

No Indirect Costs will be charged to this Subcontract.

THE UNIVERSITY OF OKLAHOMA
Norman, Oklahoma

SUBCONTRACT NO. 1997-5

Under

CONTRACT 5038

From

OKLAHOMA CENTER FOR THE ADVANCEMENT OF SCIENCE AND TECHNOLOGY

SUBCONTRACTOR:	**Oklahoma State University** **Agronomy Department** **ID#73-6017987**
ADDRESS:	**371 North Ag Hall** **Stillwater, Oklahoma 74078**
PROJECT:	**High Resolution DGPD**
TYPE OF SUBCONTRACT:	**Cost Reimbursable**
PROJECT PERIOD:	**May 1, 1996 to April 30, 1996**
TOTAL FUNDS ALLOTTED:	**$12,000.00**
ISSUED BY:	**University of Oklahoma** **Office of Grants and Contracts** **1000 Asp Avenue, Room 210** **Norman, Oklahoma 73019**

SUBCONTRACT NO. 1997-5

PREAMBLE

This Subcontract, entered into August 15, 1996 by and between the University of Oklahoma, Norman, Oklahoma (hereinafter called the "University"), and Oklahoma State University (hereinafter called the "Subcontractor") constitutes a Subcontract under OCAST Contract 5038.

WITNESSETH THAT

The Subcontractor agrees to use reasonable effort to furnish and deliver the supplies and perform the services set forth in this Subcontract for the consideration stated herein.

SCHEDULE

ARTICLE 1. STATEMENT OF WORK

This subcontractor will perform the work and otherwise exert its best efforts in assisting in the conduct of research set forth in Exhibit A.

ARTICLE 2. PROJECT PERIOD

(a) The project period of this Subcontract is from May 1, 1996 to April 30, 1997.

ARTICLE 3. ALLOWABLE COSTS AND PAYMENT

(a) The estimated total cost of performance of this Subcontract is $12,000.00. Invoices for these costs shall be submitted in triplicate to the Grants and Contracts Office for approval and processing. Funding is for the salary and fringe benefits for Mr. Jerry Speir only.

ARTICLE 4. TECHNICAL REPORTS

As needed by the University and preagreed with the Subcontractor to meet the reporting requirements of OCAST.

ARTICLE 5. FINANCIAL REPORTS

None

ARTICLE 6. DISPUTES

Should the parties to this Subcontract be unable to resolve between themselves any dispute arising from any of the provisions within this Subcontract, each party shall have recourse under the law.

ARTICLE 7. INDIRECT COST RATES

No Indirect Costs will be charged to the Subcontract.

ARTICLE 8. INCORPORATION OF PROVISIONS OF CONTRACT AGREEMENT

The Subcontractor agrees to abide by the terms and conditions of OCAST Contract 5038 which are included as Exhibit B as they apply to this Subcontract.

ARTICLE 9. KEY PERSONNEL

(a) The Project Director for the University is Dr. Kenneth Crawford.

(b) The Project Director for the Subcontractor is Mr. Jerry Speir.

ARTICLE 10. NON-DISCRIMINATION

The parties agree to be bound by applicable state and federal rules governing Equal Employment Opportunity and Non-Discrimination.

ARTICLE 11. LIABILITY

To the extent permitted by the laws of the State of Oklahoma, in the conduct of research under this Subcontract, the Subcontractor is acting in the capacity of an independent contractor, and neither party shall by reason of this subcontract be obligated to defend, assume the cost of defense, hold harmless, or indemnify the other from any liability to third parties for loss of or damage to property, death, or bodily injury arising out of or connected with the research under this Subcontract.

ARTICLE 12. PUBLICITY

Except to the extent required by law, neither party to this Subcontract may use the name of the other in news releases, publicity, advertising, or product promotion without prior written permission.

ARTICLE 13. ASSIGNMENT

This Subcontract may not be assigned in whole or in part without the prior written permission of the University.

ARTICLE 14. TERMINATION

The Subcontract shall continue in full force and effect in its present form or as subsequently amended until such time as it may be terminated, in part or in whole, by mutual consent of both parties, or until terminated by notice in writing given by one party to the other party at least 30 days prior to the date upon which termination is to become effective. Any disputes as to questions of fact shall be subject to Article 6 of this Subcontract.

ARTICLE 15. OTHER SPECIAL PROVISIONS

(a) The books of account, files, and other fiscal records of the Subcontract which are applicable to this Subcontract shall be available during all normal working hours for inspection, review, and audit by OCAST and its representatives to determine the proper application and use of all funds paid to or for the account or benefit of the Subcontract. A copy of the annual audit report prepared in accordance with OMB Circular A-133, "Audits of Educational Institutions and Other Nonprofit Institutions", shall be submitted upon its issuance to the Department of Health and Human Services, Office of Inspector General.

EXHIBIT A

High Resolution GPS Project
OSU Statement of Work
Year 2

GPS Data Collection / Analysis Objectives:

1. Determine positional accuracy that can be achieved with *micronet* of reference receivers approximately 2-4 miles apart.
    A. w/static or stationary autonomous receiver
    B. w/moving autonomous receiver - straight line course
    C. w/moving autonomous receiver - circular course (Optional)
2. Determine positional accuracy that can be achieved with *mesonet* of reference receivers approximately 20 miles apart.
    A. w/moving autonomous receiver - straight line course
    B. w/moving autonomous receiver - circular course (Optional)
3. Compare real-time positional accuracy achieved with dense network of reference receivers with standard commercially available DGPS service.
4. Compare real-time positional accuracy achieved with a dense network of reference receivers with standard commercially available DGPS service on precision farming field application.

Conduct the following data GPS data collections:

1. Static or stationary measurements of autonomous receiver with Micronet:
    - Survey four reference receiver sites (approximately 2-4 miles between reference sites).
    - Perform 1 to 2 hour data collection of with four reference receivers and autonomous receiver positioned within micronet of reference receivers.
    - Perform data analysis at 10 cm increments.
2. Kinematics measurements
    A. w/Micronet of reference receivers.
    - Survey straight line course within Micronet (established in Collection #1)
    - Perform several kinematics data collections with GPS antenna mounted on moving vehicle.
    - Perform data analysis at 10 cm increments.

    B. w/Mesonet of reference receivers (approximately 20 miles between reference sites).
    - Use same straight line surveyed course within established in Collection #2A.
    - Perform several kinematics data collections with GPS antenna mounted on moving vehicle.
    - Perform data analysis at 25 cm increments.

    C. w/Micronet of reference receivers - Circle course (Optional).
    - Survey circle course within Micronet (established in Collection #1). Circle diameter to be determined by Jerry Speir.
    - Perform several kinematics data collections with GPS antenna mounted on moving vehicle.
    - Perform data analysis at 10 cm increments.

High Resolution GPS Project
OSU Statement of Work
Year 2 (continued)

D. w/Mesonet of reference receivers - Circle course (Optional).
- Use surveyed course established in Collection #2C).
- Perform several kinematics data collections with GPS antenna mounted on moving vehicle.
- Perform data analysis at 25 cm increments.

3. Precision farming field application

A. w/Mesonet of reference receivers (approximately 20 miles between reference sites).
- Survey straight line course within Micronet (established in Collection #1)
- Perform several kinematics data collections with GPS antenna mounted on farm equipment (e.g., tractor or combine).
- Location of data collection and application to be determined by Jerry Speir. Possible applications include

○ Herbicide application:	January
○ Nitrogen application:	January - February
○ Harvest:	June (requires extending HRGPS project by one month)

Responsibilities: Jerry Speir
- Establishing and surveying reference receiver sites
- Scheduling and conducting GPS data collections experiments
- Performing data analysis

(b) The Subcontractor assumes sole responsibility for reimbursement to the University a sum of money equivalent to the amount of any expenditures disallowed should OCAST or another authorized representative rule through audit exception or some other appropriate means that expenditures from funds allocated to the Subcontractor for direct and/or indirect costs were not made in compliance with the terms and conditions of this Subcontract.

(c) This Subcontract may be renewed under such terms as the parties hereto may agree.

(d) This Subcontract may be amended as desired by the mutual written agreement of the parties hereto.

(e) Records will be maintained by the Subcontractor in accordance with OMB Circular A-110, "Uniform Administrative Requirements for Grants and Agreements with Institutions of Higher Education, Hospitals, and Other Non-Profit Organizations."

(f) This Subcontract constitutes the entire agreement between the parties and supersedes all previous agreements and understandings related to the work to be performed.

IN WITNESS WHEREOF, the University and the Subcontractor have hereunto executed this Subcontract as of the month, day, and year first above written.

THE UNIVERSITY OF OKLAHOMA	OKLAHOMA STATE UNIVERSITY
By Suzanne Turek Suzanne Turek Subcontract Administrator	By Thomas C. Collins Dr. Thomas C. Collins Vice President for Research and Dean of the Graduate College
Date 9-19-96	Date 9-3-96

APPENDIX B

PROJECT TASK IDENTIFICATION

Project Task Identification

(Preliminary)

1 April 1995

- **I. Project Management**
  - **A. Monitor Task Coordination & Completion**
    - 1. Ensure Project Goals are Addressed and Met
    - 2. Reviewer Concerns Answered
    - 3. On-time
  - **B. Obtain needed Resources & Tools**
    - 1. Administrative
      - i. Proposal Bibliography Reference Copies
        - a. 1994 International ASAE Papers - Univ. of Ga.
        - b. "Compensating for GPS Ephemeris Error", by Jiun-tsong Wu of Caltech
    - 2. Technical
      - i. Contact Nat'l Geodetic Survey - Monumentation
      - ii. Obtain Supporting Equipment
  - **C. Manage Budget**
    - 1. Expenses Covered
    - 2. Funds Expired
  - **D. Status Reports**
    - 1. Identify Project Problems in Timely Fashion
  - **E. Conduct Team Meetings**
  - **F. Marketing**
    - 1. Project Promotion - Implementation Groundwork
      - i. SBIR
      - ii. Private Funding
  - **G. Identify Additional Research**
    - 1. Atmospheric Modeling (Ionosphere/Troposphere)
    - 2. GPS-Based Control Systems
  - **H. Photographic Project Documentation**
  - **I. Final Phase I Report**

- **II. Acquire HW/SW Equipment**
  - **A. 5 Sets OEM GPS Hardware**
    1. Magellan AIV-10V Receivers
    2. Magellan A50 37dB Active Helix Antennas
    3. Power Supplies
       - i. For Bench Testing
       - ii. Automotive
    4. Electronics
       - i. TTL-to-RS232 ICs
       - ii. Voltage Regulator ICs
       - iii. Misc Capacitors/Resistors/Fuses/etc.
    5. Coax/Cables/Wire/Solder/etc.
    6. Tools
    7. Mounting HW - Chasis/Connectors/Wire/Fuses/Screws/Labels
  - **B. GPS PC Software**
    - i. Executable
    - ii. Source
  - **C. 5 Notebook Computers**
    1. ≥386-25/4MB/40MB HD/Diskette/Serial Port/DOS
  - **D. 5 Camera Tripods**
  - **E. Borrow Cellular Phones for Data Collection Coordination?**

- **III. Acquire 1st Order Monumentation Map Locations**
  - **A. National Geodetic Survey (NGS)**
    1. Oklahoma
       - i. OU - Oklahoma City/Norman
       - ii. OSU - Stillwater
    2. Texas
       - i. Dallas
       - ii. Ft. Worth
  - **B. City Data**
    1. Richardson
    2. Hurst/Ft. Worth
    3. Oklahoma City/Norman
    4. Stillwater

C. **Site Survey**
  1. Identify/Visit/Photograph the Site Locations
  2. OSU Trimble Pathfinder or 4000SE Equipment
    i. Reserve OSU Trimble Pathfinder or 4000SE Equipment
    ii. Calibrate our skills using known 1st Order Monumentation
  3. Or, use GPS Data Averaging Scheme
    i. Use Data Collected for Project Analysis
  4. Survey/Mark/Document the New Locations

D. **Documentation**
  1. Equipment Used
    i. Vendor
    ii. Model No.
    iii. Serial No.
  2. Methodology

IV. **Build Equipment**

A. **GPS Receivers - 5 Sets**
  1. Design the Assembly Circuit
  2. Mount in Chasis
  3. Wire Circuit

B. **Antennas**
  1. Calibration Equipment - 1 Set
    i. Signal Splitter Box - connection of 5 rcvrs to common antenna
    ii. Cables
  2. Field Equipment - 5 Sets
    i. Secure to Mast
    ii. Mount on Tripod
    iii. Build Cables

C. **Computer Interface - 5 Sets**
  1. TTL-to-RS232 Circuit
  2. Build Cables

D. **Power Sources - 5 Sets**
  1. Bench
  2. Automotive

- V. **Establish the Test Environment**
  - A. **GPS**
    - 1. Calibration (Antenna T-Junction)
    - 2. Data Collection
  - B. **Computers**

- VI. **Test GPS Measurement System for Normal Operation**
  - A. **Correct Data Messages**
  - B. **Positioning Calculation**
  - C. **Receiver Setup & Control**
  - D. **Data Collection/Recording**
  - E. **PC Software**

- VII. **Software**
  - A. **Functionality Definitions**
    - 1. Equipment Testing
    - 2. Receiver Setup & Control
    - 3. Data Collection
    - 4. Processing Algorithms
      - i. Positional Averaging - for determination of precise site coordinates
      - ii. High-Precision Differential - correlation of data from multiple reference rcvrs
      - iii. Optimal Separation - calculation of optimal reference-to-baseline rcvr separation
      - iv. Maximum Latency - calculation of maximum age latency for reference rcvr data
      - v. Resolution - evaluation of resolution (accuracy vs. repeatability) for test scenarios
    - 5. Commercial Software
      - i. Statistical
      - ii. Visualization
  - B. **Design**
  - C. **Programming**
  - D. **Test**
  - E. **Documentation**
  - F. **Training**

VIII. GPS Receiver Calibration

A. Definition

B. Data Collection

1. T-Junction: Common Antenna
2. Individual Antennas

IX. Data Collection at Monument Locations

A. Prepare Test Plan

1. Identify GPS Data to be Collected
    - i. Position (Latitude/Longitude)
    - ii. Time
    - iii. Ephemeris/Almanac
    - iv. Satellites
        - a. In View
        - b. Used for All-in-View Position Calculation
        - c. Health
    - v. GDOP/PDOP/HDOP
    - vi. Signal-to-Noise Ratio (SNR) for each Signal
    - vii. GPS Available
2. Identify Ancillary Data to be Collected
    - i. Mesonet
    - ii. WSR-88D NEXRAD (NIDS)
3. Surveying Procedure & Methodology - Why Cellular not Being Used
    - i. Personnel
    - ii. Test Run (Practice)
    - iii. Start & Stop Times
    - iv. Iterations
    - v. Antenna Setup
    - vi. Receiver Calibration
    - vii. Receiver Initialization - Define "Sufficient Data" from Proposal
        - a. Data Content
        - b. Sampling Frequency
    - viii. Communications between Survey Crews
4. Contingencies & Exceptions
    - a. Equipment Failure
    - b. Communications
    - c. Transportation
    - d. Personnel

- **B. Create Site Observation Logs**
  1. Project Description, Purpose, Location & Station Name, etc.
  2. Observer's Name
  3. Date and Session Number
  4. Start & Stop Times
  5. Station ID used for File Name
  6. Receiver & Antenna Serial Numbers/IDs
  7. Height of Antenna & Eccentricities in Position
  8. Monument ID
     - i. Description
     - ii. Directions to Location
     - iii. "Rubbing" of Monument Top or Photograph
  9. Meteorological Observations at Site
  10. Position Relative to Mesonet
  11. Problems Experienced & Resolution
  12. "Etc.
- **C. Train Operators**

X. Provide for Collection of Ancillary Research Data

- **A. U.S. Coast Guard (Bulletin Board)**
  1. Satellite Ephemeris
  2. Selective Availability
- **B. Mesonet Data Coinciding with GPS Sessions**
- **C. NIDS WSR-88D NEXRAD Doppler Radar**

XI. Data Reduction utilizing the Software

- **A. Descriptions**
  1. Software Modules
     - i. Developed
     - ii. Commercial
  2. Methodology
- **B. Tabulation**
- **C. Visualization**

- **B. Create Site Observation Logs**
  1. Project Description, Purpose, Location & Station Name, etc.
  2. Observer's Name
  3. Date and Session Number
  4. Start & Stop Times
  5. Station ID used for File Name
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  1. Project Description, Purpose, Location & Station Name, etc.
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  3. Date and Session Number
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  7. Height of Antenna & Eccentricities in Position
  8. Monument ID
     - i. Description
     - ii. Directions to Location
     - iii. "Rubbing" of Monument Top or Photograph
  9. Meteorological Observations at Site
  10. Position Relative to Mesonet
  11. Problems Experienced & Resolution
  12. "Etc.
- **C. Train Operators**

X. Provide for Collection of Ancillary Research Data

- **A. U.S. Coast Guard (Bulletin Board)**
  1. Satellite Ephemeris
  2. Selective Availability
- **B. Mesonet Data Coinciding with GPS Sessions**
- **C. NIDS WSR-88D NEXRAD Doppler Radar**

XI. Data Reduction utilizing the Software

- **A. Descriptions**
  1. Software Modules
     - i. Developed
     - ii. Commercial
  2. Methodology
- **B. Tabulation**
- **C. Visualization**

XIV. Final Report

- **A. Results (from XII)**
- **B. Agricultural Justification (from XIII)**
- **C. Phase II Implementation**
  - 1. Existing Mesonet System
  - 2. DWADGPS Interface to Mesonet
  - 3. Design Goals & Considerations
    - i. Fault-Tolerant
    - ii. Low Cost
    - iii. High Resolution
  - 4. Prototype System
    - i. High Level Design & Plan
    - ii. Cost Goals
- **D. Additional Research Spawned by DWADGPS**
  - 1. Precision Farming Applications
  - 2. Ionosphere/Troposphere Modeling
  - 3. GPS-Based Control Systems
- **E. Etc.**

XV. Phase II Proposal

APPENDIX C

GPS EQUIPMENT

GPS EQUIPMENT

GPS receiver evaluation and selection was based upon criteria critical to maximizing accuracy (minimizing error) at an affordable cost. The following attributes and functionality were carefully reviewed:

- Data Resolution

The number of significant digits carried in the latitude/longitude readouts. This also determines the minimum change in position the receiver is capable of reporting, which needs to be <minimum error objective.

- All-in View Algorithm

The latitude/longitude calculation utilizes all satellite signals being received, rather than just the best four. This increases positional accuracy, and simplifies the synchronization of all receivers on the same complement of satellites (see Data Collection Sessions).

- Number of Channels

The number of simultaneous satellite signals capable of being received. This works in harmony with the All-in-View Algorithm requirement. Rarely will more than 10 satellites be in view at a particular location.

- Non-Volatile (NV) RAM

NV RAM is memory which retains its setup information and date in a power-off configuration (without battery backup). The GPS receivers are configured for specific requirements; NV RAM stores this initialization data during receiver-off, and makes it a available at power-on. This ensures that all receivers operate in the same mode without operator intervention.

- Processor Onboard the Receiver

Sufficient computing capacity in the receiver microprocessor is necessary to process satellite transmissions, produce positional fixes and transmit the data messages to a PC in one-second intervals without losing data.

- Baud Rate

The data rate at the receiver's serial port. This requirement is to ensure compatibility with computing equipment used with the GPS receiver, and to ensure a sufficient bit-rate to accommodate data collection without falling behind.

- Antenna Types Supported

Since GPS satellite signals are quite weak (-130 dbm), the receiving antenna and connecting coaxial cable are important. A transmission line longer than eight feet can attenuate the received signal below the receiver's sensitivity for these low-level signals, negating its ability to detect the satellite transmission. Therefore, the receiver must be capable of powering an antenna with a preamplifier, which boosts the small satellite signal at the antenna, by providing voltage through the coaxial cable.

- Power

For fabrication purposes, the voltage and current ratings need to be known (power supply considerations).

- Electrical Interface

Connector specification and communications protocol definition for the receiver serial port. This can be RS-232 or RS-422. RS-232 is preferable for computer compatibility.

- Data Provided

Latitude, longitude (NAD83 and WGS84 ellipsoids), time, date, satellite status, and receiver status are required. It is desirable to maximize ancillary information provided for monitoring receiver operation and detection/diagnosis of problems. Low-level pseudorange data is not necessary for Phase I.

- Message Code

Encoding scheme for reported data. Choice include NMEA-0183 ASCII (NMEA Standard Specification, Version 2.01, 1994) or vendor-specific binary. Although a standard is desirable, most receivers provide greater resolution with vendor-specific binary, which requires custom PC software to decode.

- Code vs. Carrier Phase Tracking

Positional calculations onboard the receiver are based upon elapsed transmission time for the satellite signals. Time measured either by using satellite clock information transmitted as part of a data message (code tracking), or by comparison of received signal carrier phase with the phase of an internally generated bit stream (carrier phase tracking). Carrier phase can produce better results, but most receivers now use both methods for optimal results.

- RTCM-SC104 Support

Receivers supporting this capability are able to accept and process DGPS error messages from an external source, such as a DGPS receiver. Although not required for Phase I, this may become important if the receiver is used later in Phase II.

- Included Software

Example programs for controlling the receiver, and for data collection are needed to minimize the development effort.

- OEM Developer's Kit Availability

Engineering documentation for the receiver, including power, packaging, connectors, software interface, and operation specifications is required since the receivers are custom-built to suit the research.

- Price

Receiver cost must be in line with the proposed project budget. Receivers evaluated were typically $300 - $400, with some as high as $1,000.

APPENDIX D

GPS RECEIVER HARDWARE CRITERIA

GPS Receiver Hardware Criteria

5/10/95

Receiver	# Chnls/Ports	Electrical	Baud Rate (100 bps)	Power	Antenna	Size (in.)	Price	NV
Motorola *Oncore*	8/1	TTL or RS232	NMEA0183=48 MotBin=96	5/12vdc 1.1 w	Y	2.76 x 3.94	$371	Y
Magellan *AIV-10V*	10/2	TTL	96 RTCM=48/96	5vdc 1 w	Y	2.75 x 4.33	$295	Y
Rockwell *MicroTracker*	5/2	TTL	96 NMEA0183=48/96	5vdc 1 w		2.0 x 2.8	$370	N
Trimble *SVeeSix*	6/1	TTL	TSIP=96 N0183=48	5vdc 1.25 w		1.83 x 3.25	$300-400	N
Furuno *GN72* *GN74*	8/1 8/1	RS232 or TTL TTL	12/24/48	5vdc 2.0 w 5vdc 0.8 w	Y Y	3.9 x 2.7 1.6 x 3.2	$300 $300	N
Garmin *PhaseTrack 12* *MultiTrack 8*	12/2 8/2	RS232 RS232	12/24/48/96 12/24/48/96	5vdc 1.1 w 5vdc 0.8 w	Y Y	1.83 x 2.75 1.83 x 2.75	$375 $250	Y

I. GPS Receiver Hardware Criteria (con't)

5/10/95

Receiver	# Channels	Electrical Interface	Baud Rate (100 bps)	Power	Antenna Power	Size (in.)	Price	NV RAM
Si-Tex *GPS-5*	5/1	RS232/RS422	NMEA0183=24/48/96	6-35 vdc 3 w	Y	3.7 x 6.1 (chasis)		
Ashtech *Sensor II*	12/2	RS232	300 - 38,400	5vdc 2.5 w	Y	2.25 x 4.25	$1200	
Japan Radio Co. Ltd. *CCA Series*	8/2	TTL/RS232	1200/4800	5vdc 0.25w 10-16vdc	Y	2.95 x 4.72	$400	
Canadian Marconi *ALLSTAR*	12/2 (Can use 1 port)	TTL	300 - 76,800	5vdc 0.3 w	Y	2.65 x 4.0	$1200	Y

APPENDIX E

GPS SOFTWARE

GPS Receiver Software Criteria

5/10/95

Receiver	Msg Code	Msg Content	Cmd Set	Algorithm	Raw GPS Data	Code+Carrier Tracking	Resolution	RTCM SC104	Post-Proc SW	Developer Kit
Motorola *Oncore*	Mot Bin N0183	Extended+ Raw Meas	Mot Bin	AIV or B4	Y	Y	10^{-3} sec (1.22 in)	Y	Y	$1200*
Magellan *AIV-10V*	Mag Bin	Basic	Mag Bin	AIV	N	Y	10^{-7} deg (0.44 in)	Y		$135
Rockwell *MicroTracker*	N0183 RW FP Bin	Basic	RW Bin	B4	N	Y		Y		$1000*
Trimble *SVeeSix*	TSIP Bin N0183 Taip Bin	Basic	TSIP Bin TAIP Bin	B4		Y	10^{-5} deg (3.67 ft)	Y		
Furuno *GN72* *GN74*	N0183 N0183			AIV AIV		Y		Y Y		
Garmin *PhaseTrack 12* *MultiTrack 8*	N0183 N0183	Basic Basic		AIV AIV		Y Y		Y Y		$950* $650*

GPS Receiver Software Criteria (con't)

5/10/95

Receiver	Msg Code	Msg Content	Cmd Set	Algorithm	Raw GPS Data	Code+Carrier Tracking	Resolution	RTCM SC104	Post-Proc SW	Developer Kit
Si-Tex *GPS-5*	NMEA0183	Basic	N0183	B4	N	Y	10^{-2} min (7332.9 in)	Y		
Ashtech *Sensor II*	NMEA0183	Extended	N0183	AIV		Y		Y		
JRC Ltd. *CCA Series*	NMEA0183 JRC Bin	Extended	JRC Bin	AIV	N	Y		Y		
Canadian Marconi *ALLSTAR*	NMEA0183 CMC Bin	Basic	N0183 CMC BIN	AIV	Y	Y	10^{-4} min (NMEA) (7.33 in)	Y		$1200

APPENDIX F

HARN SURVEY RUBBING

HARN Survey Rubbing

Designation	- STIL				
PID	- GH1055				
State/County	OK/Payne				
USGS QUAD	Stillwater South (1980)				
HORZ Datum	NAD 83 (1993)				
VERT Datum	NAVD 88				
Position	36 02 37.98019 (N)			097 03 03.22539 (W)	Adjusted
Height	299.0	(meters)	981.	(feet)	GPSOBS
88 minus 29	+0.1				VERTCON
Laplace Corr	- 0.83				DEFLEC93
Geoid Height	- 28.18				GEOID93
Ellip Height	270.847				
X	- 633806.763				
Y	-5124306.330				
Z					
Horiz Order	B				
Ellp Order	Fourth	Class 2			

The horizontal coordinates were established by GPS observations and adjusted by the National Geodetic Survey in May 1994. This is a “special status” position. See special status under the “Datum Item” on the data sheet items page.

The orthometric height was determined by GPS observations. The Laplace correction was computed from DEFLEC93 derived deflections. The geoid height was determined by GEOID 93. The ellipsoidal height was determined by GPS observations and reference to NAD83. The X, Y, and Z were computed from the position and the ellipsoidal height.

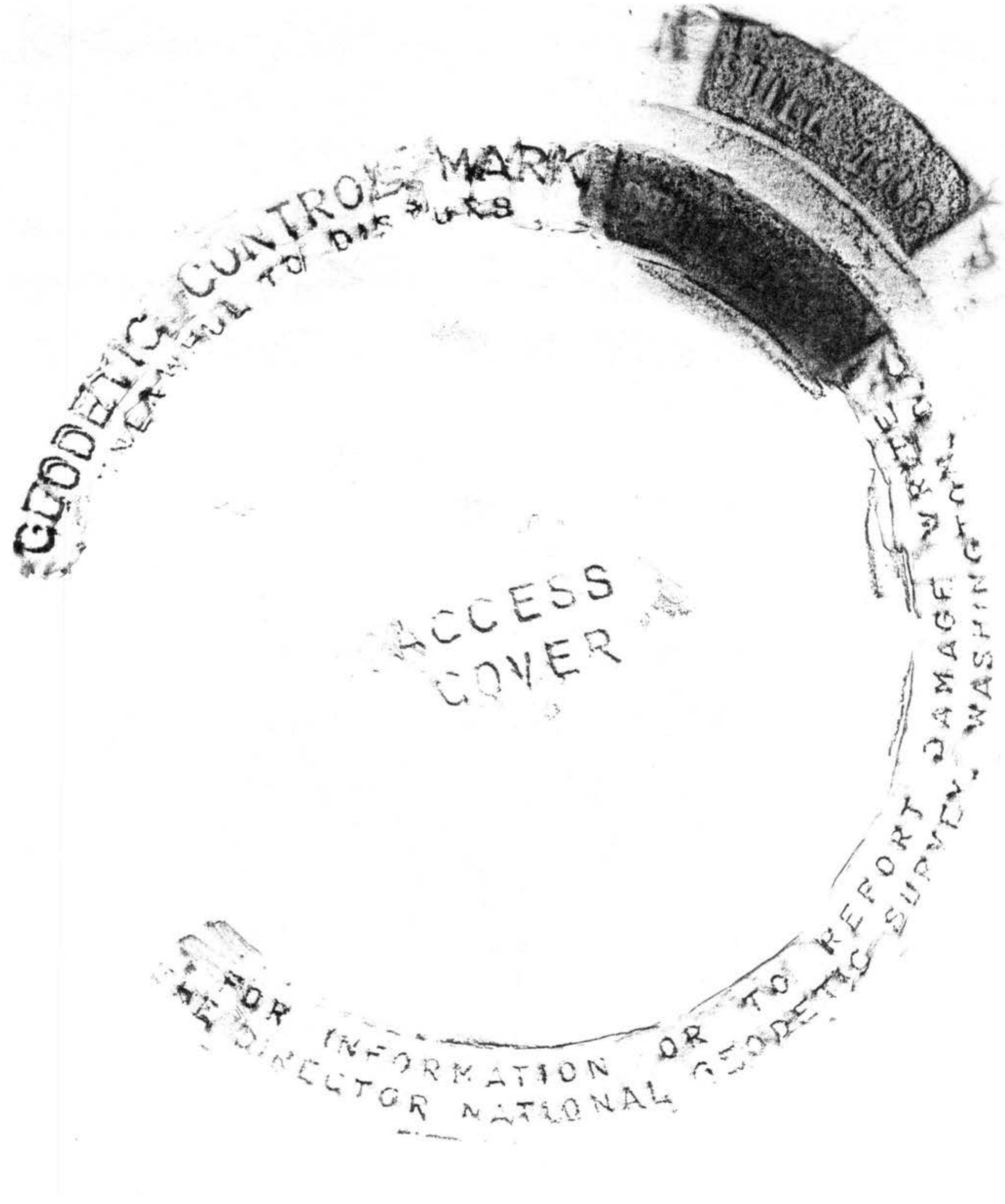
	North	East	Scale	Converg.
SPC OK N	116,239.623	685,521.453	0.99994772	+0 33 36.4 MT
UTM 14	3,990,573.437	675,581.248	0.99997987	+1 08 49.8 MT

Station mark is a metal rod with setting: Stainless steel rod in sleeve (10 ft. +). The mark is stamped: STIL 1993. Stability B = probably hold position/elevation well. Satellite: The site location was reported suitable for satellite. Satellite observations - August 25, 1993.

History	Year Condition	Recovered by
History	1993 Station Monumented	National Geodetic Survey

Station description: Described 1993. Station is located about 8 KM (4.95 miles) south of Stillwater, 4.8 KM (3.00 miles) north of the junction of U.S. Highway 177 and State Highway 33, along Highway 177, on the right-of-way, adjacent to a field, at a field entrance, in the Northeast angle of the junction of the highway and Mehan Road, in the Southwest 1/4 of Section 12, T 18 N, R 2 E. Ownership: Oklahoma Department of Transportation. To reach from the western one of two junctions of highways 177 and 33, about 13 KM (8.05 miles) south of Stillwater, go north on Highway 177 for 6.46 KM (4.00 miles) to a crossroad. Continue ahead for 0.05 KM (0.05 miles) to the station on the right. Station mark is a punch hole top center on a stainless steel rod in a grease filled sleeve 90 cm long encased in a 12.7 cm PVC pipe with logo cap surrounded by concrete set flush with the ground. It is 24.7 m (81.0 feet) east of, and slightly lower than the highway center, 49.3 m (161.7 feet) north of the center of Mehan Road, 8.7 m (28.5 feet) south of a utility pole, 2.5 m *8.2 feet) west of a steel witness post in the right-of-way fence, and 1.6 m (5.2 feet) west-southwest of a fiberglass witness post at a sawed-off utility pole braced fence post. The rod is flush with ground level and driven to a depth of 4.5 meters.

STIL - HARN Survey Rubbing



APPENDIX G

OKLAHOMA MESONETWORK

Oklahoma Mesonetwork

The Oklahoma Mesonetwork is a statewide environmental monitoring network developed through the cooperative efforts of Oklahoma State University (OSU) and the University of Oklahoma (OU). The Mesonetwork (abbreviated "Mesonet") is a bold and ambitious project to place timely and highly useful weather information in the hands of the citizens of Oklahoma. The goals of the Mesonet (Crawford et. al. 1992) are to 1) operate a high quality network of automated stations that measure about 10 variables each and transmit these data, in real time, every 15 minutes; 2) relay that information via a state-wide telecommunications network to a central processing site for quality assurance, archival product generation, and dissemination; 3) share this new data stream with the research community in Oklahoma and combine network data with other data streams for applications in agriculture, meteorology, and other disciplines; and 4) provide an efficient, highly effective mechanism to share network data with a host of federal, state, and local government users (including public and private schools) along with private agencies. Besides the agricultural, hydrological, and meteorological goals, it quickly became apparent that the network must also satisfy emergency management and energy conservation needs" (Elliott, et al., 1991).

The Oklahoma Mesonet consists of 111 automated observing stations that continuously monitor a number of important weather and soil parameters, Figure 1, Location of Mesonet sites. These Mesonet remote stations have a set of core parameters of which GPS has the promise of adding an additional Atmospheric Monitoring parameter (Businger, et al., 1996). Present parameters including rainfall, barometric station pressure, solar radiation, air temperature, and relative humidity at a height of 1.5 meters, wind speed and direction at a height of 10 meters, and soil temperature under both bare soil and a natural grass cover at a depth of 10 cm. Supplemental parameters, measured at a significant subset (about half) of the 111 sites, include air temperature at a height of nine meters, wind speed at a height of two meters, leaf wetness and soil temperature at additional depths (5 and 30 cm). Every 15 minutes data observed over five-minute intervals are relayed from each of the remote stations to a central processing site (Elliott, et al, 1994). This transfer of data is accomplished rapidly and reliably using a combination of radio telemetry and the capabilities of the Oklahoma Law Enforcement Telecommunications System (OLETS), an agency of the Oklahoma Department of Public Safety (DPS).

Base-station computers receive the data from OLETS, check their quality, manage data storage, and assist in disseminating the observations and certain-value added products to a large, statewide community of users - all within minutes of each observation time. Data are distributed via computer networks and bulletin boards, print and electronic media, and interactive public displays (Brock, et al, 1995). It is envisioned that Mesonet data will help save lives, save Oklahoma businesses and taxpayers millions of dollars annually, reduce energy consumption, educate the next generation of conservationists, and make an incredible contribution to research projects each year.

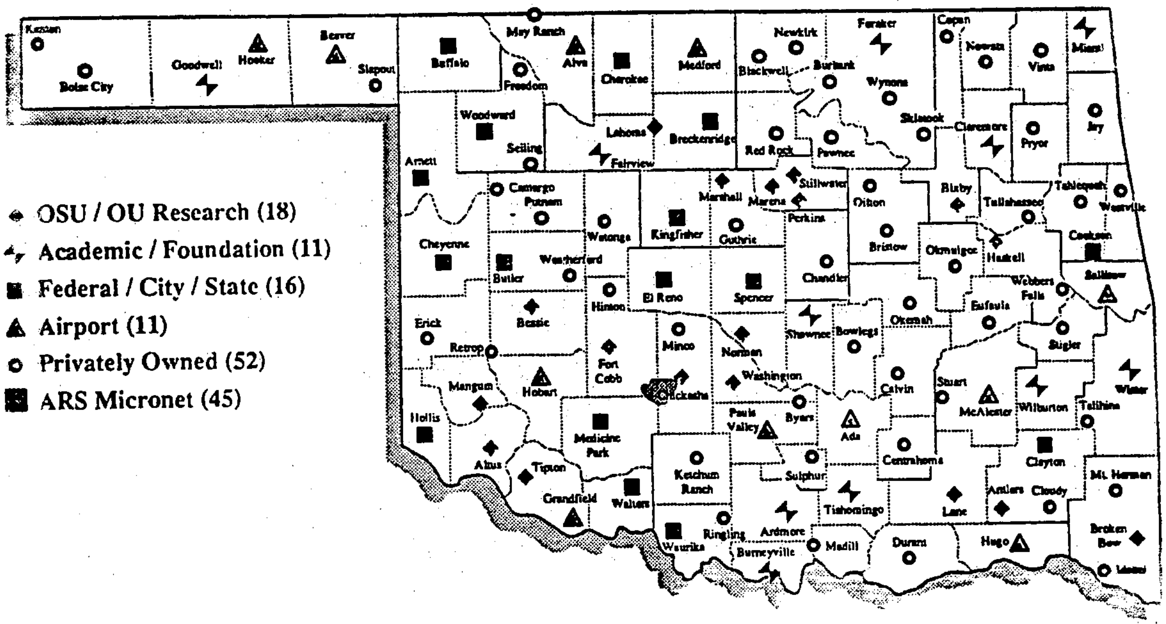


Figure 24. Locations Of Mesonet Sites

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